DEVELOPMENT AND VALIDATION OF SIMULATORS FOR POWER WHEELCHAIR DRIVING EVALUATIONS

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Of all those people with severe physical and cognitive disabilities who are rated as unsafe to drive a power wheelchair and hence denied a wheelchair, a significant number can have positive outcomes by using advanced control interfaces and by getting adequate amount of driving training. This dissertation research presents development and user evaluations with a virtual reality based wheelchair driving simulator system. Using the software systems validated in these research studies clinicians can select and customize joystick interfaces that can optimally use their client’s physical and cognitive capabilities. When people with traumatic brain injury and cerebral palsy used the isometric joystick they committed equivalent or lesser driving errors than when they used the conventional movement sensing joystick to drive a wheelchair. Potential wheelchair users can benefit from such customizable control interfaces to reliably and safely control their power wheelchairs and improve their community participation.

An immersive virtual reality simulator was further developed as a driving training and evaluation tool. People with various disabilities completed a clinically validated driving evaluation protocol in real and virtual environments. Their virtual driving performances in the simulator were predictive of their performances in real world. Experienced clinicians showed high inter and intra rater reliabilities in their driving evaluations. Research was also performed to understand the relative contribution of different system components of the simulator system to the overall mental and physical workload of users. This research may assist researchers in selecting simulator system components that best suit the clinical needs of potential users.

Clinicians who were trained to evaluate wheelchair driving using this system and wheelchair users who used it gave a general positive feedback that that this simulator has good potential for use in clinical or community settings.

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PREFACE

I would like to express my most sincere gratitude to Dr. Rory Cooper, for his vision and work ethic motivates me to continue pursuing research in the field of rehabilitation. I would also like to thank Dr. Brad Dicianno and Dr. Don Spaeth for believing in me, giving me opportunities to work with them on their research grants. I really appreciate them for being patient through my learning process and allowing me to make and correct my mistakes. Thanks are also due to Dr. Bambi Brewer and Dr. Dan Ding, my committee members, for some valuable discussions and assistance during various phases of my research and while preparing this dissertation document.

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1.0 INTRODUCTION

In a recent survey about 41.3 million civilian non institutionalized Americans reported a disability. Of these, 4.3% reported sensory disability, 9.4% reported a physical disability, 5.8% reported a mental disability and 3.0% reported a self care disability [1]. According to the 2002 United States Census Bureau's Survey of Income and Program Participation (SIPP) [2], there were around 2.7 million wheelchair users in the U.S. With an average growth rate of 8.8% per year [3], this population is estimated to be around 6 million by 2011. About 9-15% of this population (540,000 to 900,000) uses power wheelchairs for their day to day mobility [3], [4] .

Research has shown that about 25% of people who desire a power wheelchair fail in their initial clinical assessment. Up to 40% of those who use PWC's regularly have problems steering them, and 5-9% cannot steer at all [5]. About 85% of clinicians interviewed by Fehr *et.al.* [5] reported of having clients who never qualified for safely using a powered mobility device mainly because they lacked requisite skills. About one-third of all assistive technology devices are abandoned by users within the first year of use and more so later. No client involvement in selection of the assistive technology, improper device performance, and improper configuration are some of the most important factors for rejection [6–8]. Besides, clients reported an opportunity for familiarization and training with the new assistive device before final delivery is important for improving their satisfaction with the assistive technology [9]. Clients who haven't perfected skills necessary for wheelchair driving or those who have no prior experience with driving motorized vehicles could be unsafe drivers. If given a chair without adequate training with the device may result in accidents and injury to self and/or others. With training clients feel comfortable in using all features of their wheelchairs and control interfaces while performing their activities of daily living.

Research presented in this dissertation has two main research objectives: to validate a tool that will help clinicians to customize user interfaces to their client’s needs and to design and validate a tool that will assist clinicians in assessing and training potential wheelchair users.

1.1 TOOL FOR CUSTOMIZING USER INTERFACES TO WHEELCHAIRS

A wide range of functional limitations from physical and cognitive disabilities can make someone a potential client for a power wheelchair. In a rehabilitation clinic, clinicians customize the available assistive technologies to their client’s needs. In most cases such customization is based on their clinical judgment and experience from what had worked in past. There has been some prior experience with customizing mouse and joysticks for computer access tasks [10–12]. However, there is no standardized protocol followed by clinicians to select and customize wheelchair input interfaces for their clients. Ding et.al. [13] designed an optimized joystick control interface that would assist clinicians to tune joysticks to their client’s physical needs. Clients perform certain standardized tasks in this software simulation and clinicians can select appropriate gains in joystick axes, dead zones shapes and sizes, template shapes and sizes, and bias corrections in the joystick axes. A recent comparative study showed that the tuning software was able to customize joystick parameters to clients of different disabilities [14]. Other than the conventional movement joystick, this software can also be used to tune certain experimental/customized user interfaces. For example, a variable compliance joystick was designed for specific needs of clients with multiple sclerosis and the tuning software was used to derive standardized joystick parameters [15]. An isometric joystick was designed for clients with traumatic brain injury and cerebral palsy. Chapters 3 and 4 present results from research studies that used this tuning software to tune the isometric joysticks.

1.2 TOOL FOR DRIVING ASSESSMENT AND TRAINING

While using the wheelchair in their daily lives, clients have to drive in a number of different scenarios with different surfaces (grass, tile, carpet), traffic situations (inside home or on the road), and architecture (doorways, hallways, ramps, tight office spaces, elevators). They may encounter stationary and moving obstacles in these situations some of which are predictable and some sudden. Replicating all of these scenarios may be difficult, if not impossible, in a busy clinical setting. Someone who is still a marginal driver needs extra supervision while practicing wheelchair driving. A small degree of automation will help to streamline the driving assessment/training protocol that the clinician uses with their clients. To ensure effectiveness, these systems must satisfy some basic requirements of safety, reliability, and relevance to real world wheelchair driving skills.

Automated obstacle avoidance and path planning/guiding systems have used for assisting power wheelchair drivers in avoiding obstacles and path planning [16], [17]. Such automated systems, are expensive to implement and validate for clinical purposes and are typically specific to certain environments only (indoors and office rooms with specific dimensions). These systems could be useful for users who have prior motor vehicle driving experience and who need assistance in transitioning to wheelchair driving without much supervision by the clinician. Those who lack the cognitive and visual-spatial abilities essential for driving have complicated training needs which require focused and innovative training protocols under constant supervision of an experienced clinician.

A virtual reality environment is a computer program which can display high quality graphics based simulations of real world scenarios. Virtual simulations have shown promising results in training people in their activities of daily living skills [18]. Due to their flexibility and ease of use virtual environments have been used to perform highly reliable assessments of cognitive abilities [19], visual spatial neglect [20] to name a few. Knowledge and skills especially spatial skills learned in a virtual environment can transfer to tasks in real world [21], [22]. This makes them an ideal candidate for training people on navigational tasks.

With virtual environments, it is conveniently possible to generate almost any type of driving scenario the client may encounter during his or her real world driving. Real world environments that are potentially risky for a new driver or that which are inaccessible can be simulated in virtual reality (VR). VR simulators can help to remove fear of driving in those with perceptual and cognitive limitations and in those with no prior wheelchair or motor vehicle driving experience. Training protocols in virtual environments have high degree of repeatability and reliability and the clinicians can provide augmented feedback to the user. All these factors are important for motor learning [22]. A clinician can simultaneously oversee driving of multiple clients and track progress in their skills. VR can provide clinicians with a quantitative tool to evaluate driving capability of a client. Motor vehicle driving simulators have long been used to evaluate motor driving capabilities of those with perceptual and other disabilities [23–28]. There has been a good amount of research about feasibility of driving simulators for training and evaluation for motor vehicle driving. Lew *et. al.* [29] evaluated the predictive validity of one such driving simulator and found that motor vehicle driving training with such simulators is reflected in the subject's on the road driving test performance. Similarly, a high correlation was observed between motor vehicle driving performances in VR simulation and in real world [25], [26].

Conceptually similar, a power wheelchair driving simulator is also expected to provide equivalent benefits as indicated in our preliminary studies [30], [31]. Before using the wheelchair driving simulator in a clinical setting it should have proven reliability and repeatability and its outcome measures should have high validity for the population of interest. Researchers have developed virtual wheelchair driving simulators for driving training [32–40]. However, these simulators were evaluated by small samples sizes and the clinical validity of the simulators was necessarily established. There was only one prior study where researchers specifically designed simulators for wheelchair driving assessments [41]. However, the assessments metrics used in that research study were quantitative metrics derived from the user's joystick input and chair trajectory. Trajectory based evaluation metrics, derived from their equivalents in computer access research, can give an estimate of the client's driving performance for a limited number of driving tasks and they have been used in previous research [26], [42], [43]. There are however some complicated driving maneuvers/tasks that cannot be fully described only using quantitative measures. Quantitative metrics must be correlated with clinically relevant and standardized driving performance measures for them to make sense.

1.3 STRUCTURE OF THIS DISSERTATION

In order to ensure that the driving in the virtual world is perceptually similar to driving in real world, it is recommended that the virtual worlds closely mimic the real world. Other than better graphics, virtual worlds implement physics based model to simulate motion of its components. Chapter 2 presents the design and validation of one such mathematical model that simulates wheelchair driving in the virtual world.

Four different design iterations were performed with the virtual wheelchair driving simulator. The level of details in graphics, camera projection, and simulator physics model were selected considering the physical and cognitive limitations of the population the simulator was designed for. The first version (described in Chapter 3) was specifically built to use with people with traumatic brain injury [37], [42] and multiple sclerosis [15]. This was used to compare virtual driving performances using a custom isometric joystick and a conventional movement joystick. The second version (described in chapter 4) was designed to be used with people with cerebral palsy and to compare driving performances using isometric and movement joystick. Both of these versions used the tuning software to customize joysticks.

The third version of the driving simulator was intended to be used with experienced wheelchair users. This version was specifically designed as a wheelchair driving assessment tool that would simulate a real world assessment protocol. Along with some trajectory based driving performance metrics (see Chapter 5) a clinically validated performance measurement tool was used to compare the effects of display screens and software algorithms in the user’s driving performance. In the research presented in Chapter 6, intra and inter rater reliabilities of clinical driving assessment measures were established for their use in a virtual environment. Algorithms were also designed to be implemented in the virtual environment to perform an automatic assessment of user's virtual wheelchair driving. The agreement in these automated performance scores were compared with the scores from the experienced clinicians.

The fourth version of the driving simulator was designed to be used for both experienced wheelchair users and inexperienced or potential users of wheelchair in future. The virtual environment for this version was modeled to look like an actual real world office environment with realistic texture and graphics rendering. The research presented in Chapter 7 further evaluates inter and intra rater reliabilities of the virtual driving assessment tool in a larger cohort of wheelchair users. Chapter 8 presents some preliminary research about establishing concurrent validity of the virtual driving assessment tool with its real world counterpart. This is followed by future directions of research and appendixes.

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2.0 MATHEMATICAL MODELING OF WHEELCHAIR DRIVING

With a aim of present a realistic simulation of wheelchair driving in virtual environments, it is important to have a mathematical model, that can predict a real wheelchair's speed from joystick inputs. The mathematical model will help to improve our understanding of wheelchair dynamics and how to optimize them for use in the virtual environments. Such a model has other potential applications in gaming and remote wheelchair evaluation, where the user can try out a certain wheelchair configuration in a safe environment. This chapter presents research studies performed to develop and validate a mathematical model for wheelchair driving.

2.1 PRELIMINARY WORK

A simplistic wheelchair motion model was built by curve fitting the acceleration profile of a commercially available Quickie P300 rear wheel drive power wheelchair [1]. For certain preset input levels, Velocity data to build this model was collected when an able bodied person (weight: 62 kg) who drove a Quickie P300 power chair along a predefined path on a tiled floor. The curve fit model was a quasi-proportional derivative motion model with features for differential driving and braking. Figure 2-1 explains the modeling protocol.

This model was intended to simulate wheelchair driving in 2 dimensional orthographic wheelchair driving simulations. To create an orthographic view of the virtual wheelchair and the track, the camera viewpoint was set at a significantly higher distance above ground and looking straight down to create a “light house visual projection”. This way, as per the requirements of that research protocol, the chair and tracks appeared to be two Dimensional (2D) objects. This simplistic model was perceptually good enough to simulate wheelchair driving as seen from an orthographic viewpoint with low degree of local visual optical flow. Refer chapter 3 and 4 for detailed description of these research protocols. More immersive 3D simulations, especially those where the actor (driver in this case) are interacting the virtual world in a first-person-shooter like viewpoint, require to have a more engaging optical flow to feel a higher sense of presence in the virtual environment. This was a motivation to develop a better mathematical model that would more closely simulate real world wheelchair driving in the virtual world.

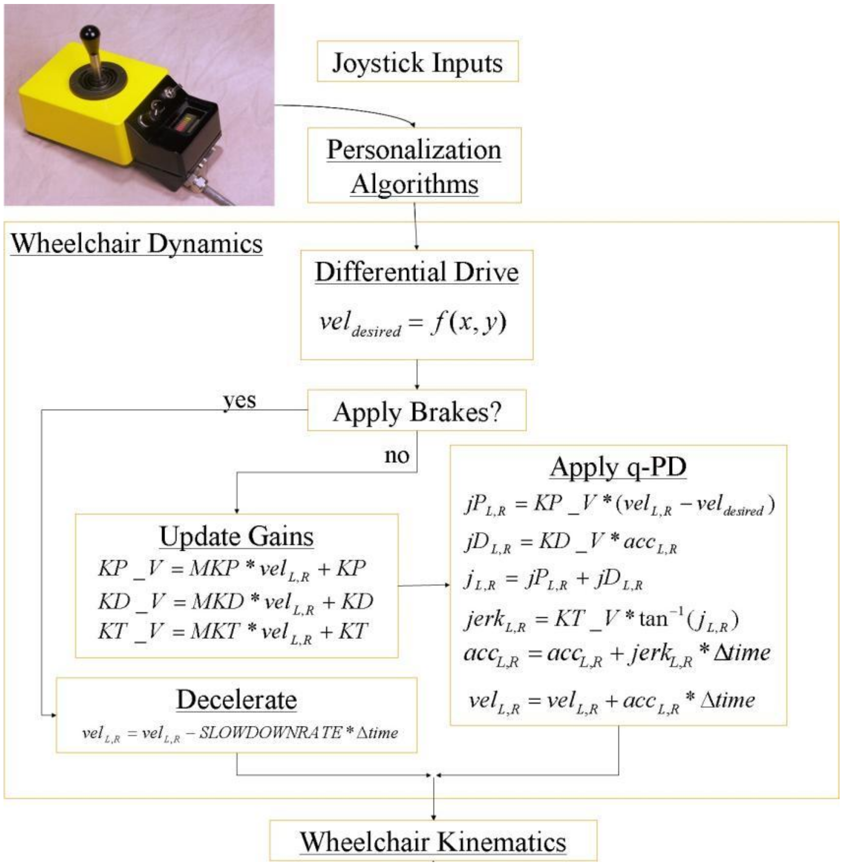

Figure 2-1: Curve fit based mathematical model of wheelchair kinematics

2.2 SYSTEM IDENTIFICATION

For its implementation in a real time virtual world, the mathematical model had certain design requirements. Firstly, the model was expected to simulate a wheelchair's kinematics as close as possible to those of a wheelchair driven in real world. Displaying the graphics in a virtual world is computationally very resource intensive. Hence, computing outputs from the model had to be relatively fast. Also, it was important that the model can be customized to the user's desirable driving speeds and accelerations.

Commercially available wheelchairs implement proprietary algorithms to generate motor currents (hence wheel velocities) from joystick input voltages. Since the wheelchair manufacturers use custom electronic and mechanical components, crucial information about these components like data processing in the joystick and motor torque-speed curves is also not readily available. Besides, it is a cumbersome process to determine kinetic properties of all wheelchair components for their use in an exact mathematical model. The process of System Identification (SI) is a promising approach to build mathematical models of systems which are too complex or too hard to model [2]. MATLAB has a resourceful system identification toolbox [3], [4]. For certain systems, there is a general idea about internal system components. Grey box SI modeling techniques can help used to determine specific parameters of the system. However, if none of mathematical relations between the system's internal components are known, it can be treated as a black box and SI techniques used to build a mathematical structure that could simulate the responses from the system components. The black box modeling approach was selected for the purpose of this study. System Identification is a highly iterative process. Once we have the input and output data from a certain system black box, there are multiple model structures and input output configurations that could be used. In black box modeling techniques, the model structure is fit to the available input output data. This modeling procedure would give an approximate model structure in form of a transfer function which satisfies the requirements of computationally efficiency and customizability. The research objective of this study was to develop a reliable and repeatable wheelchair modeling protocol using system identification techniques.

2.3 METHODS

2.3.1 Logging Wheelchair Kinematics

For building reliable models using system identification (SI), it is important to have accurate real time data of the inputs and outputs to the black box of interest. In this case, the variables of interest were joystick inputs and wheel velocities (outputs) from both drive wheels. Currently available wheelchair controllers employ a driving strategy similar to that of a 2 wheel differential drive robot.

Permobil C500, a front wheel drive wheelchair, with conventional joystick was used for this study. The joystick post deviated 0 to 20 degrees from vertical in the sagittal and coronal/lateral planes. The deviations in both axial planes were linearly related to raw voltages from two voltage channels output from the joystick’s inductive core (See Figure 2-2, refer [5]). A National Instruments Data Acquisition card (NIDAQ) 6024E was used to log these two voltage channels (Jx, Jy) in real time. One direct way to capture wheelchair kinematics from wheels is to install encoders that read wheel rotational velocities. While this approach is prone to errors from dead reckoning due to wheel and gear slippage during acceleration/deceleration of chair, the accumulation of such errors could be minimized by having better recording hardware and short (less than 50 meters) driving trials. We expect the data collected for this study will not have significant accumulation of errors since the driving trials were small (~15 meters) and on flat indoor surface. However, the amount of odometry error from the current setup was not previously tested.

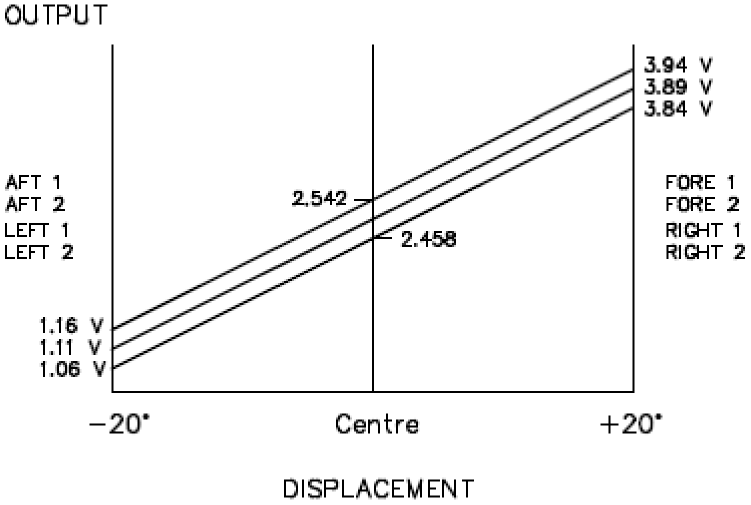

Figure 2-2: Joystick Output Voltage Vs. Angular Displacement of Joystick Post. From [5]

Optical encoders were installed on concentric gears on wheel hubs to read wheel rotation data. Voltages from the joystick were also read in real time. The wheelchair's joystick controller allows for changing the speeds from level 1 to 5. Increasing the speed level also increases the maximum speed the wheelchair could reach. The maximum speeds in reverse directions were approximately half the maximum speeds while driving in forward direction. All data for this study were collected from driving trials performed at one preset speed setting (speed level 3). This setting would give an intermediate model which could be linearly scaled to match the other speed levels.

In all, 430 individual trials were recorded while driving a wheelchair on a tile surface by the same person. Trials were collected as four separate “experiments” where each experiment involved a certain type of riving task performed multiple times. Experiment 1 involved driving along a straight hallway and stopping at a 50 ft mark. (Trials performed: 63). Experiment 2 involved turning left/right and driving straight forward along a hallway. (Trials performed: 111). Experiment 3 involved driving reverse along a hallway and included a left/right turn. (Trials performed: 109). Experiment 4 was free style driving along a hallway/office space and trials involved multiple turns around obstacles. (Trials performed: 151). These tasks were selected so as to cover most of the commonly used wheelchair movement patterns by a typical wheelchair user in an indoor environment.

2.3.2 Mathematical Modeling Protocol

MATLAB System identification toolbox [3] was used to build black box mathematical models from the joystick and wheel velocity data. The procedure followed is summarized in Figure 2-3 (adapted from [4], [6]).

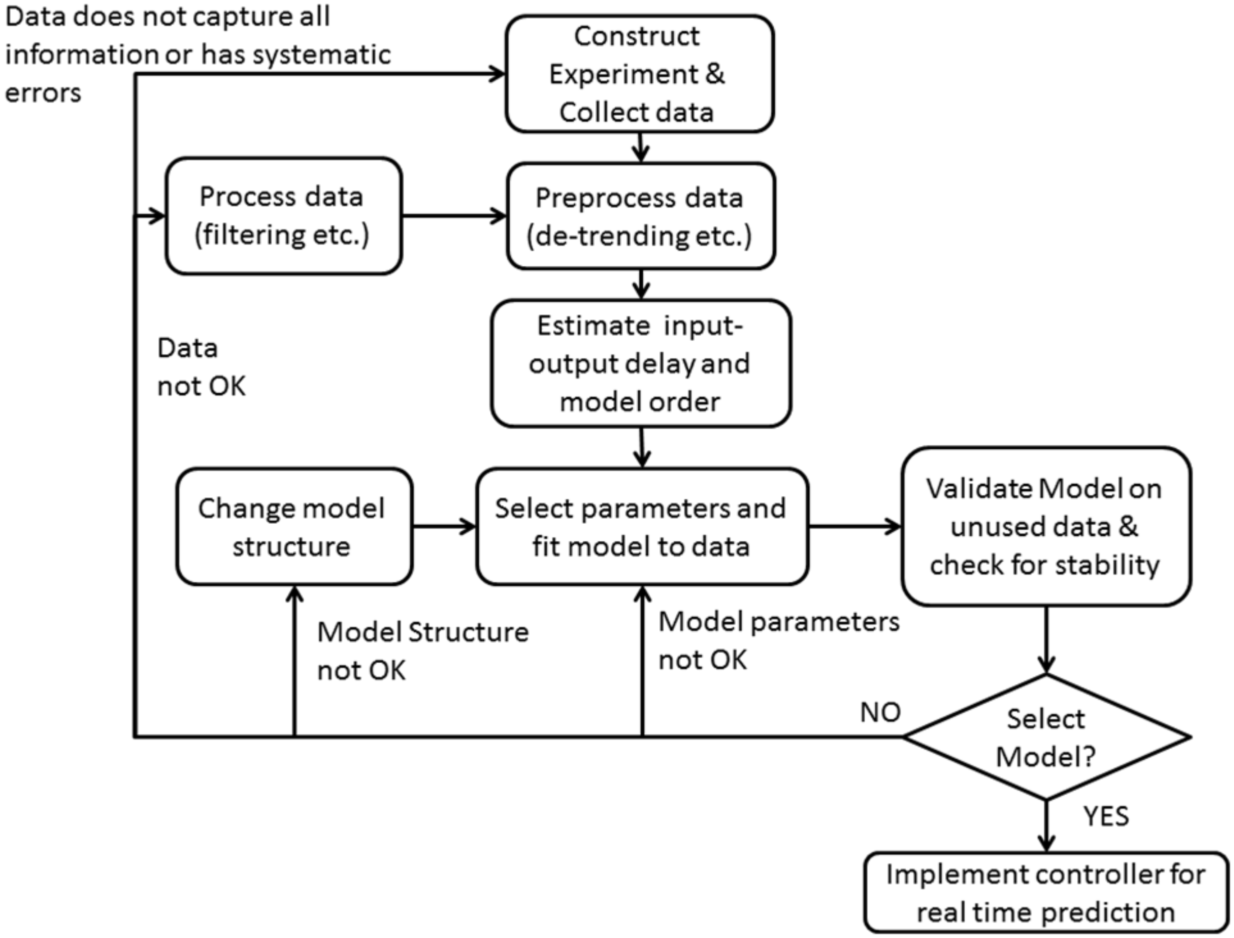

Figure 2-3: Flowchart for system identification process (adapted from [4], [6]).

From the raw data that was recorded, the encoder tick count was converted to linear velocity (meters/second) for left and right wheels using Equation 1. Data were smoothened to reduce noise and re-sampled at a specific sampling interval of 0.01 seconds and cubic spline interpolation used wherever required. Linear velocity (meters/second) and rotational velocity (radians/second) of the wheelchair were calculated using Equation 2 and Equation 3.

$$LinearWheelVelocity = \frac{Enc(t) - Enc(t-1)}{\Delta time} * \frac{\pi * WHEELDIAMETER}{\begin{matrix} EncoderTicksPerWC \\ WheelRotation \end{matrix}}$$

Equation 1: Wheel velocity from encoder tick count

$$LinearVelocity_{WC} = \frac{Velocity_{LEFTWHEEL} + Velocity_{RIGHTWHEEL}}{2}$$

Equation 2: Linear velocity of Wheelchair

$$RotationalVelocity_{WC} = \frac{Velocity_{LEFTWHEEL} - Velocity_{RIGHTWHEEL}}{CHAIRWIDTH}$$

Equation 3: Rotational velocity of Wheelchair

In order to account for complex relationships between inputs and outputs and as recommended by Ljung [6], a multi input multi output (MIMO) state space linear time invariant model structure was selected. The state space model structure is specifically suited for cases when specific internal structure of the model is not known precisely. In the state space model structure (Equation 4), $y(t)$ represents outputs at time t, $u(t)$ represents inputs (J_x, J_y) at time t, $x(t)$ is the state vector at time t, and $e(t)$ is the white noise disturbance. A, B, C, D, and K are matrices of constants specific to that model.

$$x(t+1) = A.x(t) + B.u(t) + K.e(t)$$

$$y(t) = C.x(t) + D.u(t) + e(t)$$

Equation 4: State Space model structure

For a model which has a good fit to data it is important to select appropriate inputs and outputs to the model structure. Black box models were constructed for two different outputs as shown in Figure 2-4. In “Method 1” Joystick voltages (J_x, J_y) were set as inputs and left and right wheel velocities were set as outputs. In “Method 2” Joystick voltages (J_x, J_y) were inputs and wheelchair linear velocity ($LinearVelocity_{WC}$) and rotational velocity ($RotationalVelocity_{WC}$) were the outputs.

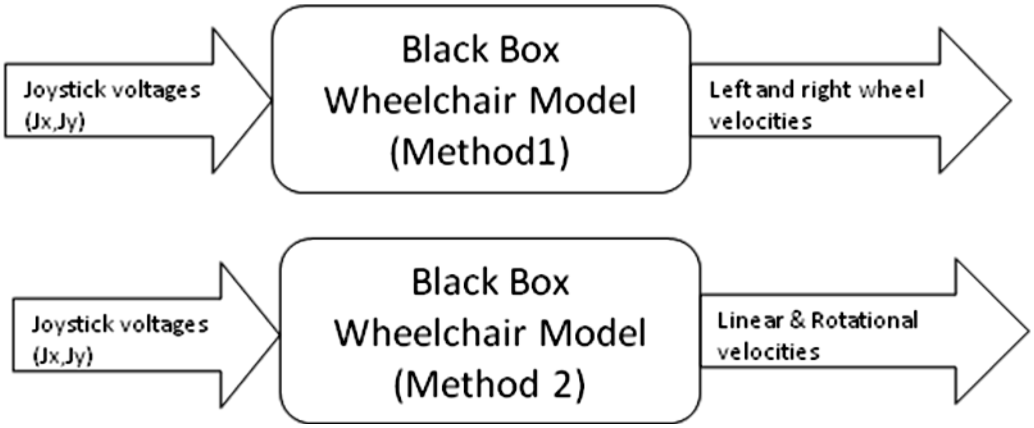

Figure 2-4: Input and Outputs to Method 1 and Method 2 Black Box Models

2.3.3 Model Selection and Validation

Two-third of driving trials from all four experiments were used for building the mathematical model and rest were used for validating the model. As seen in Figure 2-3, in the iterative process of selecting a 'good' model that fits the data sufficiently well involves selection and fine tuning of model parameters. System identification toolbox function routines were used to make an initial estimate of a model order and delay between inputs and outputs [4]. Models with different orders were built using the Numerical algorithms for Subspace state space system identification (N4SID) [7], [8] implemented in the System Identification Toolbox. Models were further refined using an iterative Prediction Error Minimization (PEM) algorithm and the model that "best" described the relation between input-output data was selected.

There are a number of tools in the system identification toolbox that assist in analyzing the quality of model fit to the data, stability and reliability of the model, and validity of the model using untrained/new data. Ljung [6] provide some practical guidelines for selecting appropriate model structure, fine tuning of model orders and noise structures for the system etc. Akaike’s information criterion (AIC) and Akaike’s final prediction error (FPE) are two measures that give an estimation of model quality [2]. According to Akaike’s theory, smaller values of AIC and FPE indicate a model more accurate in simulating model outputs. Several different models that were generated during the iterative process were compared using these criteria and the model with lowest AIC and FPE were ranked. Further, amplitude and frequency plots of these models were compared to select the model that has a better fit to data, better stability, and is computationally less expensive while implementing as a real time controller.

In order to check the validity of the best fit model, the driving trials reserved for validation were used to generate model predicted wheelchair speeds and trajectories. The real and model predicted wheelchair velocities and trajectories were compared. It was expected that the real and model predicted velocities will be highly correlated with each other. Also, Rsquared statistics between real and model predicted linear speed and rotational speed values were computed to give a “goodness of fit” estimate. Closer the correlation and Rsquared values to 1.0 better is the correlation. The predicted chair trajectories were expected to closely follow the real trajectories. The Root Mean Squared Error (RMSE) between real and model predicted trajectories were calculated for the validation data. Lower RMSE indicates a better prediction of wheelchair trajectory.

2.4 RESULTS

2.4.1 Mathematical Model

Different models derived from Methods 1 and 2 are shown in Table 2-1. The model orders ranged from 2-6. For higher model orders, the iterative N4SID algorithm did not converge to a solution. The model “Met1n4s4_PEM” had the lowest values for AIC and FPE parameters. For “Met1n4s4_PEM”, unlike some of the other models mentioned below, the input/output cross correlation and auto correlation functions mostly stayed within 99% confidence limits. Also, the pole-zero plot for Met1n4s4_PEM showed that all poles and zeros were within the unit circle. These findings indicate there is no instability in the model’s response in the frequency ranges of interest.

Table 2-1: Different models derived using system identification toolbo

Method	Name	Algorithm	Model Order	FPE	AIC
1	Met1n4s2	N4SID	2	1.05E-09	-20.6741
	Met1n4s2_PEM	N4SID+PEM	2	1.14E-12	-27.496
	Met1n4s3	N4SID	3	1.37E-09	-20.4059
	Met1n4s3_PEM	N4SID+PEM	3	5.15E-14	-30.5963
	Met1n4s4	N4SID	4	2.46E-10	-22.1268
	Met1n4s4_PEM	**N4SID+PEM**	**4**	**1.50E-14**	**-31.8282**
	Met1n4s5	N4SID	5	2.16E-10	-22.2563
	Met1n4s5_PEM	N4SID+PEM	5	2.94E-14	-31.1595
	Met1n4s6	Did not converge. No solution			
2	Met2n4s3	N4SID	3	3.46E-04	-7.9704
	Met2n4s3_PEM	N4SID+PEM	3	2.46E-04	-8.3101
	Met2n4s4	N4SID	4	6.08E-10	-21.2215
	Met2n4s4_PEM	N4SID+PEM	4	3.83E-14	-30.8928
	Met2n4s5	N4SID	5	5.14E-10	-21.388
	Met2n4s5PEM	N4SID+PEM	5	5.89E-14	-30.4623
	Met2n4s6	N4SID	6	7.15E-10	-21.0582
	Met2n4s6_PEM	N4SID+PEM	6	4.93E-14	-30.6419

$$A = \begin{matrix} 0.97935 & -0.0027345 & 0.054131 & 0.0039405 \\ -0.0060434 & 0.98853 & 0.013629 & 0.036765 \\ -0.0010782 & 0.0016248 & 0.97766 & -0.0013346 \\ 0.0034311 & -0.0048723 & -0.0068724 & 0.98132 \end{matrix}$$

$$B = \begin{matrix} -4.279\text{e}-007 & 7.6411\text{e}-006 \\ 2.5162\text{e}-005 & -1.5567\text{e}-006 \\ 9.7248\text{e}-007 & 4.7471\text{e}-005 \\ 2.6305\text{e}-005 & -2.477\text{e}-007 \end{matrix}$$

$$C = \begin{matrix} 163.03 & -36.17 & 0.95653 & -0.29943 \\ 159.11 & 23.286 & 0.94814 & 0.17668 \end{matrix}$$

$$D = \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix}$$

$$K = \begin{matrix} 0.0064579 & 0.011423 \\ -0.035058 & 0.037642 \\ 0.10524 & 0.16155 \\ -0.28675 & 0.29591 \end{matrix}$$

$$X(0) = \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Equation 5: Parameters for Met1n4s4_PEM model

2.4.2 Model Validation

The figures below show real and model predicted response curves for linear speed, rotational speed, chair trajectories, chair angles. The Met1n4s4_PEM model was used to predict linear and rotational speeds from the validation driving trials. Table 2-2 shows the cross correlations between actual (A) and model predicted (MP) linear and rotational speeds of the chair. The Root Mean Square Deviation between A and MP chair trajectories was also computed.

Table 2-2: Outcomes measures comparing actual (A) and model predicted (MP) values in validation driving trials

Outcomes measures	Experiment 1: Drive straight 50ft (n=21)	Experiment 2: Drive straight and turn (n=37)	Experiment 3: Drive reverse and turn (n=34)	Experiment 4: Freestyle driving (n=50)	Overall
Chair linear speeds: Cross correlation A and MP values	0.996±0.001	0.992±0.006	0.99±0.003	0.972±0.013	0.98±0.03
Chair linear speed: R^2 (goodness of fit)	0.969±0.02	0.671±0.32	0.936±0.06	0.934±0.04	0.89±0.18
Chair rotational speeds: Cross correlation A and MP values	0.725±0.11	0.882±0.12	0.964±0.02	0.945±0.04	0.9±0.11
Chair Rotational speed: R^2 (goodness of fit)	0.404±0.22	0.763±0.16	0.918±0.04	0.866±0.09	0.78±0.21
RMSE between A and MP chair trajectories (meters)	1.411±0.83	2.446±1.59	1.428±0.74	1.468±1.12	1.7±1.2

The A and MP linear speeds show very high correlations for all experiments. Except for Experiment 2 (driving straight and turn) all driving trials showed high Rsquared statistics. The correlation values for rotational speeds were in general lower than the correlations values for linear speeds. Especially during Experiment 1 and 2 the values were lower. Experiment 2 also showed much higher RMSE values. Overall the points on the predicted trajectories were 1.7 meters away from equivalent points on the actual trajectories. Following figures show the representative speeds and trajectories from the four experiments.

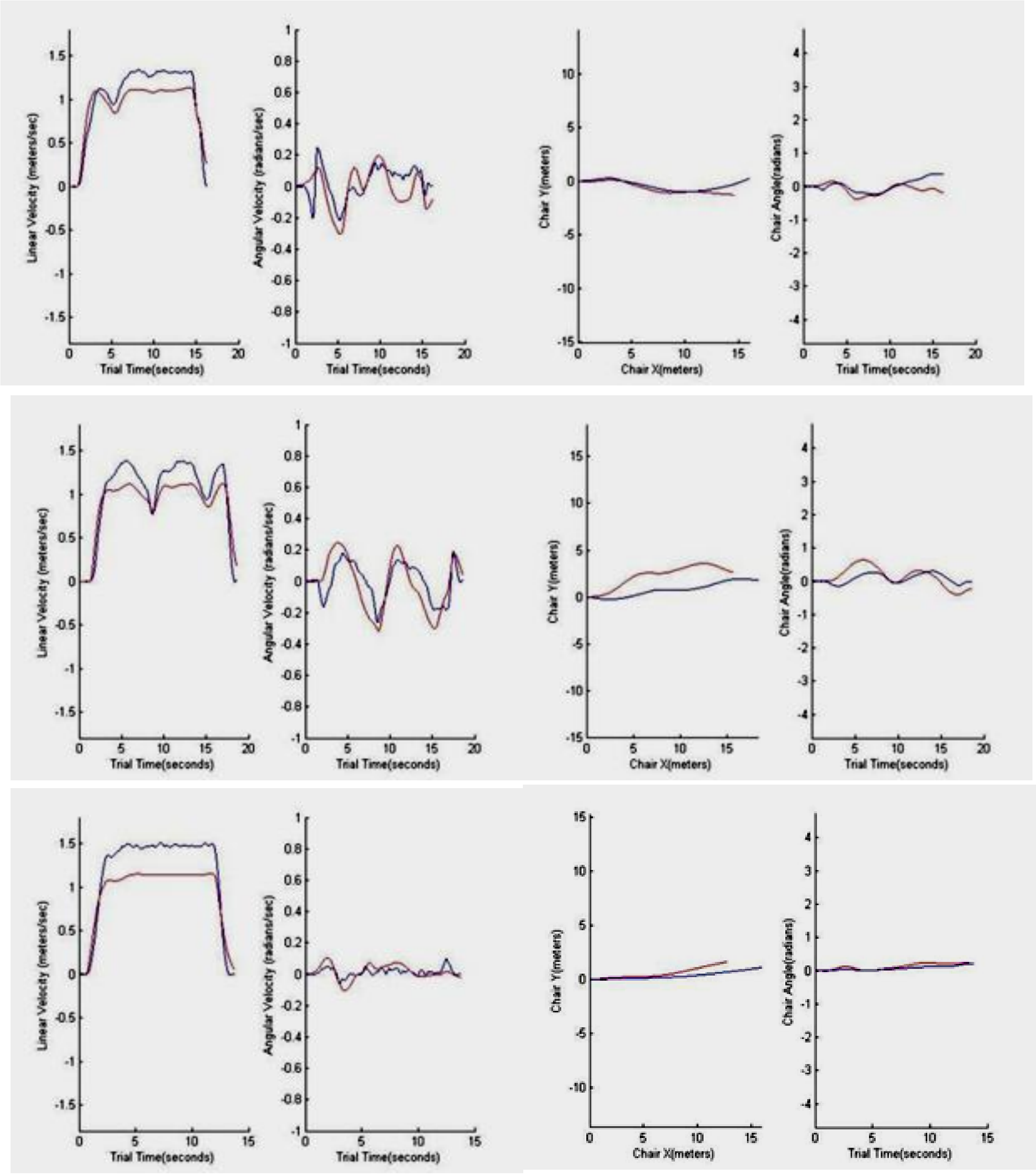

Figure 2-5: Experiment 1: Drive straight 50 ft. Actual (blue) & model predicted (red) speeds and trajectories.

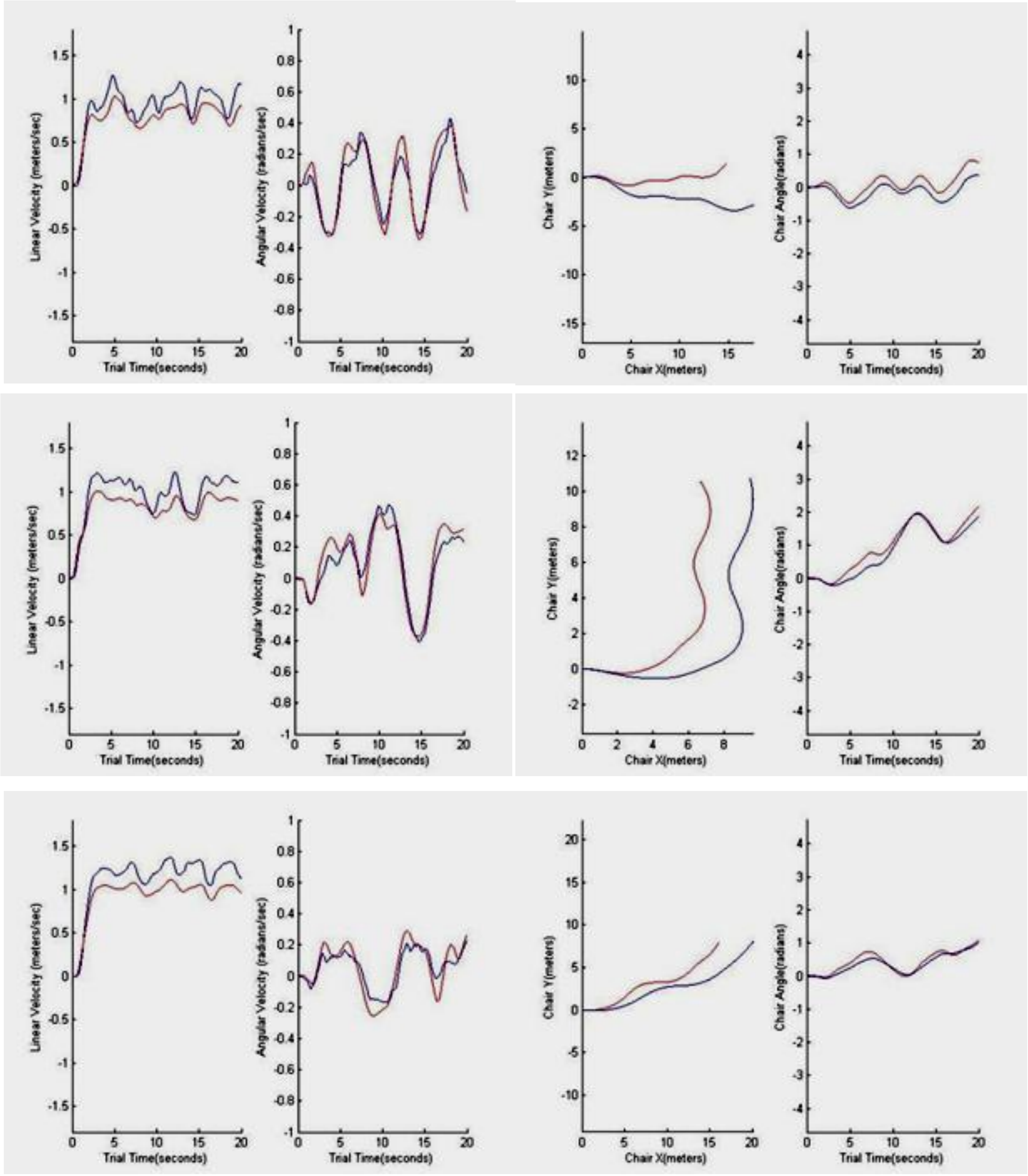

Figure 2-6: Experiment 2: Drive straight and turn. Actual (blue) & model predicted (red) speeds and trajectories.

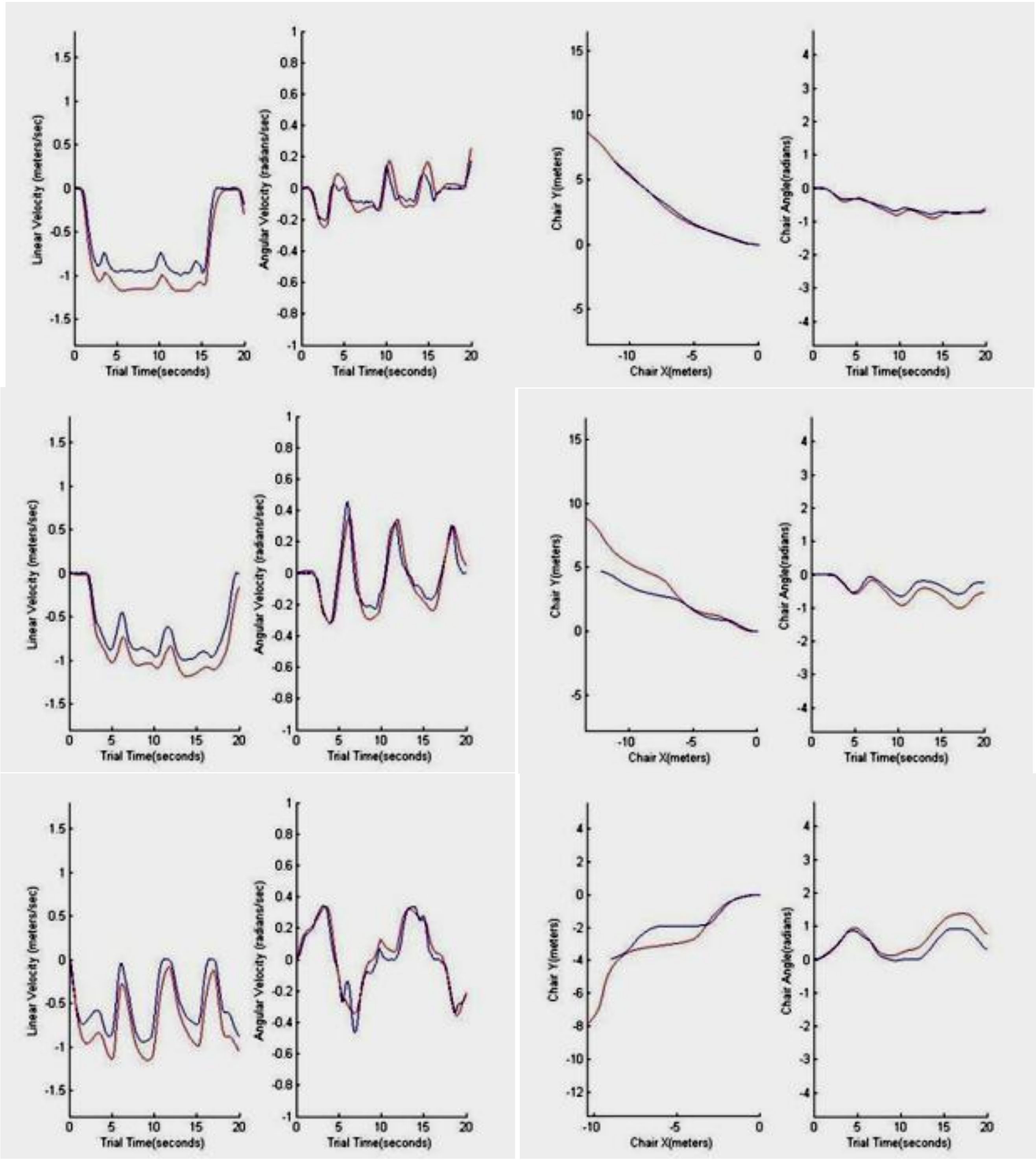

Figure 2-7: Experiment 3: Drive reverse and turn. Actual (blue) & model predicted (red) speeds and trajectories.

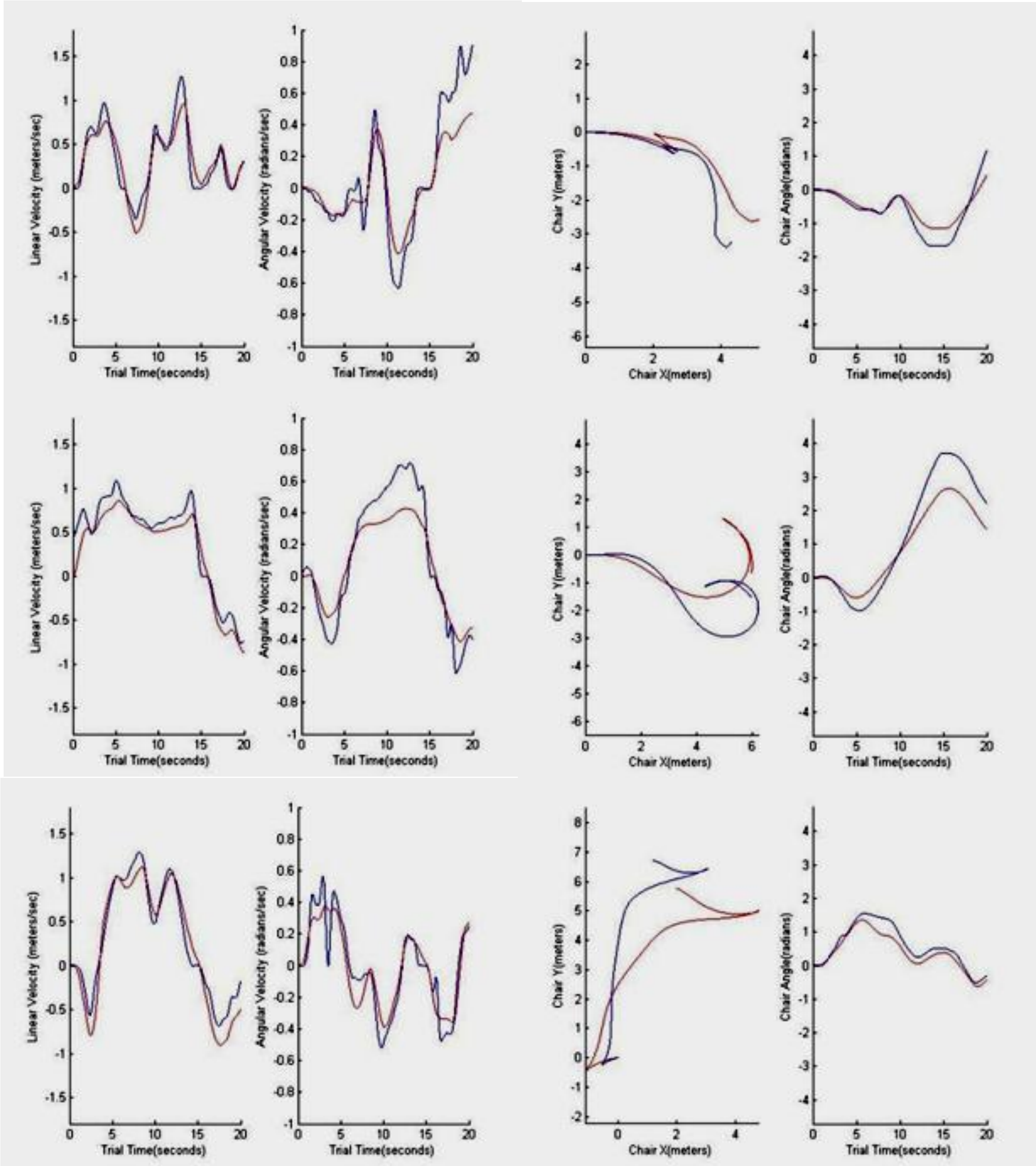

Figure 2-8: Experiment 4: Free style driving. Actual (blue) & model predicted (red) speeds and trajectories.

2.5 DISCUSSION

The model was developed from data collected from Permobil C500, a front wheel drive wheelchair with factory settings for wheelchair controller parameters (forward and reverse acceleration and deceleration, turn sensitivity etc). The wheelchair controller allows for changing the wheelchair speeds from level 1 to 5. Increasing the speed level increases the maximum speed the wheelchair could reach. The maximum speeds in reverse directions were approximately half the maximum speeds while driving in forward direction. Data for this study were collected from driving trials performed at one preset speed setting (speed level 3). Other preset speed levels were simulated in the real time driving simulation where this model was used to simulate wheelchair driving (Refer Chapters 5 and 6). In the immersive 3D virtual environment, this simulated wheelchair driving that was sufficiently precise. Ten regular wheelchair users drove chairs in a virtual environment. Half of the driving trials were performed by using their own wheelchair strapped to a roller system as an input to the virtual wheelchair. For the other half of driving trials, mathematical model was used to predict the virtual wheelchair's linear and rotational speeds. Most of the subjects felt little to no difference in the virtual driving while using the two input methods. As expected, subjects reported the turning rate while using the model was different than that while using the rollers. However, subjects were able to get used to this change and drive efficiently when model was used than when rollers were used. Refer Chapters 5 for detailed results.

Even though the linear speed values were highly correlated, the model predicted trajectories showed marked differences from actual wheelchair trajectories. One main source of errors is the compounding of dead reckoning errors from encoder noise and gear slips. Especially during higher acceleration or deceleration tasks in experiments 1 and 2, the slips were presumably much higher. Secondly, the model showed lesser reliability in predicting angular/rotational velocities of the wheelchair. The resulting errors in chair orientation prediction could have accumulated along the course of the driving trial and the final predicted chair orientation and trajectory were much farther away from the actual trajectory. In future studies, a more robust data collection protocol will be implemented so that these errors are minimized. A number of different odometry error detection and correction techniques ([9–15]) could be implemented.

Wheelchair casters introduce some disturbances in wheelchair's drive response. Especially while starting the wheelchair from rest and while making sharp turns, casters need time to follow and roll in the direction pointed by the drive wheels. This delay introduces a marked change in the chair's orientation. Caster orientation and rotation velocity data were not logged during this study and hence were not specifically accounted for while building SI models. We assumed the wheelchair velocity would have a small influence from caster parameters and would be small enough to be accounted as white noise added to the system. However, some of the caster disturbances could have contributed to under or over estimation of the wheelchair's angular velocities. Even small errors in chair's orientation can lead to significant errors in the chair's odometry. In future studies, caster orientation can be another input the black box/grey box model while building the model. Accounting for the caster's effects on wheelchair driving will make the real time implementation of the model more realistic.

There are some limitations that may limit the generalization of this mathematical model. The model was built from just one of the many front wheel drive wheelchairs currently available commercially. The driving model was based on driving style of one individual who was not a regular wheelchair user. Also, all data was collected on a level tile surface. Factors like user's driving experience, driving surface friction, number of obstacles, indoor/outdoor driving settings can significantly affect someone’s driving. Also, this model may not replicate the driving wheel and caster motions in mid or rear wheel drive wheelchairs.

Another promising alternative is to use grey box modeling techniques. Recent efforts to model the components that make the wheelchair have show fairly good results [16–18]. Using grey box modeling techniques, the researcher can build a model structure specific to the system and can determine the values of unknown parameters from the input output data that is available. Generic models for front wheel, mid wheel and rear wheel drive wheelchairs could be predetermined in the software. Only a limited amount of input (joystick voltages) and output (wheelchair speeds) data is required in order to customize the generic models to any new wheelchair.

2.6 CONCLUSION

This study explored black box modeling techniques to construct a mathematical model of wheelchair driving using the MATLAB system identification toolbox. The developed model was computationally efficient and simulated wheelchair driving with precision that was sufficient for its implementation in a real time virtual world.

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3.0 VRSIM 1.0: COMPARISON OF VIRTUAL WHEELCHAIR DRIVING PERFORMANCE OF PEOPLE WITH TBI USING AN ISOMETRIC AND A CONVENTIONAL JOYSTICK

3.1 SUMMARY

Objective: To compare wheelchair driving performance in a driving simulator using a conventional joystick and an isometric joystick.

Design: This is a completely within subjects repeated measures design. Study participants with a traumatic brain injury (TBI) drove a simulated wheelchair within 4 tasks, in 2 driving orientations (forward and reverse), and with 5 repetitions each. A total of 40 driving trials were completed for each of the 2 joysticks.

Setting: A research facility based in a hospital or in an independent living center.

Participants: Participants (N= 20; 12 men, 8 women; mean age ± SD, 30.62±10.91y) who were at least 1 year post-TBI.

Interventions: Driving performance using an isometric joystick compared with a conventional movement joystick.

Main Outcome Measures: Average trial completion time, and trajectory-specific measures measured orthogonal to the center of driving tasks: root mean squared deviation, movement offset, movement error, and number of significant changes in heading.

Results: After statistically controlling for driving speed, participants were able to complete the driving tasks faster with an isometric joystick than while using a conventional movement joystick. Compared with the conventional joystick, an isometric joystick used for driving forward demonstrated fewer driving errors. During reverse driving the conventional joystick performed better.

Conclusions: The customizable isometric joystick seems to be a promising interface for driving a powered wheelchair for individuals with TBI.

3.2 BACKGROUND

At least 1.4 million people with Traumatic Brain Injury (TBI) are seen in emergency departments every year in the United States. [1] According to estimates of the Centers for Disease Control and Prevention, about 5.3 million people (2% of the population) in United States are living with long term disability resulting from TBI. An additional 80,000 to 90,000 new cases arise every year. [2] Firearm-related injuries, vehicular crashes, and falls are the most common causes of TBI. With the escalation of the conflict in Iraq and Afghanistan, the number of soldiers with poly traumatic injuries, including TBI, has increased. As many as 28% of the personnel evacuated to the Walter Reed Army Medical Center have, in addition to other injuries, a diagnosis of TBI, with 56% of these cases being moderate or severe. [3]

Many people with TBI experience long-term sensory, cognitive, and motor changes that limit independent mobility. These individuals with TBI require some independence in personal mobility to carry out Activities of Daily Living and Instrumental Activities of Daily Living. Independence in transportation is identified as one of the largest barriers for people with TBI to overcome to maintain societal participation in activities like employment. People who reported a higher impact of these barriers on daily activities also reported lower levels of participation and life satisfaction. [4] Environmental barriers also affect outcomes after injury and, hence, the lives of survivors of TBI. In order to address some of the problems emerging from environmental barriers, effective policy level initiatives are required. Some of these policies are already in place, such as those improving architectural accessibility. However, at the individual's level, by selecting and fitting appropriate assistive technologies to the user's needs and capabilities, the impact of these barriers can be reduced. In this way, some degree of independence in mobility and transportation may be achieved.

Up to 40% of those who use Powered Wheelchairs (PWC) regularly have problems with steering, and 5-9% cannot steer at all in a clinical setting. [5] Improperly customized device features and user interfaces contribute to these problems and may eventually lead to abandonment. About one-third of all assistive technology devices are abandoned by users within the first year of using these devices. [6–8] With the sensory and cognitive issues that remain after a TBI, the demand for device interfaces and controls that can be tuned to the user's residual capabilities is even greater. This customization is especially important to prevent abandonment of the technology. One objective of this research is to address some of the aforementioned needs for customizing and improving user interfaces with power wheelchairs.

Proportional movement sensing joysticks (MSJ) are commonly used to control PWC wherein the wheelchair's velocity changes in proportion to the amount of deflection of the spring loaded joystick post. Users require proprioception and dexterity at joints to efficiently use proportional controls. In other words, the joystick post of an MSJ deflects under the applied force and the amount of deflections determines the speed of wheelchair. Isometric controls, on the other hand, respond to the forces applied to their transducers and theoretically may require less strength and dexterity for transduction. [9], [10] The Isometric Joystick (IJ) post is rigid and does not deflect. Past research using IJs as a wheelchair control interface has demonstrated that key driving performance metrics gathered while using the IJ were comparable to those achieved using a conventional MSJ. [11–14]

In our prior work, a force sensing algorithm was used with the IJ and tuned to the user's arm strength. Inexperienced joystick users with TBI were observed to adapt to the IJ faster than they could to the MSJ [9], [13], [15] Moreover, using an IJ did not significantly compromise their driving performance in a wheelchair simulator as compared to the MSJ. [10] The current study aims to evaluate if the pilot results from this latter study [10] can be replicated in a larger set of participants with TBI. The metrics for evaluating driving performance that were used in our previous work [10] were average driving speed and Root Mean Square of deviations from the center line of the driving path. Additional performance metrics are introduced in this study and an improved additional statistical analysis is presented.

Participants with TBI were hypothesized to have better driving performance while using an IJ, than while using an MSJ, to direct a simulated wheelchair in forward and reverse directions. Wheelchair users have varying levels of information processing demands during their daily wheelchair usage. A secondary objective of this research was to evaluate the wheelchair driving performances with the two joysticks under different levels of information processing loads induced by changing the width of tasks. According to the law of Steering, moving along a narrow pathway induces higher information processing load which induces a higher number of errors while driving.

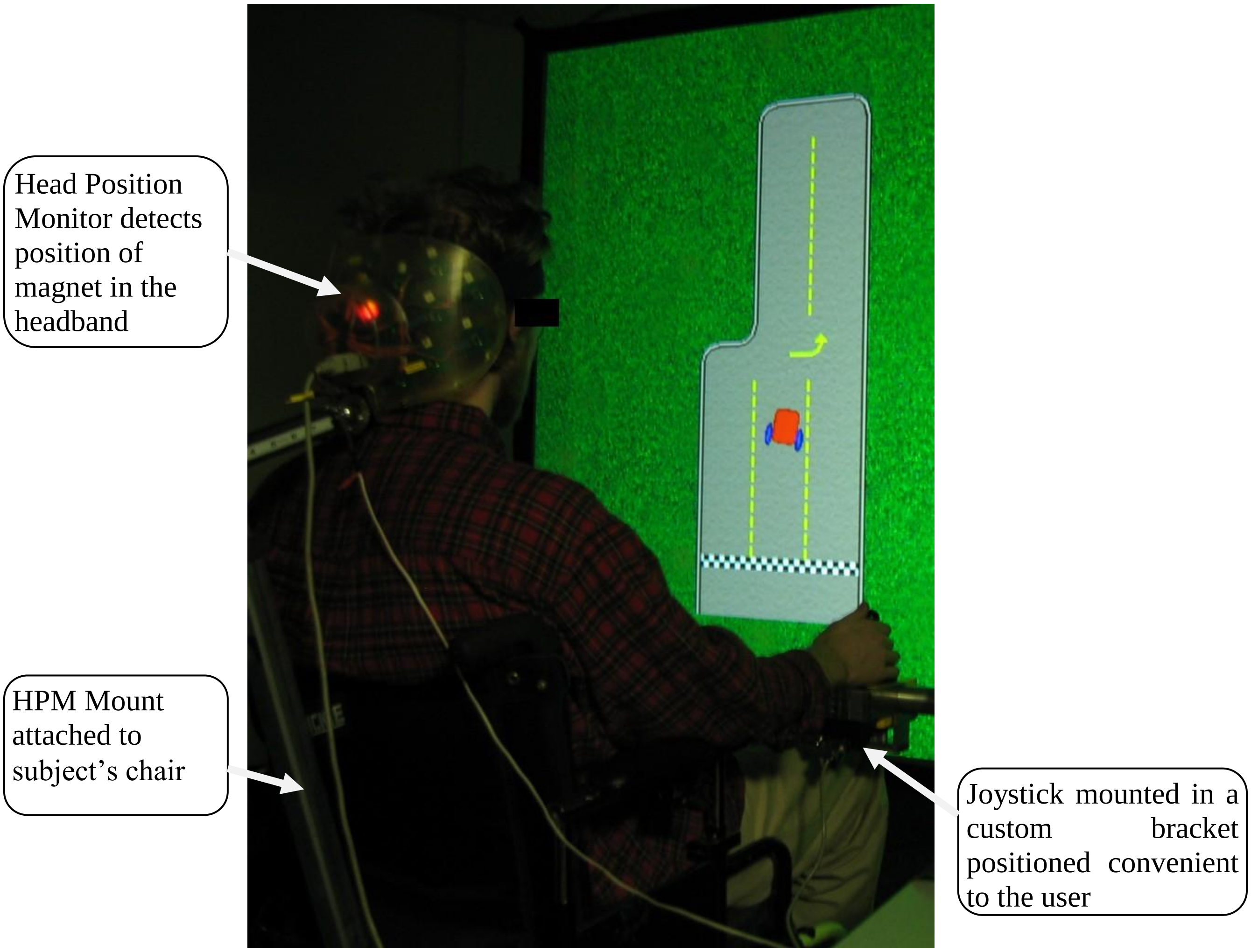
3.3 METHODS

A prior publication [10] describes the instrumentation and research protocol in detail. This study extends the analysis used in the prior publication to a larger set of participants with Traumatic Brain Injury (TBI). This research protocol was approved by the Institutional Review Boards of University of Pittsburgh and Department of Veteran Affairs. Participants were recruited from a local Independent Living Center and an outpatient assistive technology clinic. Participants were pre-screened on the telephone to determine their eligibility to participate. All participants were invited to the Human Engineering Research Laboratory or Hirem G. Andrews Independent living center to participate in the protocol. The inclusion criteria were that participants should be between 18 and 80 years of age and at least one year post TBI. Because of difficulties in recruiting and a higher attrition rate in regular PWC, the inclusion criterion was updated to include both ambulatory and non ambulatory participants who had a TBI. Exclusion criteria were self reported active pressure sores that would prevent participants from sitting in wheelchair for two hours and a seizure within the past 6 months.

3.3.1 Experiment Setup

Due to short attention span and other cognitive limitations that are typically seen in people with TBI, distraction from the task at hand is common. Some people with TBI also presented with some degree of visual neglect. Studies have shown that one strategy to improve task efficiency of people with visual neglect is to cue them in using a light house visual imagery strategy while performing functional tasks. [16], [17] A horizon illuminating light house typically has a light at its top that sweeps left to right to guide ships at sea to safety. The light house visual imagery strategy encourages users to scan the environment around them by turning their heads as and when required. In this study we encouraged users to adopt a light house strategy while driving in a simulated environment by presenting the driving tasks as if they were viewed from “bird’s eye” perspective or in orthogonal projection. See Figure 3-1and Figure 3-2. Use of the 6’ x 8’ screen further encourages this visual imagery strategy. The simulation environment was built using simplistic graphics to avoid a certain amount of risk of participants getting overwhelmed and fatigued from increased information overload from fast changing and immersive 3D graphics. Even though the 2 dimensional graphics of the test environment were simplistic, they were presented at a resolution that created sharp images when projected on the screen.

The participants used their dominant hand to operate the joysticks which moved a 2D icon of a wheelchair. The tasks simulated typical maneuvers one might perform during their day to day wheelchair driving. The first two tasks were equivalent to driving along a hallway that took a turn (left and right) along the way from its start to finish points. The third task was equivalent to driving along a hallway and entering a small elevator. The fourth task was equivalent to maneuvering in a tightly spaced office area. A custom built head position monitor (HPM) recorded the participant’s head orientation. The HPM has an array of Hall Effect sensors built into a head rest mounted on the participant’s wheelchair. The participants wore a headband with a magnet. If the participant became distracted and looked away from the screen, the wheelchair icon would stop moving. During driving a real wheelchair, such a safeguard would warn and/or correct users who are about to hit an obstacle because they got distracted from the direction they intended to move their wheelchair. During this study, the HPM encouraged participants to focus on the screen while driving. Real time data from the joystick, the wheelchair icon’s orientation, trajectory, speed, boundary violations, and head position violations detected by the head position monitor were recorded during every update of graphics frame by the simulation software and used for data analysis. After completing the protocol, participants were asked about their subjective experiences while interacting with the IJ and simulated wheelchair.


[redacted]

Head Position Monitor detects position of magnet in the headband

HPM Mount attached to subject’s chair

Joystick mounted in a custom bracket positioned convenient to the user

Figure 3-1: Experiment Setup.

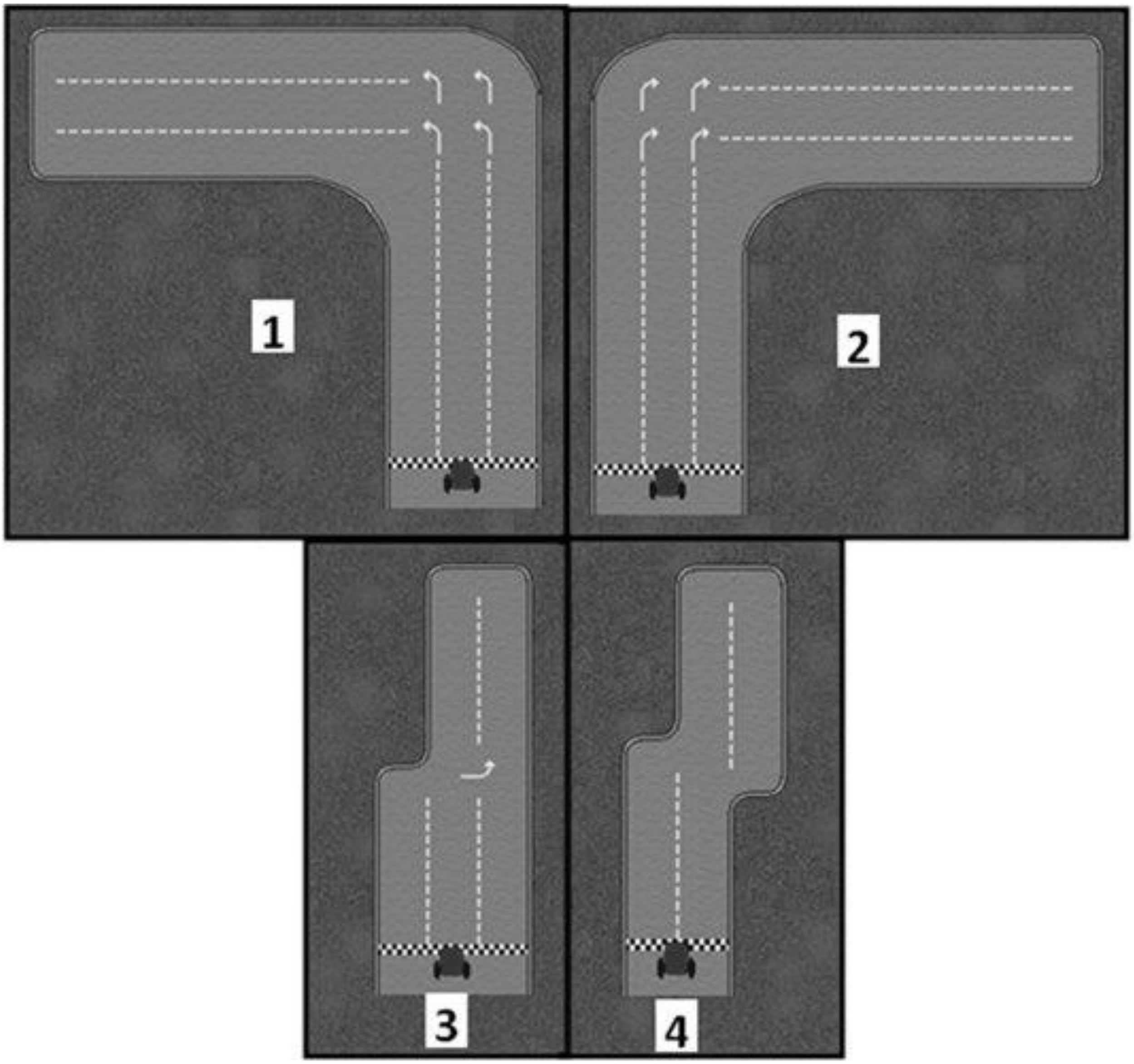


Figure 3-2: Driving tasks. Task 1: left turn along hallway. Task 2: right turn along hallway. Task 3: drive straight along hallway and enter an elevator. Task 4: maneuver in a tight office area.

3.3.2 Experiment Protocol

All eligible participants were invited to complete two visits to the research center. During the first visit, after informed consent, a certified clinician evaluated all participants for their arm range of motion and strength (shoulder, elbow, and wrist), visual acuity, and field of view. Any limitations in motor coordination of participants were evaluated using a finger-to-nose test, visual tracking of H and X shaped pursuits, and saccades. The purpose of this evaluation was to guide the clinician in setup of the equipment and determine if the participant's visual and motor skills were sufficient to interact with the experimental setup (view/scan the entire screen and operate both joysticks). If participants had their own wheelchair they sat in it during the testing. Otherwise a test wheelchair was provided to them. Any seating and positioning requirements of the participant were addressed by the clinician. The participant's real world wheelchair driving skills were rated on a 7 point Likert scale as they drove their own or a test power wheelchair along a driving course comprised of driving straight along a hallway and turns.

A conventional MSJ was used for driving. This MSJ had attributes such as dead zone, joystick template, bias axis rotation, and directional gains that shape the joystick's response to the user's physical inputs (deviation of joystick post) [9]. Since the IJ has a rigid post, these attributes were simulated in the joystick interfacing software. A validated tuning protocol [9], [10] was used to derive values for these attributes when the participant used an IJ. By tuning the IJ to have similar attributes as the conventional MSJ, variations in joystick usage performance could then be attributed to differences in the physical interfaces of joysticks and not to the actual software used. During the computer based driving evaluation, participants parked their chairs in front of a 6' by 8' back projected screen. A custom bracket was used to position the joystick being used so that it was in a functional position for the user. During the first visit, after these customizations, each participant was acquainted with the computer based driving environment and joysticks by driving a simulated wheelchair on the screen. The participant was trained to use both the IJ and MSJ to drive the simulated chair along a practice task. The practice task was a wide rectangular hallway loop with four turns at equal intervals and participants drove along the task in two driving orientations (forwards and backwards). The clinician made a judgment about the participant's confidence in driving in the simulation by their ease in controlling the simulated chair along the practice task. The aim was to achieve a plateau in the participant's learning curve with the experimental setup. After a participant felt sufficient confidence in using each joystick, he/she was asked to drive once along each of the 4 test tasks designed for this study. Since all trials from first visit were used for familiarization and training of the participants, data from this visit were not used for statistical analysis. Tuning the IJ and practicing driving with both joysticks was accomplished in about one hour. During the second visit each participant was re acquainted with the experimental setup by driving along the practice task once before starting with the experiment trials. This was followed by the actual driving protocol in which a participant drove on the 4 test tasks in 2 driving orientations (forwards and backwards) performing 5 repetitions of each combination. These 40 driving trials were performed with each of the two joysticks (IJ, MSJ). The order of these two blocks (joysticks) was randomly selected. All trials within a 40 trials block performed with each joystick, were randomized using the Random Permutation (randperm) function in MATLAB. This way the trials with both the joysticks were performed in a single session one block of trials followed by the other. Participants were instructed to drive the simulated chair by keeping the chair along the center of each task segment and complete each task as quickly and as accurately as possible. Only the data from the second visits of all participants were used for further analysis.

3.3.3 Trajectory data processing

At times, the sampling frequency of the main program loop was higher than the rate at which the user would respond to change the wheelchair icon's position. This would result in redundant trajectory data recordings. For example, if the wheelchair icon stayed parked far away from the track centerline without moving, it would accumulate large position errors for the time segment when the wheelchair was not moving. To account for this, only the unique position coordinates of the simulated wheelchair were considered for further analysis and the records representing repeated/redundant readings of position coordinates were deleted while computing outcome measures involving trajectory data.

The participants traversed the trajectories with different self selected speeds. In order to ensure consistency, the performance measures from trajectory data were evaluated by sampling each trajectory at equal number of sampling gates at regular intervals of spatial coordinates. Figure 3-3 shows one tenth of the sampling gates used for part of task 4. Screen coordinates (in pixels) of boundaries of the four tasks were extracted from their screen captured images using the boundary recognition tool in the MATLAB curve fitting toolbox. A space based sampling technique, adapted from Roduit et al. [18] was implemented for all four tasks. Briefly, this sampling technique gives non-intersecting sampling gates that are most orthogonal to the inner and outer boundaries of the task. Sampling gates are hypothetical landmarks on the tasks where the user's trajectory is sampled or interpolated and recorded as valid observation points. Thus the ideally expected path was considered to be the locus of midpoints of these sampling gates. Such a sampling strategy is especially important to extract trajectory deviation from tasks that involve turns. The real world equivalent of sampling gates is a clinician checking the wheelchair's position every few meters when a user is driving along a hallway. During such a driving activity, it is important that the wheelchair driver takes a path that does not endanger his or her own safety and of others sharing the hallway.

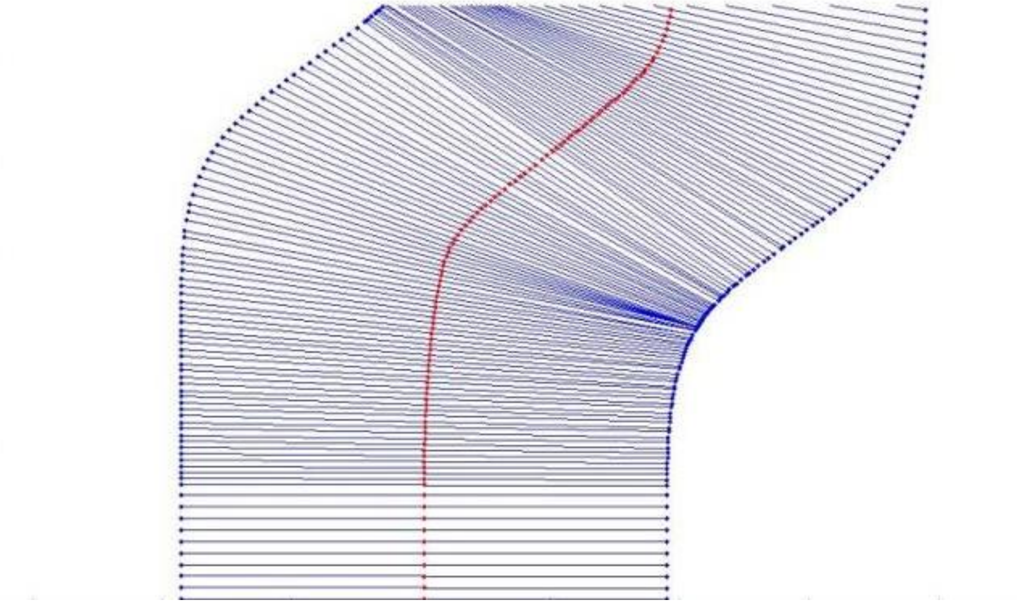


Figure 3-3: Sampling gates (in blue). The task trajectory is sampled to generate gates that are most orthogonal to the two boundaries. Locus of midpoints (in red) of these gates defines the ideal path in that task segment.

3.3.4 Performance Measures

In addition to the driving performance measure “Root Mean Square of deviations from the center line of the driving path” which was used in our previous work [10], this study introduces new performance measures trial time, movement offset, movement error, and number of significant changes in heading. These new performance measures were derived from their equivalents in computer access applications that evaluate a user’s performance in moving computer cursor along steering tasks in a graphical user interface (GUI). [19] A steering task in a GUI based application has a predefined pathway, defined by at least two boundaries such as Menu navigation in Windows applications. During menu navigation, if the user does not keep the cursor within a narrow vertical and/or horizontal path while dragging through the menu choices, the menu linkage will be dropped and the pull-down menu task must be restarted. Hence this task has two objectives, first to move the cursor from start to end of the pathway as quickly as possible and second, to maintain the cursor within the boundaries. The task of driving a wheelchair along a predefined path along a hallway or a pathway is similar to performing a steering task on a computer screen. Maintaining accuracy while driving is important since it encourages the wheelchair user to avoid bumping into hallway walls or to fall off a curb.

We expect these new performance measures from computer access research to give insights into certain unique aspects of the user's driving performance. Task completion time is one of the most important performance metrics to estimate a user's efficiency in completing a task. Movement offset and movement error indicate whether users have a tendency to drive closer to one boundary wall when they are specifically instructed to drive along the center of the path. Root mean square deviation gives an estimate of mean deviation from the center line. The number of significant changes in heading indicates whether the users drive mostly straight or follow a "zig zag" driving pattern with many small turns. The new measures of errors in driving are computed orthogonally to the driving task and, hence, are not affected by the length of the task. Since lack of foresight and awareness of hazards are frequently compromised by a person with TBI, a wheelchair driving simulator must be used to train in pathway adherence if it is to be an effective training tool. Throughput or Index of Performance is a measure that captures both speed and accuracy of an input device on a given set of tasks. Measured in bits per second, higher throughput values indicate a better performance by the input device [19], [20].

Three clinically relevant measures of wheelchair driving were also recorded by the simulation software. The HPM was installed to restrict the simulated wheelchair's motion if the participant got distracted from the driving task. The number of times the HPM detected violations was recorded. While driving a wheelchair in the real world, it is important that the drivers steer away from walls/boundaries lining a hallway. In cases of a crash with walls or when they just stop short before a crash, the drivers must be able to get themselves out of the situation and continue driving safely. Hence the following variables were recorded: the number of times the wheelchair crashes into the outer boundaries of the driving task, and the number of times the wheelchair is stuck in place for more than 3 seconds. A cumulative sum of each of these variables over five trial repetitions is reported here.

3.3.5 Statistical Analysis

Tasks one and two were grouped as “wide tasks” (average width 125 pixels or 3.18 meters equivalent in the real world) while tasks three and four were grouped as “narrow tasks” (average width 86 pixels or 2.19 meters equivalent in the real world). The wide tasks were about twice in length (612 pixels or 15.54 meters equivalent in the real world) of the narrow tasks (309 pixels or 7.84 meters equivalent in the real world). A power analysis based on pilot data from our earlier studies indicated that a sample size of 20 would yield a power of 70% [9], [10], [13] A net throughput was calculated for both joysticks by averaging throughput values across the four tasks (four Indexes of Difficulties) and then across all participants. [21] Since driving the wheelchair in forward and backwards orientations in the computer based testing environment required considerable change in perspective, these were considered two different experimental paradigms and outcome measures from each of these paradigms were analyzed separately. Although the participants were allowed to practice with the joysticks, it is possible that a learning effect while performing the experiment may have biased some driving scores. Hence the scores from the five repetitions of each of the joystick, task, and driving direction were averaged to give a better representation of the participant's driving score. Averaging the trials also simplified the repeated measures mixed models that were built for statistical analysis.

Since all participants completed driving trials with all possible combinations of tasks, joysticks and driving directions, the participants served as their own controls and so repeated measures analyses were selected. The distributions of the variables 'trial completion time' and 'absolute average speed in a trial' were significantly and positively skewed. We corrected for these skewed data with a base ten logarithmic transformation. [22] A repeated-measures Analysis of Covariance (ANCOVA) was performed using SPSS [23] Linear Mixed Modeling procedure to test if log of trial time was different for the two joysticks when they were used by participants to complete tasks of two different widths. The log of 'absolute average speed of the simulated wheelchair was used as a covariate for this ANCOVA model. A Mixed model approach was employed for trial time instead of a General Linear Model because the covariate was different for each level of the repeated factors. A base ten logarithmic transformation was used to address significant deviation from normal data distribution for absolute Movement Offset (MO), Root Mean Squared Deviation (RMSD) and Movement Error (ME). A 2x2 (joystick type x task width) completely within-subjects repeated measures Analysis of Variance (rmANOVA) was performed for each of these outcome measures and for median 'Number of significant Changes in Heading' (NCH). Post hoc pair-wise comparisons were performed if significance was found for any of the within-subjects independent variables. A multivariate analysis was avoided for this study due to the small sample size. For each combination of driving direction and task type T tests with bonferroni correction were used to compare joysticks using the performance measures number of HPM violations, number of boundary crashes, and number of times wheelchair was stuck for more than 3 seconds.

3.4 RESULTS

Overall, 29 participants were recruited, out of whom 8 participants did not complete the two required visits. One participant died from medical reasons unrelated to this research and hence was withdrawn. Demographics of all participants are shown in Table 3-1. There was almost twice the number of ambulatory participants than regular wheelchairs users in those who finished the complete protocol. To avoid bias in statistics the two mobility groups were not separated during analyses. All participants had sufficient arm strength and range of motion to interact with the experiment setup. On average, the participants took 3.2±2.3 seconds to complete the Finger Nose Test. All participants were able to complete the visual tracking tasks except four ambulatory participants who had little difficulty in smoothly following the H and X trajectories. All participants had sufficient visual field and visual acuity to view the display screen. The net throughput of both joysticks after averaging over all indexes of difficulty and across all participants was comparable for both joysticks. Throughput was 0.444 for the MSJ and 0.465 for the IJ.

Table 3-1: Demographics of participants and withdrawn candidates*

Demographics		**Participants**	**Withdrawn candidates**
Gender	**male**	12	6
	female	8	2
Average age (years)		30.62±10.91 (n=18)	41.22±6.15 (n=4)
Average time since Injury (years)		10.34±7.56	7.5±6.75
Median gap between 2 visits (days)		10.5	NA
Day to day mobility	Using PWC	7	5
	Ambulatory	13	3
Experience with PWC (years)		10.61±7.67	6.95±6.5
Joystick Preference	Left	6	3
	Right	14	5
Real world driving Score (median)		6.2 (n=19)	6.6 (n=7)

* Values are Mean ± SD. Except wherever mentioned, all variables were measured for n = 20 for participants and n = 8 for withdrawn candidates.

3.4.1 Forward Driving

The mixed model repeated-analysis for trial time indicated a significant main effect of joystick (p=0.001, F(1,136)=12.02). The mean trial time for the MSJ was 3.4% higher than the mean trial time for the IJ, after controlling for wheelchair icon speed. As expected, a significant main effect of task-width (p<0.005, F(1,135)=5968.25) was found. The average trial time on wider tasks was 110.38% higher than the average trial time on narrow tasks. All other interactions were not significant.

Table 3-2: Summarizes the number of boundary collisions, number of times HPM detected that the participant was distracted from driving task, and number of times the wheelchair was stuck for more than 3 seconds along the driving task*.

Direction	Track Type	Joystick	Crash Count	HPM Violations	Stuck Count
Forward	Wide	IJ	1.3 ±2.7[a]	3.6 ±10.6	0.6 ±0.9[c]
		MJ	4.1 ±5.6[b]	3.6 ±9.9	1.6 ±2.3[d]
	Narrow	IJ	1.9 ±2.6	0.9 ±3.0	1.0 ±1.4
		MJ	3.2 ±3.3	0.8 ±1.9	1.0 ±1.5
Backwards	Wide	IJ	3.6 ±5.8	2.6 ±9.1	1.4 ±1.9
		MJ	4.7 ±6.1	4.3 ±9.9	1.7 ±1.9
	Narrow	IJ	4.0 ±4.2	1.2 ±3.4	1.2 ±1.1
		MJ	4.1 ±4.2	3.5 ±9.2	1.5 ±1.6

* Values are Mean ± SD. After bonferroni correction, statistically significant differences were seen in the joystick pairs a-b (p = 0.007) and c-d (p = 0.016).

Univariate repeated-measures tests for the other outcome measures gave the following results. All outcome measures did not show a significant main effect of joystick type. The joystick*task-width interaction effect was significant for RMSD (p=0.035, partial η^2= 0.109).

For wider tasks RMSD on driving trials using the MSJ was 12.7% higher than on trials using the IJ.

No significant differences were found in other outcome measures when compared across the two joystick groups. However, all of the outcome measures were significantly different across the two task widths groups. Compared to the narrower tasks group, the wider tasks group had higher MO ($p=0.005$, partial $\eta^2= 0.187$), higher RMSD ($p<0.001$, partial $\eta^2= 0.633$), higher ME ($p<0.001$, partial $\eta^2= 0.609$), and higher NCH ($p<0.001$, partial $\eta^2= 0.381$). Table 2 describes the outcomes measures number of HPM violations, number of boundary crashes, and number of times wheelchair was stuck for more than 3 seconds for each combination of driving direction, task width, and joystick type. For both wide and narrow tasks there were more boundary crashes when participants used the MSJ instead of the IJ for driving. This difference in number of boundary crashes was significantly different for wider driving tasks. On all task types, the number of HPM violations observed was similar with both joysticks. While driving along the wider tasks using an MSJ the wheelchair icon was stuck more often than while using an IJ.

3.4.2 Backwards Driving

From the mixed model analysis for trial time, the interactions of joystick and task width with the covariate absolute average speed were not significant. However, a significant difference in log of trial times between the two joysticks (main effect, $p=0.038$, $F(1,135)= 4.38$) was observed. The mean trial time when using the MSJ was about 2.5% higher than the trial time when using the IJ. As expected, a significant main effect of task-width ($p<0.005$, $F(1,137)=3645.5$) was found. The average trial time on wider tasks was 112.32% higher than the average trial time on narrow tasks.

Univariate repeated-measures tests for the other outcome measures gave the following results. The log of absolute Movement Offset (MO) was significantly different (p=0.027, partial η^2= 0.119) across both joysticks. On average, participants had 38.04% higher MO while using the IJ than while using the MSJ. A significant joystick x task-width interaction effect was seen for log of Root Mean Squared Deviation (RMSD, p=0.002, partial η^2= 0.217) and log of Movement Error (ME, p=0.006, partial η^2= 0.177). For wider tasks no differences were found in either RMSD or ME if driving trials were performed using the IJ or MSJ. For narrow tasks, driving trials using the IJ showed 15.88% higher RMSD and 17.76% higher ME than trials using the MSJ. Median Number of significant Changes in Heading (NCH) was not significantly different across the two joysticks. As seen during forward driving, all of the outcome measures were significantly different across the two task widths groups. Compared to the narrower tasks group, the wider tasks group had higher MO (p<0.001, partial η^2= 0.321), higher RMSD (p<0.001, partial η^2= 0.679), higher ME (p<0.001, partial η^2= 0.664), and higher NCH (p<0.001, partial η^2= 0.683). No statistically significant differences were seen between the two joysticks in driving performance measures boundary collisions, number of HPM violations, and number of times wheelchair got stuck.

3.5 DISCUSSION

Attrition in subject population was mainly due to problems with transportation of the participant to the research center, prolonged medical illness, or loss of contact from participants moving away. On average the PWC users had 10.61 years of experience of real world wheelchair driving compared to the ambulatory participants. This may have led to bias in joystick performance because of practice effect with the MSJ. We presume the ample training sessions and averaging of repeated trials might have reduced the bias in the subject's driving from prior practice effect with the MSJ. Some ambulatory participants had used power wheelchairs during their rehabilitation after injury. A few others had experience with commercial joysticks to play computer games. The commercial joysticks have a proportional control like the MSJ but may have slightly different grasping mechanisms.

Throughput values of both joysticks were similar. This indicates that joystick usage performance using both joysticks is not significantly different. While driving the simulated wheelchair, the goal was to complete the driving tasks as quickly and as accurately as possible. During both forward and backwards driving, participants completed driving tasks faster with the IJ than with the MSJ after we controlled for their driving speed. Our hypothesis that the IJ would outperform the MSJ was confirmed when participants drove in the forward direction. While driving in the forward direction, participants drove with a lower root mean squared deviation when using the IJ than when using the MSJ. This suggests that with the IJ the participants were better able to control the heading of the simulated wheelchair and keep it closer to the centerline of the track. This difference in RMSD values was more prominent on wider tasks than on narrow tasks. On wider tasks, participants had fewer boundary crashes and the wheelchair got stuck fewer times while driving using the IJ than while using the MSJ.

While driving in reverse in real world, wheelchair drivers use their peripheral vision to gather environmental cues for maintaining heading and for estimating distance from their destination. From a bird's eye view drivers have a clear view of their trajectories while driving in reverse. Although this minor advantage may decrease some cognitive load on drivers it might not significantly affect the number of driving errors they would perform. Our hypothesis that the IJ would also outperform the MSJ was not confirmed when participants drove in the reverse direction. During backwards driving, participants showed a tendency to drive farther away from the centerline, that is, with a higher movement offset, when using the IJ compared to when using the MSJ. On the narrow tasks, the RMSD and ME were significantly higher when participants used the IJ than when they used the MSJ. During a force application task, applying a pushing force away from body is comparatively easier than applying a pulling force towards the body. The participants had to exert a considerable pulling force while grasping the IJ post in order to instigate a backwards or reverse motion of the simulated chair. This could be one possible reason that that the participants found it difficult to maintain the heading of the simulated chair using an IJ. While using the MSJ for driving, users typically grasped the joystick post between their thumb and index finger but they had to use their whole hand to grasp the IJ post. Since the IJ reacts to force applied to its post, the effectiveness of using an IJ also depends on the effectiveness of the user's hand grip on the joystick post. Difficulty in properly maintaining a hand grasp on the joystick post especially while pulling on the post could be one reason for the poorer backwards driving performance (higher RMSD and higher ME values) using an IJ compared to MSJ. Future studies will explore an ergonomically better fitting grip on the joystick post.

As seen in previous research studies, participants who did not use any wheeled mobility devices on a regular basis appeared to adapt better to an IJ compared to an MSJ. [24], [25] A similar trend was seen from the comments participants gave after they completed this study. Some ambulatory users felt comfortable in learning to use the IJ before the MSJ. Some of the regular wheelchair users were initially somewhat frustrated with the IJ since it required them to apply a higher amount of force to produce the same amount of transduction in the simulated wheelchair. However, with enough practice, all participants were comfortable in driving the simulated wheelchair with both joysticks. Recent studies have shown that performance in computer access tasks and navigation in simulated environments can be modeled using similar information processing laws. [26]

According to the steering law, which has been validated in computer access tasks and navigation in simulated environments [26], people tend to move their cursor with fewer errors on a narrow task than while on a wider task. Similar results were seen in this study, regardless of joystick used. The wider tasks had a higher margin of error; thus participants had more driving errors on wider tasks compared to the narrower tasks. The wider tasks were about twice as long as the narrow tasks, and after statistically controlling for speed, participants took twice as long to complete the wider tasks. This suggests that length of tasks was not a confounder and outcome measures were not affected. During this research study, the participants were free to choose a how accurate they were while driving (measured as closeness to the center of the tasks) and their driving speed. Different self- selected speeds by the participants were a primary reason for statistically controlling for average driving speed of the participants. During the steering law evaluation paradigm, participants were asked to complete tasks of different widths as fast as possible, and thus the researchers derived a relationship between task width and trial completion time. Such a relationship was hard to derive during this study given the different self-selected driving speeds and cognitive abilities of participants.

The outcome measures MO, RMSD, ME, and NCH used in this research are borrowed from well documented research on computer input devices. [19] In accordance to the law of steering, these error measures were higher on wider tasks than on narrow tasks. These measures can give some insights and help us to describe certain aspects of a power wheelchair user's driving performance in computer-based and simulated reality based driving simulators. The seven-point Likert scale used to score the participant's real world driving showed a ceiling effect. Hence it was difficult to draw direct correlations between the scores from real world and simulated driving tasks. While analyzing their simulated driving performance, because of this ceiling effect, we could not control for the participant's real world driving skill. In our future research, we plan to use validated evaluation tools for the participant's visual motor coordination, functional performance, and wheelchair driving skills. The clinical significance and validation of the outcome measures of this study as predictors of the power wheelchair user's real world wheelchair driving performance is still an open research question. Future research studies will address some of these questions about determining appropriate outcome measures for wheelchair driving in simulated environments and validating them with reliable qualitative and quantitative performance measures of wheelchair driving in real world using a larger cohort of wheelchair users.

3.6 CONCLUSION

People with TBI were able to learn to drive a simulated wheelchair using an IJ. During both forward and reverse driving, and after statistically controlling for driving speed, participants were able to complete the tasks faster with an IJ than with a conventional MSJ. While forward driving the simulated wheelchair, participants showed equivalent or lesser trajectory errors with an IJ than while using a conventional MSJ. During reverse driving, the MSJ showed better performance metrics. The IJ may be a promising interface for driving a real-world PWC.

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4.0 VRSIM 2.0: VIRTUAL WHEELCHAIR DRIVING PERFORMANCE OF PEOPLE WITH CEREBRAL PALSY

4.1 BACKGROUND

Over 750,000 individuals in U.S. are affected by Cerebral Palsy (CP) [1] of which as many as 77% have spasticity [2]. Spasticity in the lower extremities may necessitate the use of wheeled mobility devices including joystick operated power wheelchairs. Forty six percent of adults with CP report limitations in mobility in their community settings. Spasticity in the upper limbs can make it difficult for those with CP independently operate a wheelchair. Individuals with spastic CP are known to have increased resting muscle tone, hyper-excitable reflexes, dystonia, and clonus [3]. These problems may make it difficult for those with CP to use a joystick either to drive a wheelchair or to access a computer. Only a few research studies have developed and evaluated usability of advanced control interfaces that can assist those with spasticity [4], [5]. We have developed an isometric joystick (IJ) that can be customized to the specific needs of people with multiple sclerosis [6], [7], traumatic brain injury[8], and tremor[9]. We believe that the IJ can be a promising user interface device for people with spastic CP. People with spasticity in upper extremities tend to show higher shoulder involvement with little or no elbow extension during their reaching and grasping tasks and there may be issues in fine motor control using the wrist joint [10]. The IJ encourages use of elbow and shoulder joints unlike the conventional movement sensing joystick (MSJ) which requires better fine motor control using the wrist joint.

Also, wheelchair driving is impaired when people with spastic CP apply high jerks and forces to the compliant spring loaded joystick post of the MSJ. We expect the isometric post will have a damping effect on the tone and spasticity and hence improve driving.

Virtual reality systems provide safe and reliable environments for training and evaluation of mobility tasks. Immersive virtual reality systems and non immersive interactive computer/video games based systems are used for pediatric rehabilitation [11], for arm function improvement [12], and to motivate children with cerebral palsy in their physical therapy [13], [14]. This study aims to compare the joystick usage performance of the IJ and MSJ in a virtual reality based wheelchair driving simulation. Since this particular virtual environment based testing scenario is used for the first time with people with CP, we wish to explore the sensitivity of the program and outcome measures to people with different levels of spasticity in their upper extremities. Effects on virtual driving due to different information processing loads are explored.

4.2 Research OBJECTIVES, SPECIFIC AIMS, AND HYPOTHESES

Objective 1: To characterize wheelchair driving performance of individuals with spastic Cerebral Palsy (CP) and matched controls.

Specific Aim 1a: To compare wheelchair driving performance of subjects with spastic CP to matched controls in a virtual wheelchair driving simulator.

> **Hypothesis 1a:** Compared to controls, and regardless of joystick used and driving task implemented, subjects with spastic CP will have decreased performance because of the deficits already known to occur in grasping, reaching, and striking tasks. [10], [15–17]

Specific Aim 1b: To evaluate the effect of a customized joystick on virtual wheelchair driving.

> **Hypothesis 1b:** Compared to when using a conventional motion-sensing joystick, subjects will show poor driving performance metrics when using the IJ.
>
> **Hypothesis 1c:** Subjects with spastic CP will show poor driving performance metrics when using a conventional motion-sensing joystick compared to a customized IJ.

Rationale: IJs are rigid, force sensing joysticks. Compared to conventional motion-sensing joysticks, they have been shown to improve target acquisition in subjects with impaired upper limb function[18–20]. Thus, we expect more errors to occur when the subject with spastic CP use the MSJ, compared to the IJ. Even though IJs are thought to improve performance by correcting or filtering excess or unintentional movements[8], [21], we do not expect control subjects to have enough of these movements to see a difference in their performance based on joystick alone.

Objective 2: To understand the importance of "lead time," or the amount of time a subject needs to make a movement decision, in driving performance of subjects with spastic CP versus controls.

Specific Aim 2: To evaluate the effect of different lead times when individuals with spastic CP versus controls use two joysticks to drive a virtual EPW.

> **Hypothesis 2a:** Smaller warning times, regardless of joystick used, will be associated with poor virtual driving performance metrics in all subjects
>
> **Hypothesis 2b:** Compared to controls, subjects with spastic CP will show a greater magnitude of difference in driving performances between the smallest and longest warning times.

Rationale: Subjects with spasticity have been shown to estimate visually a point of contact with a moving target by aiming at a point much farther ahead of the target than do subjects without spasticity [22]. Subjects with spasticity therefore are likely to need more “lead time,” or time to predict a target’s position. When an entire driving path is visible, all subjects should be able to plan movements ahead of time considering the nearest obstacle/turn. When the driving paths appear in fixed or variable increments, as is the case in real world driving, the planning time available to subjects to react before an obstacle decreases. Decreased warning time should not affect a subject’s reaction times or response to turns because reaction time is known to remain constant for both groups in repeated tasks. Since reaction time usually is constant for these subjects, movement time will be increased due to performance errors and variation in driving velocities. We expect reduced warning for turns to impair performance more for those with spastic CP than for controls. Thus, the magnitude of differences seen when the tasks are compared should be greater for those with spastic CP.

4.3 METHODS

4.3.1 Virtual Environment

The virtual environment (VE) was modeled using a commercial modeling program (Multigen Paradigm Creator Studio [23]). The base software application, written in C++, interfaced the graphics engine (Multigen Paradigm Vega Prime [24]) Application Programming Interface (API). The main application read and processed raw data from the joysticks. A proportional derivative (PD) mathematical model was used to simulate motion of the virtual wheelchair. Refer to chapter 2 details about this model. The virtual simulation ran on a DELL Latitude laptop with 2GHz Intel Pentium processor and 1GB of Random Access Memory (RAM).

Six driving tasks that simulated driving along a hallway were designed for this study (See Figure 4-1: Driving Tasks). Hallway dimensions (length 10 meters, width 1.5 meters) were selected based on ADA guidelines for accessible routes [25]) The practice task was a straight 10 meters long hallway with no turns. Each of the 5 test tasks had four alternating left and right turns between their start and finish points. The turns were separated by hallways of equal lengths to allow for sufficient recovery time for mistakes made during previous turns. The virtual wheelchair was represented as a rectangular sprite (0.635x0.655 meters).

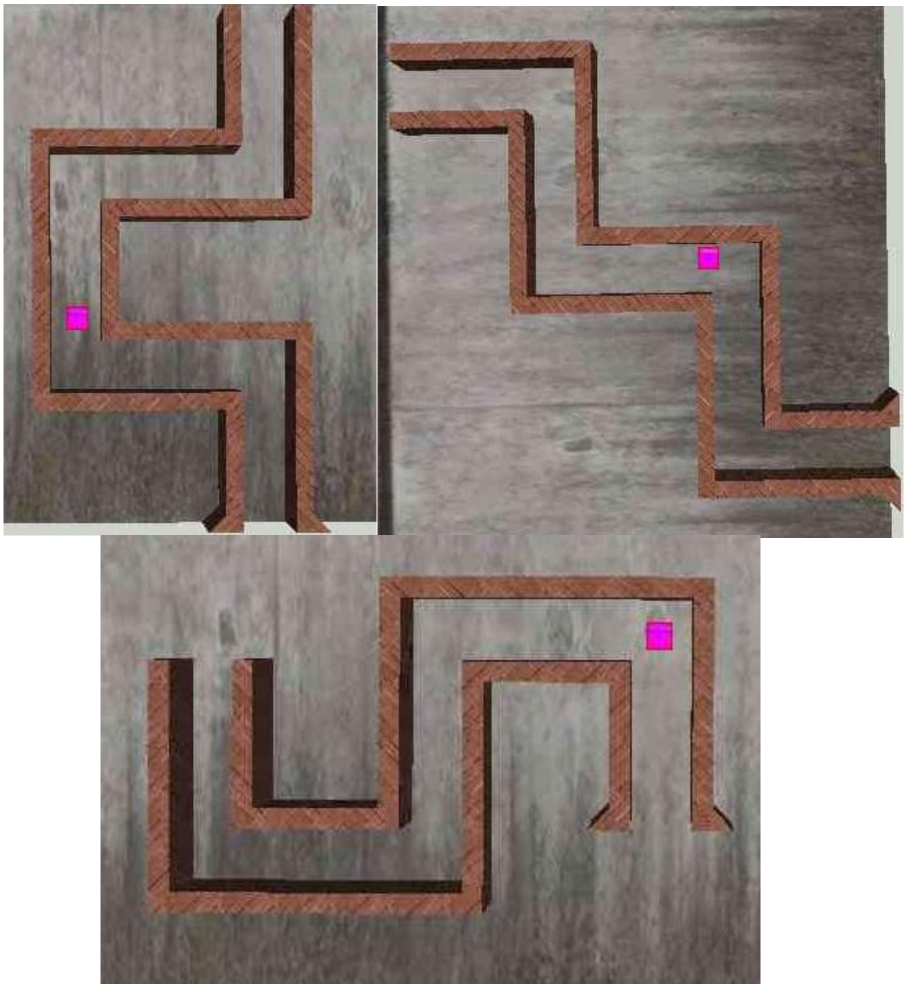

Figure 4-1: Driving Tasks

The virtual world was seen from a "bird's eye" viewpoint where the camera was tethered to the virtual chair and pointed downwards and perpendicular to floor. This camera position ensured that subjects saw the virtual world from a third person shooter viewpoint [26], [27]. Our previous research showed that interacting with the virtual world from this viewpoint reduced the effects of inattention and neglect in people with stroke [28] and traumatic brain injury [8]. In order to maintain a specific lead time ahead, the camera height varied in proportion to the virtual chair's velocity. The schematic in Figure 4-2 and Equation 6 shows the relationship between look-ahead distance (d) and camera height (h).

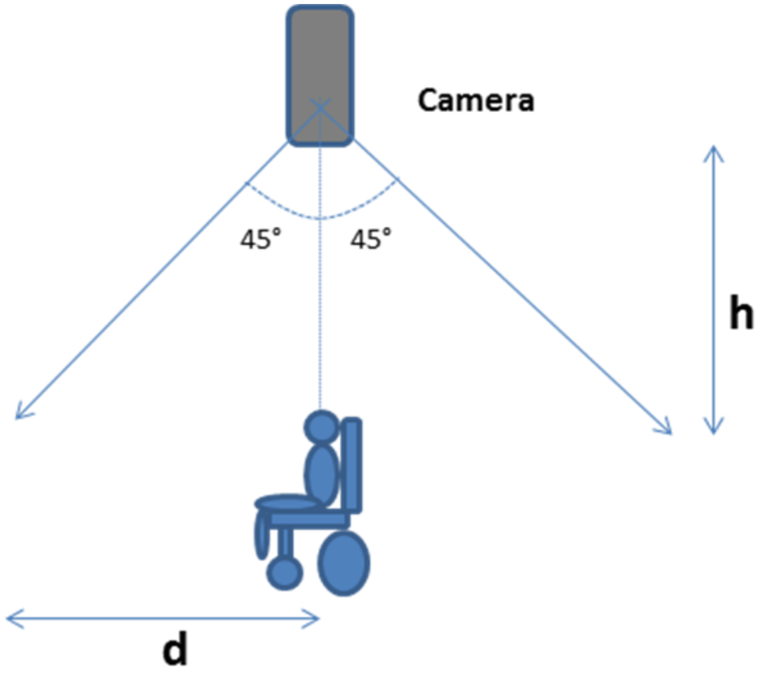

Figure 4-2: Schematic to explain implementation of lead time

$$h = h_{min} \qquad if\ chairSpeed < chairSpeed_{min}$$

$$= maximum(h_{min}, leadTime * \ chairSpeed)$$

$$if\ chairSpeed_{min} < chairSpeed < chairSpeed_{max}$$

$$= minimum(leadTime * \ chairSpeed, leadTime * chairSpeed_{max})$$

$$if chairSpeed > chairSpeed_{max}$$

$$d = h$$

$$h_{min} \ = 1\ meter$$

$$chairSpeed_{min} = 0.8\ meters/second$$

$$chairSpeed_{max} = 1.8\ meters/second$$

Equation 6: Camera height (h), chair speed, lead time, and look ahead distance (d)

Since the camera had a 90° horizontal field of view, the look-ahead distance and camera height were equal. Subjects were encouraged to drive as fast and as accurately as possible while maintaining a speed between 0.8 and 1.8 m/s, which discouraged them from driving at unrealistically low speeds to avoid errors. These speed ranges were selected based on average human walking speed of 1.4 m/s [29], [30]. The camera height varied from a minimum of h_{min} (1 meter) from the virtual driver's head to a maximum of leadTime * maximum recommended chair speed ($chairSpeed_{max}$). The minimum camera height of 1 meter ensured a look ahead distance of at least 1 meter in front of the virtual chair. $chairSpeed_{max}$ and $chairSpeed_{min}$ are the maximum and minimum recommended chair speeds. Subject could drive the virtual chair beyond

$chairSpeed_{max}$ but this higher speed did not change their look-ahead distance (equal to camera height). This prevented subjects from taking unfair advantage of viewing a larger section of path by driving faster than recommended. The sprite turned green when the subject was driving with acceptable speed ($chairSpeed_{min} < chairSpeed < chairSpeed_{max}$), yellow if driving too fast ($chairSpeed > chairSpeed_{max}$), and red if driving too slow ($chairSpeed < chairSpeed_{min}$).

4.3.2 Inclusion Criteria

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

4.3.3 Exclusion Criteria

1. Subjects who are not able to tolerate sitting for 2 hours (the estimated length of the experiment)
2. Subjects who have active pelvic or thigh wounds (they may be worsened by prolonged sitting)
3. Subjects with a history of seizures in the last 90 days

4.3.4 Experimental Protocol

“Operating limb” was defined as the limb control subjects or subjects with bilateral upper extremity involvement prefer to use, or the involved limb for subjects with unilateral involvement. After giving informed consent, all subjects underwent a brief upper limb neurological examination by a physiatrist to include Modified Ashworth Scale [19], [31], [32]. Subjects with spastic CP completed (with assistance if needed) a questionnaire that included questions on demographics, medical history including visual problems, Barthel Index[20], [33], Penn Spasm Frequency Scale[34], [35], and assistive technology use.

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

Subjects used a stock Quickie [36] brand movement joystick (MJ) and the HERL Isometric Joystick (IJ) [7], [37] to interact with the virtual simulation. The joysticks were connected only to the computer running simulation and not to the subject’s wheelchair. Since the IJ post is rigid, essential joystick parameters like dead zone shape and size, perimeter template shape and size, axes gains, and rotation of biased axes must be programmed in software. The IJ was customized for each subject using a previously validated protocol [8], [38], [39].

All subjects in control and cerebral palsy groups used both MJ and IJ to complete the virtual driving trials. The order of the joysticks was random to account for bias and carry over effects. Subjects were allowed to practice for 5 minutes with each joystick on the practice track (straight hallway with no turns). Subjects performed driving trials with each of the five lead times (0, 1, 2, 3, 10 seconds) on three of the five test tasks available, making a total of 15 (5 lead times x 3 tasks) trials with each joystick. When lead time was 0 seconds, only a minimum look ahead distance (1 meter) was seen by the driver. When the lead time was 10 seconds the entire task with all 4 turns was visible. The order of lead times and tasks were randomized to minimize learning effect.

4.3.5 Data Processing

The simulation program recorded various state variables in real time. Time instances, joystick voltages, virtual wheelchair speed, acceleration, Cartesian position coordinates (x, y), orientation (theta), and collision status were recorded. This data was post processed using MATLAB [40] outcome variables of interest were derived.

Even though participants received feedback when they were driving slower or faster than recommended, the average self selected driving speed of every subject was slightly different. This resulted in higher number of data points in trajectories of slower drivers than those of faster drivers for the same task. If a driver took exactly same trajectory driving slow and fast, the slow trajectory would show a higher measure of error just because of higher number of data points. Hence, in order to avoid the bias arising from speed differences, spatial sampling of the task trajectories was performed at superimposed imaginary sampling gates. These sampling gates were drawn equidistant from each other and perpendicular to the boundaries that define the task. The locus of midpoints of these sampling gates is also the midline of the task and is the ideal trajectory subject is expected to take. The participants' actual driving trajectories were sampled at these imaginary gates and used to derive unbiased deviation from center of the tasks. Trajectory based driving performance measures are computed similar to their equivalent measures in computer access tasks [41]. Movement error (ME) for a task was the average of all deviations measured at these sampling gates while movement variability (MV) was the standard deviation. While driving along a hallway in real world, lower values ME and MV may indicate higher accuracy of the participant's driving. Any sudden change in the wheelchair's heading angle was recorded as a "significant" change in heading (CH). In all the driving tasks, participants are expected to drive in forward direction along the task. However, if a participant drove the wheelchair such that its current trajectory intersected its old trajectory, the self intersecting loop (SIL) thus formed was also recorded. These SILs are especially common when the hallway turns. They indicate a driving behavior when the driver gets too close to a wall and has to back off the chair before continuing to driving forward. When driving along a real world hallway with no obstacles, more number of sudden changes in heading and self intersecting loops may indicate an unsafe driving behavior. Outcome measures trial completion time (TT) and average speed (AS), computed from the raw driving data, give measures of efficiency in completing driving tasks. Reaction Time (RT) was defined as the time the participant took to start a voluntary motion of the virtual wheelchair after a 3-2-1-GO! prompt. The participant was thought to have begun the driving trial when force applied to the joystick moved the chair 0.01 meters. Average acceleration (AA) gave an estimate of level of smoothness in the participants driving. Higher acceleration while driving the real wheelchair makes it harder to control. All driving trials that were left incomplete by the participants were not considered for further analysis.

4.3.6 Statistical Analysis

Participants in the CP group were matched with those in control group based on their age and gender. The statistical level of confidence was set at 0.05 for all analyses. The variables TT and RT were log transformed (natural log) to correct for the skewness in their distributions. To evaluate the hypotheses 1a and 1b we performed a completely within subjects Multivariate Analysis of Covariance (MANCOVA) using procedure MIXED in SPSS [42]. Lead time was the covariate, joystick type was the within subjects repeated factor, and subject group was the between subjects factor. The main and interaction effects were evaluated in a full factorial model. To evaluate hypothesis 2, a similar completely within subjects repeated measures MANCOVA analysis was performed with joystick type as the covariate, lead time as within subjects repeated factor, and subject group as between subjects factor. Univariate and post hoc pairwise multiple comparisons were performed for effects that were significant.

4.4 RESULTS

4.4.1 Demographics

In all there were a total of 17 age and gender matched pairs of subjects with CP and controls. A total of 9 subjects from CP group and 11 subjects from the control group stated that they preferred the IJ over the MSJ.

Table 4-1: Demographics and for subjects from CP (cases) and Control groups

Demographics		CP (cases)	Controls
Number of Participants		17	17
Mean Age ±SD in years		36.5 ±15.9	36.1 ±16.6
Number of females		8	8
Ethnicity	Caucasian	13	15
	African American	4	0
	Asian American	0	2
Mean Barthel Score		50.0 ± 23.9	100 ± 0.0
Median Penn Spasm Frequency (range)		1 (0,4)	0 (0,4)
No. Prior Joystick Experience		12	10
No. Met Joystick Customization Inclusion Criteria		14	17
No. Preference for IJ		9	11

4.4.2 Research Objective 1: To characterize wheelchair driving performance of individuals with spastic Cerebral Palsy (CP) and matched controls.

Table 4-2: Overall driving performance metrics of both subject groups after controlling for Lead Time

Outcomes	**CP**	**Control**	**CP-Control**	**P value**	**partial η^2**
Trial Time (seconds)	78.13±1.65	37.56±1.25	40.57	<0.001	0.519
Reaction Time (seconds)	0.93±2.08	0.76±1.6	0.17	0.016	0.036
Movement Error (meters)	0.17±0.03	0.14±0.03	0.03	<0.001	0.179
Movement Variability (meters)	0.19±0.03	0.17±0.03	0.01	0.013	0.039
Absolute Speed (meters /seconds)	0.28±0.1	0.29±0.07	-0.02	NS	NS
Average Acceleration (meters /seconds^2)	0.4±0.13	0.67±0.14	-0.27	<0.001	0.542
Direction Changes	30±12.56	21.82±2.88	8.18	<0.001	0.189
Self Intersecting Loops	4.3±3.88	0.79±0.93	3.52	<0.001	0.321

Since Lead time (LT) had a significant main effect ($p = 0.012$, partial $\eta 2=0.122$) and it did not significantly interact other independent variables it was considered a valid covariate. Within subjects repeated measures analysis, with LT as covariate, indicates significant main effects of Subject group ($p< 0.001$, partial $\eta2=0.739$), joystick type ($p< 0.001$, partial $\eta2=0.46$), and subject group x joystick type interaction ($p< 0.001$, partial $\eta2=0.25$). No other interactions were significant. Table 4-2 shows that irrespective of the LT, both CP and control groups drove with approximately same average speeds. After controlling for LT, the CP group showed significantly higher trial completion times, higher reaction times, higher movement errors, higher movement variability, lower acceleration, more direction changes, and self intersecting loops than the control group.

The subject group x joystick type interaction effect was significant for reaction time ($p< 0.001$, partial $\eta2=0.101$), average speed ($p< 0.001$, partial $\eta2=0.082$), acceleration ($p=0.042$, partial $\eta2=0.026$), direction changes ($p< 0.001$, partial $\eta2=0.081$), and number of self intersection loops ($p< 0.001$, partial $\eta2=0.119$). When using IJ, the CP group had a reaction time of 0.422 seconds higher than when using the MJ. When using MJ, the reaction time for CP and control groups were not significantly different. When using a MJ, the average speed was higher and less variable (CP-control= 0.013 m/s) between CP and control groups. When using the IJ, the control group drove with average speed 0.045 m/s more than CP group and hence average speed was more variable. Similar trends were seen in variables direction changes and number of loops. While using the IJ, less variation was seen among CP and control groups in direction changes (CP-control= 5.99) and number of loops (CP-control= 2.531). On the other hand, while using the MJ, the differences between CP and control groups were larger for direction changes (CP-control= 10.43) and number of loops (CP-control = 4.5).

Univariate analysis comparing joysticks (Table 4-3) showed that participants showed a higher reaction time, lower movement variability, lower movement error, lower absolute speed, and lesser number of direction changes and loops while using an IJ than when using the MJ.

A within subjects repeated measures analysis similar to that for Hypothesis 1a were performed for CP and Control groups separately with LT as covariate. Significant main effects of joystick type (Case group: $p < 0.001$, partial $\eta 2=0.525$; Control group: $p < 0.001$, partial $\eta 2=0.507$) were seen. No other interactions were significant. Multiple comparison analysis gave the following differences in driving parameters when IJ and MJ were used. The IJ – MJ differences in all performance metrics were higher for the Case group than the control group. Using the IJ the control group drove much faster and with lesser trajectory errors than when they used the MJ. Similar trend was seen in the control group as well but for them the differences in performance metrics were not as big as the case group. This shows that using an IJ over the MJ was of much more of an advantage for the case group than the control group.

Table 4-3: Driving performances with the two joystick type after controlling for Lead Time

Outcomes	**Isometric Joystick (IJ)**	**Movement Joystick (MJ)**	**IJ - MJ**	**P value**	**partial η^2**
Trial Time (seconds)	52.55±1.42	55.85±1.46	-3.31	NS	NS
Reaction Time (seconds)	1.01±1.89	0.7±1.76	0.31	<0.001	0.244792
Movement Error (meters)	0.15±0.03	0.16±0.03	-0.01	<0.001	0.207193
Movement Variability (meters)	0.17±0.04	0.19±0.03	-0.01	<0.001	0.223745
Absolute Speed (meters /seconds)	0.25±0.09	0.32±0.08	-0.08	<0.001	0.351142
Average Acceleration (meters /seconds^2)	0.54±0.14	0.54±0.13	NS	NS	NS
Direction Changes	24.05±5.99	27.77±9.44	-3.72	<0.001	0.191984
Self Intersecting Loops	1.6±1.73	3.49±3.08	-1.89	<0.001	0.413367

Table 4-4: Differences in driving parameters for IJ and MJ for both Case (CP) and Control groups after controlling for Lead Time

Outcomes	**IJ – MJ (Case)**	**IJ-MJ P values (Case)**	**IJ – MJ (Controls)**	**IJ-MJ P values (Controls)**
Trial Time (seconds)	-5.265	NS	-2.055	0.009
Reaction Time (seconds)	0.55	<0.001	0.107	0.007
Movement Error (meters)	-0.011	0.004	-0.008	0.010
Movement Variability (meters)	-0.014	0.003	-0.01	0.004
Absolute Speed (meters /seconds)	-0.107	<0.001	-0.048	<0.001
Average Acceleration (meters /seconds^2)	-0.021	NS	0.0104	NS
Direction Changes	-5.949	<0.001	-1.475	<0.001
Self Intersecting Loops	-2.861	<0.001	-0.906	<0.001

4.4.3 Research Objective 2: To understand the importance of lead time on driving performance of CP and Control groups.

To answer hypothesis 2a and 2b, joystick type was used as a covariate. The between subjects main effects of Subject group ($p < 0.001$, partial $\eta 2=0.745$) were significant. The within subjects main effects of LT ($p = 0.045$, partial $\eta 2=0.047$) were significant. No interactions were significant. After controlling for the effects of joystick, the CP group showed higher trial completion time, lower acceleration, higher ME, higher direction changes, and higher SIL than the control group. Comparing the outcome measures across the 5 levels (0, 1, 2, 3, 10 seconds) of LTs gave following results. The trial time was not significantly different across the different levels of LTs. Both Movement error and Movement Variability significantly increased with increase in LT. Average acceleration decreased with increase in LT with significantly low values for LT = 10s. Number of loops was higher for LT =10s and this variation across LTs was large for IJ than for MJ. As it was expected, compared to the Control group, subjects in the CP group showed a higher variation in most of their driving performance metrics between the lowest and highest lead time settings (see

Table 4-6).

Table 4-5: Overall driving performance metrics for subjects while driving with the five lead times after controlling for joystick usage

	Lead Time/Warning Time (seconds)*				
Outcomes	0	1	2	3	10
Trial Time (seconds)	54.89±1.43	56.06±1.43	54.58±1.44	54.88±1.45	65.93±1.5
Reaction Time (seconds)	0.83±2.03	0.89±1.84	0.88±1.94	0.8±1.9	0.88±1.89
Movement Error (meters)	0.15±0.03	0.15±0.03	0.15±0.03	0.16±0.03	0.17±0.03
Movement Variability (meters)	0.18±0.03	0.17±0.03	0.18±0.03	0.18±0.03	0.19±0.04
Absolute Speed (meters /seconds)	0.29±0.09	0.28±0.1	0.29±0.09	0.29±0.1	0.27±0.1
Average Acceleration (meters /seconds2)	0.55±0.14	0.55±0.14	0.55±0.13	0.55±0.14	0.5±0.13
Direction Changes	25.78±8.5	25.12±6	25.38±7.5	24.92±9	26.74±10
Self Intersecting Loops	2.54±3	2.15±2.5	2.18±2.5	2.42±2.5	2.94±2.5

*Note: During the “zero second” lead time the camera displayed certain minimum distance in front of the chair.

Table 4-6: Differences in lowest and highest Lead Times for Case/CP and Control groups after controlling for joystick usage

Outcomes	**LT0 – LT10 (Case/CP)**	**LT0 – LT10 (Controls)**
Trial Time (seconds)	-18.3381	-3.74285
Reaction Time (seconds)	-0.0362	-0.05404
Movement Error (meters)	-0.012	-0.017
Movement Variability (meters)	-0.013	-0.019
Absolute Speed (meters /seconds)	0.025	0.01
Average Acceleration (meters /seconds^2)	0.058	0.05
Direction Changes	-2.222	0.308
Self Intersecting Loops	-0.763	-0.041

When asked about their preference for the two joysticks, 9 from the CP group and 11 from the control group preferred to use the IJ. They stated that IJ was much easier for them to use compared to the MSJ which was more sensitive. This group liked the rigid post and felt more in control with the IJ. Those who preferred the MSJ stated that they did not like the rigid post and the IJ required them to apply more force.

4.5 DISCUSSION

The IJ and MSJ are slightly different in the amount of force required to produce proper transduction. However, subjects with CP and Controls were able to adapt and interact with the virtual simulation with both joysticks irrespective of their prior exposure to either one of them. The training and familiarization seemed to be sufficient. Since the lead times and joysticks were randomly assigned to users we do not expect significant learning or carry over effects. The customization of Isometric Joystick (IJ) was performed to derive dead zone, template, axes gains, bias axis rotation for the joystick. For the Movement Sensing Joystick (MSJ) these parameters (except axes gains) were defined by the hardware setup of the joystick. This could be one of the limitations of this study since it was not possible to isolate the effect of the joystick tuning parameters on overall driving performance.

Even though this simulation gave subjects a visual feedback on their “within limit” and “out of limit” driving speeds, they were not required to follow that driving speed. Subjects typically self selected a certain speed range to drive with and continued to use it throughout rest of the trial. More research is required in making sure that subjects follow they expected speed as closely as possible. Maintaining a fixed driving speed (which could be different for different users and test conditions) will help in explaining and modeling the influence of driving speed on the other driving performance metrics. In future studies, subjects could track a target moving at a fixed speed while driving the virtual chair.

Subjects from the CP group showed a significantly higher trial completion time than the controls irrespective of the joystick they were using or the lead time for driving trials. Joystick use was slightly different within the two matched subject groups as well. CP group users showed a statistically larger difference in their IJ and MJ reaction times. This difference was much smaller in the control group's reaction times. This makes sense since the rigid IJ post requires a higher amount of force to cause a valid motion in the virtual wheelchair. The movement joystick required less force to actuate motion. Hence it was easier for users to drive faster and at a higher acceleration. However, driving faster users made higher errors in their driving trajectories (higher movement error and movement variability, higher number of unnecessary direction changes, and self intersecting loops). Overall this improvement in speed did not translate into overall better trial performance with the MSJ since the trial times with both joysticks were same. Instead of driving primarily straight, while using MSJ, subjects took a more winding or ”zig zag” path along the ideal path contributing to higher direction changes and self intersecting loops compared to while driving with the IJ. One explanation to the difference in driving performance metrics for the IJ and MJ could be that the spasticity and involuntary movements in the operating limbs of CP subjects made driving with MJ slightly harder whereas the IJ provided a damping effect on the unintended movements applied to the joysticks. The rigid post of IJ may be assisting users in limiting any devious/oscillating motions possibly associated with their upper motor neuron syndrome (tone/tremor).

After accounting for the effects on dependant variables from the two joysticks, as it was expected, reaction times of subjects did not change with changes in lead time. The results for other driving parameters are contrary to what was expected. We expected that when the lead times were small subjects would have higher errors compared to longer lead times when they would theoretically have more time to react to obstacles. With increase in lead times, however, subjects showed higher errors in driving trajectories. This brings into question whether turns along a hallway could be considered as obstacles in true sense. Driving along a hallway is a steering task and obeys different information processing laws. The law of steering [43], [44] states that the time to complete a task is directly proportional to the index of difficulty for that task which means higher the difficulty of a task longer it takes to complete the task. For steering along a straight hallway the index of difficulty is the ratio of hallway length to its width. With higher lead times the subjects saw more of the hallway in front of them and hence the perceived difficulty of the task increased. This might explain the decrease in speed. We are currently conducting another research study in which obstacles like a bouncing ball and a walking person unexpectedly appears in the wheelchair driver's path along a straight hallway. More relevant reaction times to specific obstacles can be calculated. Frequent turns in the hallways used for this study could be another reason for this discrepancy. Especially for longer lead times, subjects saw a longer portion of track with one or more turns ahead. In future research, subjects will be evaluated along driving tasks with longer hallways of varying widths.

The top-down bird's eye or "God" viewpoint was used with this system to provide a less visually demanding experience with the virtual environment. However, we did not collect quantitative information about the mental, physical, or cognitive workloads associated with virtual driving. In a recently ongoing study, we are evaluating driving performance of subjects in immersive virtual reality environments and specifically collecting mental, physical, temporal, and other workloads using the National Aeronautics and Space Administration Task Load Index (NASA-TLX) [45].

4.6 CONCLUSION

The IJ encouraged subjects to drive the virtual wheelchair slower but with higher accuracy with little to no compromise on the overall driving performance. The IJ may be used as an alternative input device to the conventional movement sensing joystick for people with upper extremity spasticity for both power mobility and computer access tasks.

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5.0 VRSIM 3.0: COMPARISON OF DRIVING PERFORMANCE IN AN IMMERSIVE VIRTUAL REALITY WHEELCHAIR DRIVING SIMULATION

5.1 BACKGROUND

Virtual environments (VE), in the form of computer games, are traditionally being used for entertainment purposes. In recent years, the significant advancements in graphics and gaming technologies have made VEs an ideal platform for training, collaboration, and information exchange among other things. Moreover, the skills learned in the VE seem to transfer into real world activities [1], [2]. Researchers have developed and tested simulators for the purposes of wheelchair driving training[3–6], some of which have shown high correlations to real world driving tasks[3], [5], [7], [8]. This research study investigates a virtual wheelchair driving simulator that is specifically designed to serve as a clinical tool that can assist clinicians in their wheelchair driving assessments. The simulator can also certainly be used as a training tool. Earlier, we have developed simulators specifically for people with Traumatic Brain Injury [9], [10], Multiple Sclerosis [11], and Cerebral Palsy [12]. These simulators had their own metrics to judge the user’s driving performance. In the current version of the simulator, in addition to using the previously used driving performance metrics, we have incorporated a clinically proven wheelchair driving assessment tool. The standardized assessment protocol will improve the reliability in comparisons between real and virtual world driving.

There are few wheelchair driving assessment tools that have shown good intra and inter rater reliability and validity [13–15]. These assessment tools require clients to drive a wheelchair in certain standardized tasks that are evaluated by clinicians. The Power Mobility Road Test (PMRT) [14] is a tool to assess real world wheelchair driving performance. The PMRT was developed as a tool for use in a wheelchair clinic to evaluate driving of clients who may be candidates for getting a power wheelchair. The PMRT was tested and validated on 62 wheelchair users driving through real world driving tasks. The PMRT driving assessment scale showed high inter rater reliability and internal consistency. Driving performance predicted by the composite PMRT scores was significantly correlated with visual perception and alertness of environment, two factors that are relevant in a wheelchair user's real world driving performance. Massengale et.al [14] also found that clients who had average total PMRT scores $\geq 95\%$ showed better scores on motor co-ordination tasks, had better near and far visual acuity and field of view, were less likely to bump into obstacles, and completed the real world PMRT in lesser time thus indicating in general a better wheelchair driving performance. The PMRT consists of 12 structured tasks with static obstacles and 4 unstructured tasks with moving/dynamic obstacles. The wheelchair driver is expected to avoid these obstacles and complete the PMRT driving course as quickly and driving as accurately as possible. The clinician assessing wheelchair driving, rates the user's performance on every task using a 4 point scale. The possible scores are: 1 (unable to complete task), 2 (Completes task hesitantly, requires several tries, requires speed restriction, bumps objects lightly without causing harm), 3 (Bumps objects and people in a way that could cause harm to driver or other persons or objects), and 4(Completely independent in completing task, with optimal performance and able to perform task smoothly and in one attempt). Composite scores are derived for the structured and unstructured tasks and a total score is derived from clinician's ratings on all tasks. Appendix A shows the PMRT scoring sheet used for this study and formulae used to compute the composite scores.

Humans have limited information processing and control capacity [16]. Due to random noise in the human action-perception system or in the environment, errors start compounding in the task. If the task is to drive a vehicle along a path, then due to accumulation of noise, the vehicle will start deviating from the desired or ideal path. The higher the current speed of the vehicle, the faster errors will compound in the vehicle's trajectory, the faster the lateral deviation will increase and the sooner the vehicle will reach the lateral edge of the path. The driver takes a certain amount of time to process the information about deviation in a trajectory. On narrow roads, where the possibility committing error is high, the driver would drive slower to allow him enough time for correcting trajectory if a deviation were to occur and vice versa. The steering law attempts to model this change in the efficiency of task completion per unit increase in task difficulty [17].

The efficiency in completing a task is directly related to the difficulty of the task. Researchers have modeled this relationship in multiple contexts such as performing a 2 dimensional computer access task[18–20] and 3 dimensional tasks in a virtual environment[17], [21], [22] to name a few. Tasks that involve following a trajectory with boundaries, such as menu navigation on a computer or navigating a car along a marked path in a VE [17], could be modeled using the Steering law. The Steering law models a relationship between task completion time and difficulty of that task [23] and is given by

$$T_C = a + b \times ID_C$$

$$ID_C = \int_C \frac{ds}{W(s)}$$

Equation 5-1: Generalized Equation Steering Law

T_C is the task completion time. ID_C is the index of difficulty of the task and is obtained by integrating the inverse of path width along the trajectory. For a linear hallway of fixed width (W) and length (L) the ID_C integral becomes L/W. If a wheelchair of width D is navigating along this hallway, effectively a width of W-D is available to the user before an error is committed by impacting the hallway walls. Hence the task completion time equation becomes

$$T_C = a + b \times \frac{L}{W - D}$$

Equation 5-2: Steering Law equations for a hallway of length L and width W

Some researchers have evaluated validity of the Steering Law for navigation tasks in a virtual environment [17], [21], [22], [24] and in real world driving tasks [25]. The law provides a standardized framework that can be used to compare different input devices or different virtual world setting. The index of performance or throughput (calculated as 1/b, units: bits/second) values could be used for this comparison. The lower the slope (b) of completion time vs ID plot, the higher the index of performance will be and the higher the efficiency will be with which users would complete the task. Steering law relationships can assist in designing activities in virtual and the real world (office spaces, hallways) such that they have an index of difficulty that does not seriously affect the user’s mobility performance.

The purpose of this research study was to design a VE that simulates the tasks of the real world PMRT assessment protocol and to compare the driving performances of experienced wheelchair users for different input mechanisms and display screens.

5.2 RESEARCH QUESTIONS, SPECIFIC AIMS, AND HYPOTHESES

This study will address two main research questions:

5.2.1 Is wheelchair driving in an immersive virtual reality environment (IVRE) different from driving in a computer based virtual environment (CVE)?

Specific Aim 1: To develop a virtual environment for wheelchair driving assessment that simulates an accepted real-world driving assessment Power Mobility Road Test (PMRT) [14]) and compare driving performance scores in IVRE and CVE, with and without the roller system.

Hypothesis 1a: With the test wheelchair strapped onto the roller system, the driving performance in the IVRE will be better than in CVE indicated by lower trial completion time, lower reaction time, lower path length, and lower root mean squared deviation.

Hypothesis 1b: With the mathematical model simulating wheelchair dynamics, the driving performance in the IVRE will be better than in CVE indicated by lower trial completion time, lower reaction time, lower path length, and lower root mean squared deviation.

Hypothesis 1c: Irrespective of whether driving trials were performed in the IVRE or CVE, compared to the trials using the rollers, trials using mathematical model will show better driving performance indicated by lower trial completion time, lower reaction time, lower path length, and lower root mean squared deviation.

Rationale: It is important to compare the driving performances in the IVRE and CVE since both displays present two completely different display form factors and show different fields of view.

Specific Aim 2: To determine if the information processing loads experienced while driving in the hallway with decreasing widths, could be modeled using the Law of Steering [17].

Rationale: If validated, the Law of Steering will provide a standardized framework that can be used to compare driving performances while using the two input methods/driving modes (rollers and mathematical model)

5.2.2 Will the clinicians' scores on tasks in the virtual driving assessment course allow for classification of safe and borderline safe wheelchair drivers?

Exploratory Analysis: We will use an exploratory analysis to determine if either a computer-based or VR assessment can help to identify driving deficits in borderline safe drivers.

5.3 METHODS

5.3.1 Subject Recruitment

The protocol for this research study was approved by the Institutional Review Boards of the Veteran Affairs (VA) Pittsburgh Healthcare System and the University of Pittsburgh. Subjects were recruited by posting flyers at the Center for Assistive Technology (CAT) and other clinics associated with the University of Pittsburgh Medical Center (UPMC). When interested participants enquired about the research study they were briefed about the study procedures by clinicians and were scheduled for a visit to research center.

5.3.2 Inclusion Criteria

1. Subjects must be between 18 to 80 years old
2. Subjects must use a power wheelchair or an attendant propelled manual wheelchair for all or part of their mobility.
3. Subjects who use a power wheelchair must use a standard proportional joystick.
4. Subjects must be able to provide informed consent.
5. Subjects must have very basic cognitive, visual, and motor skills to interact with an interface.

5.3.3 Exclusion Criteria

1. Subjects who have active pelvic or thigh wounds. (They may be worsened by prolonged sitting).

5.3.4 Screening Procedures

A written informed consent was obtained from participants before screening. All screening procedures were administered by a trained Occupational Therapist or a physiatrist. The screening criteria were as follows:

1. *Subjects must have sufficient short term memory to recall that interaction with the joystick produces results on the computer screen.* Subjects must be able to move the simulated wheelchair without additional prompting in order to proceed with testing.
2. *Subjects must have the ability to perceive the moving simulated wheelchair on the computer screen.* They may indicate perception with words, sounds, gestures, or other responses.
3. *Subjects must be able to tap or hit the joystick*. They must be able to exert approximately 2N of force on the joystick, which is the typical amount of force it requires for operation[26] and which will result in simulated wheelchair movement on the computer screen.

5.3.5 Experiment Setup.

The virtual environment (VE) that implemented the Power Mobility Road Test (PMRT) was modeled using a commercial modeling program (Multigen Paradigm Creator Studio [27]). The base software application, written in C++, interfaced the graphics engine (Multigen Paradigm Vega Prime [28]) Application Programming Interface (API) with National Instruments Measurement Services (NIDAQMx,) [29] API for reading analog voltages from joystick, and US Digital Serial Encoder Interface (SEI) [30] for reading encoders. The virtual simulation software ran on a Dell XPS laptop with 2GHz Intel Core2Duo processor and 4GB of Random Access Memory (RAM).

Participants were seated in their own power wheelchairs all time during this protocol. They were asked to park their wheelchairs on a 33”x33”x6” roller platform (Figure 5-1). Two sets of dual rollers were instrumented in the roller platform such that each of them interfaced with one drive wheel of the wheelchair. Four securement straps of the Q'Straint 4 Point Securement System [31] were mounted on corners of the roller platform to tie down the wheelchair to the rollers. Incremental encoders mounted in the rollers read the wheelchair wheel rotations. Analog voltages from a conventional movement sensing joystick, similar to the participant’s wheelchair joystick, were read into a computer through a National Instruments Data Acquisition (NIDAQ) card 6024E. The rollers and customized joystick were two input mechanisms subjects used to interact with the virtual simulation. The simulation was projected on three 6’x8’ back projected screens or on a single generic 22” widescreen LCD monitor.

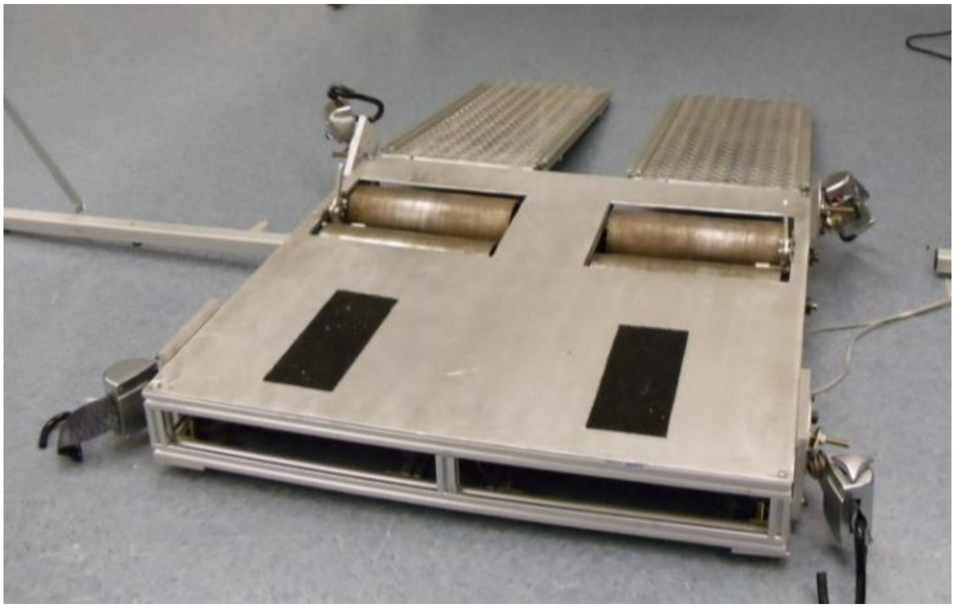

Figure 5-1: Platform with rollers and tie down straps

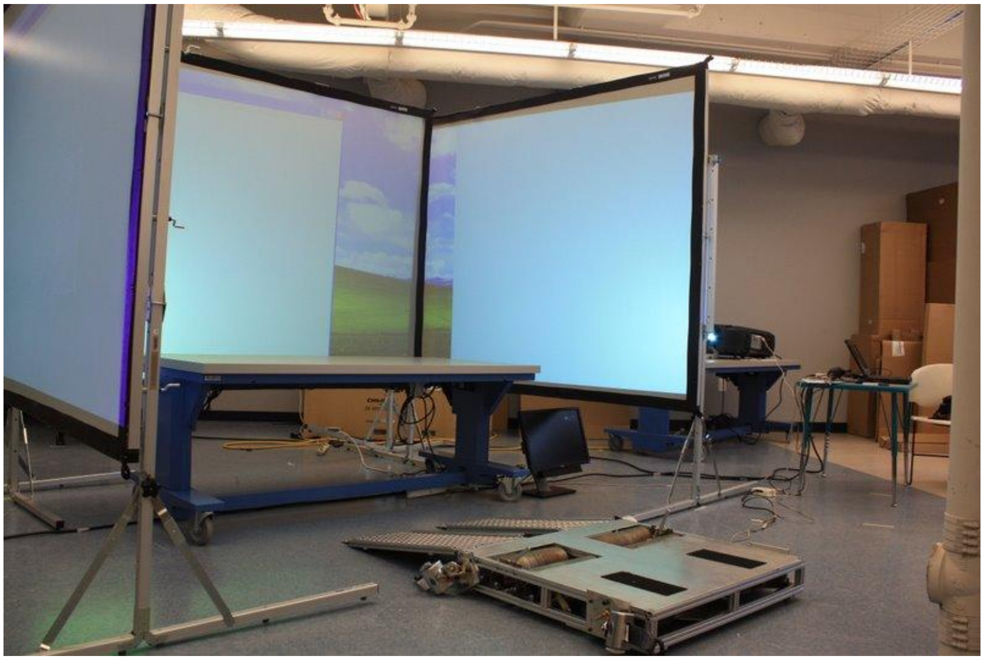

Figure 5-2: Experiment Setup with the VR screens, roller platform, and table to mount PC screen

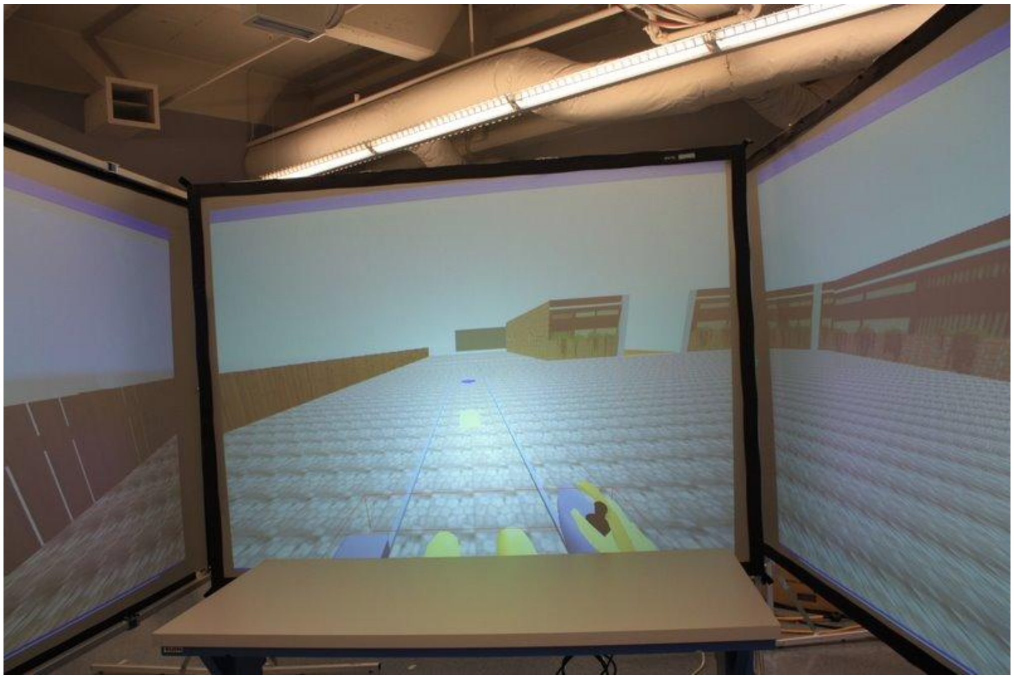

Figure 5-3: First Person Viewpoint on the three VR screens

5.3.6 Virtual Power Mobility Road Test (VPMRT)

The VPMRT modeled in the simulation was based on real world testing scenario of the rehabilitation clinic where the real world PMRT was developed and validated [14]. The testing scenario consisted of a house with living room, a garage, and some open area around it. The testing scenario consists of a large indoor lab space with a simulated kitchen and living room and a set of hallways lined by offices. The task assigned to the user was to drive the virtual wheelchair to along the driving course through certain preset milestones. These sequentially displayed milestones defined the 12 static/structured and 4 dynamic/unstructured tasks of the PMRT. The structured tasks had fixed obstacles while the dynamic tasks had moving obstacles such as a bouncing ball or a person walking in the virtual wheelchair's driving path. Computer generated audio instructions were played when required by a PMRT task. The users were instructed to complete these tasks as accurately as possible. After completing the 16 tasks of the virtual PMRT, subjects were asked to drive along a long hallway. The width of the hallway decreased progressively (in steps of 1.829, 1.524, 1.372, 1.067, 0.914 meters) in order to simulate an increase in cognitive load while driving. This section of VPMRT might be useful in identifying driving deficits that distinguish drivers with experience from new or borderline safe wheelchair drivers.

The "actor" in the VE was a person sitting in a power wheelchair (seat width= 0.671m, length/depth= 0.701m) that was controlled by the user's inputs to the joystick or rollers. The user saw the VE from a "First Person Shooter" point of view [32]. Refer to Appendix B for the screen grabs of driving tasks in the VE from the user's viewpoint. The VE also showed animation of a virtual joystick that mimicked the user's physical inputs (tilt of the joystick post) to the real world joystick. Appendix A lists PMRT tasks in the order they appear in the VE and the PMRT scoring sheet used by clinicians.

In real world, various binocular visual cues like stereopsis and convergence aid in depth perception. In this VE where the graphics are projected on flat screens and the camera was "fixed" or locked to the virtual chair in a FPS point of view, certain monocular cues were emphasized to create a perception of depth and distance between objects. Multiple textures were added to sections of the driving circuit to enhance optical flow. Gourhand shading was used with the virtual objects to aid the depth perception [33]. To give a sense of wheelchair boundaries, a red wire frame box was placed around the complete footprint of the virtual wheelchair. This box also aided in detection of collisions of the chair with other VE components. A short beep sounded to indicate collision with obstacles. After a collision, the virtual chair was slightly bounced back to facilitate maneuvering of the chair. Subjects had a limited about of time to move the virtual wheelchair away from the obstacle depending on their speed before impact. If the user did not move the chair soon enough after the collision, the program terminated the driving trial. This feature made users to anticipate and avoid accidents/collisions and react promptly to drive themselves away from the collision site.

5.3.7 Research Protocol

Subjects performed driving trials for four test conditions: combinations of the two display screens (PC and VR screen) and two driving modes (Rollers On and Off). See Table 5-1. During the 'Rollers On' mode, subjects used their own joystick to drive their wheelchair on the rollers and hence move the virtual wheelchair. Encoder readings from each wheel were used by the simulation program to determine the wheelchair's instantaneous linear and rotational speeds.

During the ‘Rollers Off’ mode, subjects used the customized joystick, and the simulation program applied a mathematical model to estimate the virtual wheelchair’s linear and rotational speeds. Subjects performed 1-2 practice trials to familiarize themselves with the experimental setup and driving in the VE. A balanced randomization scheme was used to set the sequence of the four test conditions. Up to 3 repetitions were performed for each of the test conditions, resulting in a maximum of 12 driving trials per subject. Subjects were allowed to take rest breaks for a few minutes if they felt any fatigue. Subjects self selected their acceleration of the virtual wheelchair, and this value was kept unchanged during the rest of the experiment. Two clinicians trained in real world wheelchair driving evaluations independently assessed the driving performance of participants during every driving trial. The PMRT scoring sheet (Appendix A) lists the scoring criteria used to assess the driving performance on the 12 Structured driving tasks (with static obstacles), 4 Unstructured (with dynamic obstacles), and the decreasing hallway task. Compound scores from these tasks were used to establish intra and inter rater reliability of the PMRT for the VE. Refer to Chapter 5 for details.

Task components in the driving circuit involved driving between two milestones (indicated by green balloons (for start) and blue balloons (for end)) or turning in the direction of an arrow. After one milestone was reached, arrows pointed to the next milestone. An ideally expected path for each of these task components was predetermined and deviations from this path were calculated. The ideal trajectory for any section of the driving circuit was defined as trajectory equidistant from the objects (walls or furniture) lining the path. For example, for a 6ft wide hallway, the ideal trajectory is the line that is 3ft from the walls lining the hallway. For cases where the driving task involved a turn, ideal trajectory was defined as circular arc between the midpoints of the preceding and following hallways. The balloons and arrows marking the milestones were placed along the ideal trajectory and thus provided an easy to follow guide for users.

A root mean squared deviation (RMSD) of the virtual chair from the ideal trajectory was recorded for all task components. Also, during every driving trial, the simulation program recorded joystick voltages and encoder inputs, actual and model predicted wheelchair speeds, virtual wheelchair position and orientation coordinates, and collisions with static and moving obstacles. These data were post processed to determine the subject's wheelchair driving proficiency.

After finishing the research protocol subjects were asked to give their feedback on the VEs. Subjects were specifically asked for their preference for PC and VR screens and the Rollers ON and OFF modes. Subjects were asked if the virtual driving was comparable to real world driving. Subejects were also asked for their general comments suggestions for improvement.

Table 5-1: Four experiment test conditions

Test Condition	Driving Mode	Display	Inputs to VE
1	Rollers OFF	PC	Customized joystick + Math Model
2	Rollers OFF	VR	Customized joystick + Math Model
3	Rollers ON	PC	Encoders on Rollers
4	Rollers ON	VR	Encoders on Rollers

5.3.8 Data Preprocessing and Statistical Analyses

Raw data from the driving trials were processed to derive certain performance metrics for driving performance. These metrics are derived from their equivalents in computer access research [34] and have been used in past research to evaluate wheelchair[9], [10], [12], [35] and car driving

[36] in virtual environments. Trial completion time was the time it took to complete all components of the driving circuit in the virtual simulation. Reaction time was defined as the time it took for the subject to move the virtual wheelchair 0.01 meters. The length of the actual path taken by the virtual wheelchair and the number of collisions were also recorded. RMSD and collision counts from individual task components were used to derive an Automated Power Mobility Road Test (Auto PMRT) score. SPSS (version 18.0) [37] and MATLAB (version 7.11) [38] were used for all analyses. Significance level was set at 0.05 *a priori*. A 2x2 (2 displays and 2 driving modes) completely within subjects repeated measures Analysis of Variance (ANOVA) was performed to answer hypotheses 1a and 1b using the above mentioned driving performance metrics. Additional post hoc analyses were performed if main effects were statistically significant.

The hallway with decreasing widths is not part of the real world PMRT validated my Massengale et. al [14]. This task was added to the virtual PMRT driving course in order to test if subjects could navigate hallway widths recommended by the Americans with Disabilities Act (ADA) [39]. The hallways would help isolate certain risky driving behaviors (such as impulsive driving) and other driving deficits. The Steering Law [23] models the relationship between trial completion time and difficulty of the task (related to the width of task). The times taken to drive through each of the hallway sections were recorded. The index of difficulty values were computed using Equation 5-2, and linear regression equations were formed for the Task Completion times vs. Index of difficulty plots. For the exploratory analysis, data from all driving trials for every subject were analyzed to evaluate what was the minimum hallway width subject could drive through comfortably. If there were a collision along the decreasing hallway that hallway width was noted. Secondly, a descriptive analysis of PMRT composite scores from all subjects was performed to identify safe and borderline safe drivers.

5.4 RESULTS

Eleven regular power wheelchair users were recruited for this research protocol. Clinicians terminated the driving session for one subject who could not complete any of the virtual driving trials because of fatigue and dizziness. Another subject partially completed the required number of driving trials but couldn't return to complete the rest of the protocol due to scheduling conflicts.

Table 5-2: Demographics

Demographics		
Participants	Male	3
	Female	7
	Unable to complete protocol	1
Average Age (years)		39.45±15.87
Disability	Spinal Cord Injury	4
	Cerebral Palsy	3
	Muscular Dystrophy or Spinal Muscular Atrophy	2
	Others	2
Number of subjects who use a Computer	Home	10 out of 11
	Office	8 out of 11
Average number of hours of computer use per week		32.4±8.15

5.4.1 Results from within subjects repeated measures ANOVA

There was a significant main effect of Drive Mode ($p<0.001$, $\eta^2= 0.511$) and Display Type ($p<0.001$, $\eta^2= 0.677$) for Trial completion time. Participants took about 111.97 seconds

($p<0.001$) more to complete driving trials when using the VR screen than when using the PC screen. Also, for both screens, trial completion times were 54.82 seconds ($p= 0.001$) higher when participants used Rollers as input than when they used the customized joystick and mathematical model (Rollers OFF).

The Main effect of Drive mode on Reaction time was significant ($p=0.006$, $\eta^2= 0.286$). There were no differences in reaction times across PC and VR screen driving trials. While driving with the rollers ON, Reaction Time was about 0.69 seconds ($p=0.006$) higher than when not using the rollers. The path length covered by the virtual chair was significantly different only across the two drive modes (Main effect Drive mode, $p<0.001$, $\eta^2= 0.609$) and not between the two screens. When the rollers were OFF participants covered an extra 5.08 meters ($p<0.001$) compared to when rollers were ON. The main effect of RMSD was significant only for the type of display screens ($p=0.035$, $\eta^2= 0.195$) and not for the drive mode. Irrespective of the driving mode, RMSD values for the VR screens were 0.11 meters ($p = 0.035$) higher than those on PC screen.

Table 5-3: Repeated Measures ANOVA for Trial Time, Reaction Time, Path Length, and RMSD.

Mode	Display	Trial Time (seconds)	Reaction Time (seconds)	Path Length (meters)	RMSD (meters)
Rollers OFF	PC	231.7± 49.13*	0.966±0.67*	137.69±6.02*	0.415±0.15*
Rollers OFF	VR	344.96± 93.58*	1.61±0.97	139.03±6.99	0.51±0.37*
Rollers ON	PC	287.81± 72.96*	2.09±1.48*	132.38±3.16*	0.333±0.08
Rollers ON	VR	398.49± 162.72*	1.87±1.21	134.18±7.0	0.456+0.39

* indicates a pair with a statistically significant difference

All but two participants had at least one driving trial in which they hit a wall or moving obstacle and could not self correct before the program self terminated the trial. Nine out of eleven such trials were on the PC screen.

5.4.2 Steering Law validation

The Index of Difficulty (ID) values for the four hallways are shown in Table 5-4. The average times taken to drive through the hallways are shown in Table 5-5 while the regression equations are shown in Table 5-6. Trial time vs ID curves for all driving conditions gave a very good linear regression fit (R^2 statistic 0.82-0.99). This gives reasonable confidence that the Steering law can be applied to tasks in this VE.

The inverse of the slope of Trial completion time vs ID, 1/b, from Equation 5-2 is called the index of performance or throughput. The lower the value of the slope b, the lesser is the variation in trial completion times per unit change in ID. Thus low values of slopes indicate a much more efficient task completion. Regression analysis shows that the values of the slope during the Rollers OFF driving mode were about half the values during Rollers ON mode. Also the slope values were lower for the PC screen than for the VR screens. This indicates that tasks performed on a PC screen with Rollers OFF should have the best performance.

Table 5-4: Effective Index of Difficulty for different hallways using Equation 5-2. Wheelchair width D = 0.671 m

Hallway	Width (D) of Hallway (m)	Length (A) of Hallway (m)	Index of Difficulty
1	0.914	5.486	22.5
2	1.067	5.334	13.462
3	1.372	5.486	7.826
4	1.524	5.486	6.429

Table 5-5: Average ± Std Dev time (seconds) spent in each of the hallways during each test condition

Mode	Display	Time (seconds) taken to complete these tasks				R^2 value
		Hallway 1	Hallway 2	Hallway 3	Hallway 4	
Rollers OFF	PC (CVE)	7.186±3.18	6.097±1.65	6.232±1.68	5.818±1.03	0.839
Rollers OFF	VR (IVRE)	10.754±5.11	8.926±2.81	9.156±3.54	8.527±2.8	0.834
Rollers ON	PC (CVE)	12.302±6.59	9.837±2.65	10.074±2.65	9.635±2.51	0.825
Rollers ON	VR (IVRE)	16.192±12.94	13.904±8.07	12.704±7.22	12.38±6.48	0.998

Table 5-6: Regression Equations and R-squared values for the "Trial Time vs. Index of Difficulty" plots for all test conditions

Mode	Display	Regression Equations	R^2 value
Rollers OFF	PC (CVE)	$TIME = 0.075 * ID + 5.397$	0.839
Rollers OFF	VR (IVRE)	$TIME = 0.122 * ID + 7.805$	0.834
Rollers ON	PC (CVE)	$TIME = 0.154 * ID + 8.525$	0.825
Rollers ON	VR (IVRE)	$TIME = 0.237 * ID + 10.825$	0.998

5.4.3 Exploratory analysis to evaluate driving deficits

Except for one participant who did not have wall collisions in the decreasing hallway section, participants had a median of 3 (range 1 to 7) driving trials in which they had a collision in the decreasing hallway walls. Since subject VR07 had a collision with the walls of hallway 2 (width= 1.067 m/3.5 ft) the minimum hallway width this subject could navigate was 1.372m (4.5ft). All others had at least one collision with the walls of hallway 1 (width 0.9144 m/3 ft). Hence, the minimum width most could safely navigate safely was 1.067 m (3.5 ft). When collisions during decreasing hallway tasks were computed for the two driving modes and screens, the PC screen with Rollers OFF driving mode showed the least number of collisions (5) while the VR screens with Rollers ON mode showed the most number of collisions (10).

Table 5-7 shows the average values of driving performance indicators. C1TOTAL and C2TOTAL are the composite PMRT scores given by Clinician 1 and Clinician 2. The "Total" scores derived from every trial are averaged in order to generate one representative value for per subject. Similarly, averages for other outcome measures were computed. Clinician1 rated driving trials of subjects VR07 and VR09 with PMRT scores less than 0.9 while Clinician2 rated them with scores less than 0.93. Among all participants, these two subjects showed highest amount of RMSD and longest path length. Their median boundary collisions were highest among all subjects. The trial time and reaction time for these two subjects was significantly above the group average of rest of the group.

Table 5-7: Average PMRT scores and driving performance indicators for all subjects

Subject ID	C1TOTAL	C2TOTAL	Trial Time	Reaction Time	RMSD	Path Length	Collisions
VR01	0.996	0.996	208.835	0.747	0.269	137.549	2
VR02	0.997	0.992	499.634	2.212	0.300	135.554	1
VR03	0.992	0.991	334.089	1.111	0.361	132.348	2
VR04	0.984	0.983	260.125	1.110	0.377	134.469	4
VR05	Did not complete the experiment						
VR06	0.986	0.986	274.254	1.246	0.510	138.819	6
VR07	0.786	0.901	1020.712	2.729	1.310	176.415	61
VR08	0.982	0.988	319.885	1.561	0.374	127.170	3
VR09	0.899	0.929	330.746	2.533	0.805	147.404	10
VR10	0.997	0.999	241.554	1.468	0.306	134.247	0
VR11	0.982	0.978	419.414	3.116	0.386	135.674	8

Subjective preferences of subjects in this study are summarized in Table 5-8. Most of the subjects preferred the PC screen (CVE) over the VR screen (IVRE). Those who preferred the PC screen over the VR screen suggested that the driving in IVRE was more realistic but it made them dizzy. They reported that the three screens presented a lot of information which sometimes overwhelmed them and made them feel tired. Most of the subjects felt no significant difference between the two driving modes. Subjects were able to adapt to the change in the virtual wheelchair's dynamics when the mathematical model was used (Rollers OFF mode). The PC screen+ Rollers ON combination was most appreciated. All subjects agreed that the virtual simulation was a good first step towards a driving training tool and they would recommend and use it if such a tool were commercially available. Subjects suggested that the future versions of the simulation can include a wider range of and more challenging tasks including navigating outside home, through traffic, and in tight spaces (for example: public transportation).

Table 5-8: Subjective preferences of subjects for display screens and driving modes

	Number of subjects		
Screen	PC screen (CVE)	VR screen (IVRE)	No Preference/Equally good
	8	1	1
Driving Mode	Rollers ON	Rollers OFF	No Preference/Equally good
	3	2	5

5.5 DISCUSSION

Comparisons of driving performance scores across the two screens and two driving modes clearly showed significant differences in the driving modes. The driving trials on the VR screen took longer to complete than the driving trials on PC screen yet had no significant difference in the length of path covered. Subjects also had higher RMSD on VR screens than when on PC screen. It could be that the VR screens, due to their larger field of view, created enhanced perception "openness" in the virtual driving track hence resulting in more driving errors. A 4 feet wide hallway on the VR screen, for example, might have been perceived as bigger with respect to the chair than it appeared on the PC screen. In other words, larger Field Of View (FOV) on VR screens lead to greater visually induced self motion [40]. Compared to the single PC screen (FOV = 90°) the three VR screens together (FOV = 180°) gave a much wider field of view and displayed a larger part of the VE. This extra information might have induced a higher cognitive load on subjects which made them commit more errors and drive slower to compensate for increased information processing requirements from extra visual inputs. The higher field of view from the VR screens was of some advantage for the subject's response to wall collisions as they were able to avoid and correct their paths away from potential obstacles. Subjects got stuck after collision more often on the PC screen than on the VR screen. Similar results were found by Tan et.al (2006) [41].

When Rollers were not used the customize joystick was mounted on subject's wheelchair. We expect the mounting to have less impact on the driving since most of the subjects felt comfortable driving with a joystick positioned slightly differently than their regular joystick. However, this may be an issue with subjects who have significant seating and positioning requirements. When rollers were not used subjects showed lower reaction times compared to when rollers were used. Subjects were comfortable driving faster without the rollers and using the mathematical model but they showed a slight increase in the length of path travelled compared to when the rollers were used. This indicates that subjects took a path with more turns when not using rollers. The mathematical model used to simulate wheelchair dynamics tends to make the wheelchair slightly more sensitive to turns. Few participants noted this difference in turn sensitivity when Rollers were OFF compared to when Rollers were ON but they were able to adapt to the turning rate after one practice trial.

The steering law evaluations showed that the driving performances in the decreasing hallways could be modeled using the steering law equation. Of the four driving modes, subjects showed the best index of performance values for Rollers OFF + PC screen combination and the worst values for the Rollers ON + VR screen combination. Similar trends were seen in the number of wall collisions in the decreasing hallway section. The PC screen provides a low cost and portable display for implementing the virtual driving experience in a home environment. Moreover, some users who are prone to fatigue and cybersickness from the immersive VR screens report to be more comfortable with the PC screen. The mathematical model, although not perfect, closely simulates wheelchair driving and enables potential users to interact with the VE using a simple joystick. This software could be implemented and customized by an experienced clinician through a web interface to which the potential users could log in from their homes or remote clinics.

While validating the real world PMRT, Massengale et al. (2005) [14] found that wheelchair drivers with ≥ 95% score were safe drivers. This group also showed higher near scores on motor coordination, high near and far visual acuity, lower collisions with obstacles, and had a higher alertness to details in environment. Out of the 10 subjects who completed this research protocol, two subjects received significantly low (<95%) total PMRT scores (average of scores from all 16 tasks) from both clinicians. Based on the poor driving performance metrics (high trial time, high reaction time, high RMSD, high path length, and more collisions) these two participants could be classified as not to include in the group of “good/safe” drivers as far as virtual driving tasks are concerned. In real life however, both of these participants were regular power chair users and usually drove their chairs independently without bumping into obstacles. The researchers observed few instances of impulsive driving in real world hallways when one of the two participants classified above arrived to the research center. However, the program does not distinguish between an impulsive and non impulsive driver. Since impulsive driving in the real world may be one of the main reasons for wheelchair accidents, it will be useful to introduce driving tasks and evaluation metrics that can specifically quantify impulsive driving.

Since this is the first study that uses the PMRT in virtual environments, there were no "normal" limits to the any of the performance measures analyzed. The only reliable score for safe/unsafe classification was the PMRT total score. In future studies, after collecting data from a larger cohort of wheelchair drivers will help us identify certain safe score ranges for the driving performance metrics like average driving speed and RMSD. Feedback received from the subjects was quite useful in deciding the future plan of action with the virtual simulation software. However, more user research in a wider cohort of wheelchair users is required to gauge subjective preferences of users for display screens and rollers.

There were some limitations to this study. The mathematical model that was implemented was designed only for front wheel drive chairs. This significantly limited the participants we could recruit. The mathematical model itself was slightly more sensitive to turns which caused the virtual chair to over steer. A future version of this model used in will employ tuning parameters to control the linear and rotational accelerations. Also, for use in a future clinical application, a library of mathematical models of commonly prescribed front wheel, mid wheel, and rear wheel drive wheelchairs will be created. The mathematical model can be customized by experienced clinicians as required by clinical needs of a potential user.

Small sample size was another limitation of this study; however we believe the within subjects design allowed for sufficient power in all statistical analyses. All participants recruited for this study were regular power chair users. Because users had significant experience driving the wheelchair in the real world, the driving deficits identified in this study should be compared with driving in real world tasks. Comparison of virtual and real world driving performances of wheelchair users is currently examined in the second phase of this study. The participants were not specifically evaluated for their motor coordination and visual acuity/field of view. The screening relied on self report from the participant. In future studies, tests such as the Motor-Free Visual Perception Test [42] could be used to test overall visual perceptual skills.

5.6 CONCLUSION

The Power Mobility Road Test was implemented in a virtual environment. There were significant differences in the driving performance of participants when they were driving the virtual chair in the two driving modes and across the two display screens. Participants showed the best driving performance when using the combination of computer screen with rollers off (using mathematical model) while their worst driving performance was seen with the combination of virtual reality screen and rollers on. Using the total PMRT score, 2 participants were classified as poor drivers and this was consistent from the driving performance metrics derived from their trajectory data. The steering law is applicable in modeling a participant's driving performance when driving along a virtual hallway with decreasing widths. Overall this virtual environment seems to be a promising platform for future work with virtual driving assessments.

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6.0 VRSIM 3.0: ESTABLISHING RELIABILITY OF THE VIRTUAL POWER MOBILITY ROAD TEST

6.1 INTRODUCTION

In the last chapter we evaluated driving performance of participants completing the virtual driving course. The driving course was composed of components from a real world wheelchair driving assessment Power Mobility Road Test (PMRT) [1]. The PMRT was tested and validated on 62 wheelchair users driving through real world driving tasks by Massengale and colleagues. The PMRT driving assessment scale showed high inter rater reliability and internal consistency. The composite PMRT scores were significantly correlated with visual perception and alertness of environment, two factors that are relevant in a wheelchair user's real world driving performance.

This study intends to explore the use of PMRT in virtual environments. This chapter focuses on evaluating inter and intra rater reliabilities between clinicians when they use the PMRT as a wheelchair driving assessment tool for tasks in a Virtual Environment (VE). An automated scoring system is designed to generate an instantaneous driving performance indicating score for the user and augment the clinician's judgment. This study further explores the reliabilities between the scores from the clinicians and the automated system algorithms.

6.2 Research QUESTIONS, SPECIFIC AIMS, AND HYPOTHESES

6.2.1 Are virtual assessments reliable measures of power wheelchair mobility?

Specific Aim 1: Test the intra rater reliability of the virtual wheelchair driving assessment tool by comparing repeated assessments from clinicians.

Rationale: For a measurement tool to be clinically useful and widely used, independent raters must agree with the ratings assigned to a particular task. Also, when asked to rate the same task again, the previous and current rating of every rater should match with each other. This way we ensure reliability and repeatability in the rating scores.

Specific Aim 2: Test the inter rater reliability of the virtual wheelchair driving assessment tool by comparing assessments from experienced clinicians.

Rationale: The computer based and virtual reality VEs have significantly different form factors. Almost twice as much field of view of the VE is displayed on the virtual reality screens than on computer screen. Hence there is a reason to believe that the clinicians may rate their

Specific Aim 3: To develop an automated virtual driving assessment algorithm and test reliability of the predicted scores.

> **Hypothesis 3a:** For the CVE, scores from the automated virtual driving assessment algorithm differ significantly from the scores from clinicians.
>
> **Hypothesis 3b:** For the VRE, scores from the automated virtual driving assessment algorithm differ significantly from the scores from clinicians.

6.3 METHODS

Refer to Chapter 4 for inclusion exclusion criteria and the detailed experimental protocol. Briefly, experienced power wheelchair users were recruited and after their informed consent drove a wheelchair in a virtual environment under four test conditions: combinations of the two display screens (PC and VR screen) and two driving modes (Rollers On and Off). See Table 5-1. During the ‘Rollers On’ mode, subjects used their own joystick to drive their wheelchair on the rollers and hence move the virtual wheelchair. Encoder readings from each wheel were used by the simulation program to determine the wheelchair’s instantaneous linear and rotational speeds. During the ‘Rollers Off’ mode, subjects used the customized joystick and the simulation program applied a mathematical model to estimate the virtual wheelchair’s linear and rotational speeds. Subjects performed a few practice trials to familiarize themselves with the experimental setup and driving in the VE. A balanced randomization scheme was used to set the sequence of the four test conditions. Up to 3 repetitions were performed for each of the test condition, making a maximum of 12 driving trials per subject. During every driving trial, the simulation program recorded joystick voltages and encoder inputs, actual and model predicted wheelchair speeds, virtual wheelchair position and orientation coordinates, root mean squared deviation (RMSD) from ideally expected trajectory, and collisions with static and moving obstacles.

Table 6-1: Four experiment test conditions

Test Condition	Driving Mode	Display	Inputs to VE
1	Rollers OFF	PC	Customized joystick + Math Model
2	Rollers OFF	VR	Customized joystick + Math Model
3	Rollers ON	PC	Encoders on Rollers
4	Rollers ON	VR	Encoders on Rollers

Every virtual driving trial completed by the user was independently scored by two clinicians experienced with assessment of wheelchair driving in real world. Each task was rated on a 1(unable to complete) to 4(completely independent) scale. Refer to Appendix A for the PMRT scoring sheet. The clinicians were experienced in using the PMRT for their real world wheelchair driving assessments. Before any of the research participants were evaluated, clinicians discussed scoring criteria for the virtual PMRT. They independently evaluated all virtual driving trials. After a majority of the research participants completed testing, the two clinicians completed a survey about their individual virtual driving assessment strategies. These inputs were used to formulate algorithms to derive Automated PMRT (APMRT) scores for the virtual PMRT tasks. Subjects were asked for their feedback on the VE and experiment setup after completing all driving trials.

The real world PMRT suggests using the following scoring criteria for the structured and un structured tasks.

4: Completely independent: optimal performance; able to perform task in one attempt smoothly and safely

3: Complete task hesitantly, require several tries, require speed restriction, and/or bumps wall, objects lightly without causing harm

2: Bumps objects and people in a way that causes harm or could cause harm to driver, other persons or objects

1: Unable to complete the task.

A survey was conducted to determine how the two clinicians interpreted these scores in the context of a virtual wheelchair driving evaluation. In the survey they were asked to describe their virtual driving assessment strategies for the 16 PMRT tasks. The survey showed that for majority of cases Clinician 1 gave higher importance to safety of the wheelchair driver while completing a task than the accuracy with which it was performed. Hence, as long as the user completed the task and the virtual chair did not collide with walls/obstacles the task was scored as “4: completed independently”. Clinician 2, on the other hand, gave about equal weights to the “safety” and “accuracy” of the driver while completing the task. Hence, if a subject completed a task while taking a devious/winding path, managing to avoid collisions to the wall, would get lesser score (3: Completed task hesitantly) than someone who took a more direct path.

6.3.1 Data Preprocessing

The raw trajectory and other data from the driving trials were processed to derive performance metrics for driving performance. These metrics were derived from their equivalents in computer access research [2] and have been used in past research to evaluate wheelchair [3–6] and car driving [7] in virtual environments. Trial completion time was the time it took to complete all components of the driving circuit in the virtual simulation. Reaction time was defined as the time it took for the subject to move the virtual wheelchair 0.01 meters.

The assessment scores from both clinicians for each task in every driving trial were used to compute three cumulative scores. Refer to Appendix A for the scoring scheme. The “Structured score” was calculated from scores from the “structured/static” tasks (tasks 1-12). The “Skilled Score” was calculated from scores from the “unstructured/skilled driving tasks” (tasks 13-16). A “Total Score” was calculated from scores from all tasks. Since the ordinal values of PMRT ratings were averaged to get the combined scores, the combined scores were treated as continuous variables and parametric statistical analyses were used with them. The task “decreasing hallway” was added to the original PMRT to evaluate certain driving deficits in participants. Since this task was not part of the original PMRT, it was not included in any of the composite PMRT scores. The outcome variables like raw wheelchair trajectory data, root mean squared deviations (RMSD) of the wheelchair from the ideal path (hence from the fixed walls and furniture), and number of collisions with virtual objects, were used to construct two algorithms, each mimicking one clinician's driving assessment style. These Automated $\text{PMRT}_{\text{Safety}}$ and Automated $\text{PMRT}_{\text{SafetyAccuracy}}$ scores were computed for all PMRT tasks in every driving trial and composite scores derived for every trial. The decision rules were based on the individual evaluation styles of the two clinicians. The MATLAB code can be seen in Appendix C.

6.3.2 Statistical Analyses

SPSS (version 18.0) [8] and MATLAB (version 7.11) [9] were used for all analyses. Significance level was set at 0.05 *a priori* for all statistical comparisons. In order to evaluate test retest or intra rater reliability of the two clinicians (Specific Aim 1), the assessment scores on the repeated driving trials were compared. Since adequate training time was allowed for the participants, they were not expected to perform significantly different in trial repetitions. Pearson's correlation coefficient [10] was used to estimate the level of correlation in a clinician's assessment scores from the repeated trials. Higher correlations indicated better intra rater reliability. Analyses for the two display screen were performed separately.

In order to address Specific Aim 2, Inter rater reliability analyses were performed with the three compounded scores [10]. A two way random effects model was used since both participants and clinicians were considered to be random samples. The Intra Class Correlation (ICC) values for PC and VR screens were computed separately. The ICC value of 1 indicates best inter rater reliability (or 100% agreement and correspondence) among the ratings, while a score of zero indicates that agreement is attributed only to chance. The reliability ranges for ICC values were fixed as follows: ICC less than 0.5 indicated poor reliability, between 0.5 and 0.75 indicated moderate reliability, between 0.75 and 0.9 indicated good reliability, and above 0.90 indicated very good reliability. [10]

In order to determine agreement between scores from clinicians and their respective automated scores, a Cohen's kappa analysis [11] was performed for individual task item scores. The NSKAPPA SPSS macro [12] was used since it accounts for cases when the raters did not use all available categories in their ratings. As in the case of other agreement statistics, the ratings received for a single task must vary for the statistical assumptions to be satisfied. In other words, Kappa and ICC values could not be computed for a task if one or both raters gave same score to all participants for that task. These composite scores from the Automated $\mathrm{PMRT}_{\mathrm{Safety}}$ and Automated $\mathrm{PMRT}_{\mathrm{SafetyAccuracy}}$ algorithms were used to check Inter rater reliability with the PMRT scores from the clinicians.

6.4 RESULTS

6.4.1 Survey about driving assessments

Responses from the clinicians about their experience with real world wheelchair driving assessments are as shown in Table 6-2. While

Table 6-3 shows responses from the two clinicians about their assessment strategies for virtual PMRT driving tasks.

Table 6-2: Experience with wheelchair driving assessments

	Clinician 1	Clinician 2
Primary clinical specialty	Occupational Therapy	Rehabilitation Medicine
Number of years of experience you have with power wheelchair (PWC) driving evaluation	9+	6
Approximate number of PWC evaluations you perform every month	12-15	About 60 clients but don't directly evaluate PWC driving
On Average how many of these do you think are **unsafe/unfit for driving power wheelchairs.**	1-2	1
On Average how many of these do you think are **borderline drivers** who can drive better after some training	1-2	20

Table 6-3: Driving task assessment strategy of Clinician1 and Clinician 2

	Task	**Clinician 1**	**Clinician 2**
1	Approaching people/Furniture without bumping into them	4: No problems driving. 3: bumps furniture, does not display good judgment or awareness of space 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all	4: No collisions 3: Collides with furniture 2: Collides more than once 1: Cannot navigate around furniture
2	Starting and Stopping the wheelchair at will	4: No problems 1: Unable to complete task	4: No problems 1: Unable to complete task
3	Passing through doorways without hitting walls (36" doorways)	4: No problems driving. 3: Bumps walls or does not display good judgment or awareness of space, require a significant amount of time to exit. 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is no collisions 3: Collides with edge of doorway 2: Collides more than once with edge of doorway 1: Cannot navigate through door
4	Turning around a 90º right hand corner (90º right turn)	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct), or gently hits wall/object, but self corrects, does not slow down/display good judgment prior to turning 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is makes turn in right direction with a sharp angle is good 3: Average is the angle is slightly large 2: Poor is comes close to wall or stops multiple times 1: Unsafe is collided.

	Task	**Clinician 1**	**Clinician 2**
5	Turning around a 90º left hand corner (90º left turn)	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct), or gently hits wall/object, but self corrects, does not slow down/display good judgment prior to turning 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Makes turn in left direction with a sharp angle is good 3: Average is the angle is slightly large 2: Poor is comes close to wall or stops multiple times 1: Unsafe is collided.
6	Driving straight forward (15 ft) in an open area	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct) 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is does not turn, pushes joystick in directly forward position 3: Average is slight turning, 2: Poor is excessive turning or stopping during task, 1: Unsafe is causes collision
7	Driving straight backward (10 ft) in an open area	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct), experiences problems maintaining alignment when the casters turn 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is does not turn, pushes joystick in directly backwards position 3: Average is slight turning 2: Poor is excessive turning or stopping during task, 1: Unsafe is causes collision
8	Turning 180º	4: No problems driving. 3: does not display good judgment or awareness of space, bumps walls, requires significant amount of tries or time to complete. 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is can accomplish with proper speed and no collisions, 3: Average is uses multiple stops, 2: Poor is needs to use a K turn or uses improper speed, 1: Unsafe is cannot complete or collides with walls
9	Starting and Stopping the wheelchair upon request	4: No problems 1: Unable to complete task	4: No problems 1: Unable to complete task

	Task	**Clinician 1**	**Clinician 2**
10	Turning right and left upon command	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight before or after turn(does not self correct), does not slow down/display good judgment prior to turning 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Makes turn in right direction with a sharp angle is good 3: Average is the angle is slightly large 2: Poor is comes close to wall or stops multiple times 1: Unsafe is collided.
11	Driving straight forward (15 ft) in a narrow corridor without hitting walls	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct), or gently hits wall/object, but self corrects 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is does not turn, pushes joystick in directly forward position 3: Average is slight turning, 2: Poor is excessive turning or stopping during task, 1: Unsafe is causes collision
12	Maneuver between objects	4: No problems driving. 3: bumps walls/doorways, furniture does not display good judgment or awareness of space, corners self and gets “stuck” 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is drives into and can turn around in confined spaces 3: Average is multiple stops but can accomplish, 2: Poor is uses high speed while doing it or door closes on chair while attempting, 1: Unsafe is cannot complete or cannot turn around in confined spaces or hits walls
13	Avoid unexpected obstacles (ball)	4: No problems driving. 3: does not display good judgment (impulsive), does not acknowledge oncoming “traffic” or obstacles. 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is uses proper speed and stopping to accommodate pedestrian and moves out of way 3: Average is waits for ball to roll out of the way instead of trying to proactively go around it 2: Poor is stops and waits and ball hits the chair, 1: Unsafe is drives right into ball

	Task	**Clinician 1**	**Clinician 2**
14	Avoid unexpected obstacles (person entering hallway)	4: No problems driving. 3: does not display good judgment (impulsive), does not acknowledge oncoming “traffic” or obstacles. 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is uses proper speed and stopping to accommodate pedestrian and moves out of way 3: Average is waits for person pass instead of trying to proactively go around, 2: Poor is stops and waits and ball hits the chair, 1: Unsafe is drives right into ball
15	One person coming towards participant in hallway	4: No problems driving. 3: does not display good judgment (impulsive), does not acknowledge oncoming “traffic” 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	4: Good is uses proper speed and stopping to accommodate pedestrian and moves out of way, 3: Average is stops and waits for pedestrian to accommodate wheelchair, 2: Poor is ignores person and person moves out of way of wheelchair, 1: Unsafe is drives directly into person.
16	"Wet floor" sign, crossing to wait or speed up	4: No problems driving. 3: Requires decreased speed settings, or is unable to go relatively straight (does not self correct), or does not display good judgement or awareness of space, or does not acknowledge oncoming “traffic” or obstacles. 2: I'm required to physically intervene (hand over hand operation) 1: Unable to complete task at all.	same as person except for ball, Average is waits for ball to roll out of the way instead of trying to proactively go around it, Poor is stops and waits and ball hits the chair, unsafe is drives right into ball

6.4.2 Results from PMRT Reliability Analysis

Table 6-4: Raw virtual PMRT ratings from the two clinicians

Subject ID	Clinician 1			Clinician 2		
	Structured	Skilled	Total	Structured	Skilled	Total
VR01	0.998	0.989	0.996	0.998	0.989	0.996
VR02	1.0	0.988	0.997	0.996	0.981	0.992
VR03	0.993	0.990	0.992	0.991	0.990	0.991
VR04	0.990	0.969	0.984	0.990	0.964	0.983
VR05	Did not complete the experiment					
VR06	0.986	0.984	0.986	0.988	0.979	0.986
VR07	0.764	0.625	0.786	0.896	0.646	0.901
VR08	0.982	0.901	0.982	0.989	0.901	0.988
VR09	0.888	0.875	0.899	0.919	0.885	0.929
VR10	1.0	0.979	0.997	1.0	0.990	0.999
VR11	0.983	0.892	0.982	0.978	0.892	0.978

Table 6-5: Intra rater reliability for both clinicians. All coefficients except the ones marked with ‘a’ are significant at $p<0.05$

Clinician	**Score**	**Display**	**Pearson Correlation coefficient**	**Significance**
Clinician1	Structured	PC (CVE)	0.928	<0.001
Clinician1	Structured	VR (IVRE)	0.912	<0.001
Clinician1	Skilled	PC (CVE)	0.393[a]	0.107
Clinician1	Skilled	VR (IVRE)	0.456 [a]	0.049
Clinician1	Total	PC (CVE)	0.897	<0.001
Clinician1	Total	VR (IVRE)	0.911	<0.001
Clinician2	Structured	PC (CVE)	0.838	<0.001
Clinician2	Structured	VR (IVRE)	0.7	0.001
Clinician2	Skilled	PC (CVE)	-0.139 [a]	0.582
Clinician2	Skilled	VR (IVRE)	0.224 [a]	0.357
Clinician2	Total	PC (CVE)	0.713	0.001
Clinician2	Total	VR (IVRE)	0.763	<0.001

Raw PMRT scores form the two clinicians are as shown in Table 6-4. Pearson's correlation coefficients between the PMRT ratings of repeated trials for every driving mode from the two clinicians are shown in Table 6-5.

For both clinicians, the Structured and Total scores were statistically significant and highly correlated between the two repeated trails assessed by them. Clinician 1's Structured and Total scores showed a 90% and higher correlation for both PC and VR screens. Clinician 2's Structured and Total scores showed slightly lesser correlation than Clinician 1. Both clinicians were consistent in their scores irrespective of the display screens except Clinician 2's Structured score values were significantly higher for the PC screen trials than the VR screen trials.

The clinician's assessment scores from the two driving modes (Rollers ON and Rollers OFF) show high intra rater reliability for the structured and total scores (see Table 6-6). The reliability is poor for the skilled driving scores. Also, scores from Clinician 1 show higher correlations coefficients (>90%) than scores from Clinician 2 (58% & 70%).

Table 6-6: Intra rater reliability for scores from Roller OFF and Roller ON driving modes. All coefficients except the one marked with 'a' are significant at $p<0.05$

	Score	**Pearson Correlation coefficient**	**Significance**
Clinician1	Structured	0.924	<0.001
Clinician1	Skilled	0.339	0.04
Clinician1	Total	0.928	<0.001
Clinician2	Structured	0.701	0
Clinician2	Skilled	-0.077 [a]	0.65
Clinician2	Total	0.582	0

The inter rater reliability analysis gave the following results (Table 6-7) for each of the two displays. All combined scores show a moderate to high degree of agreement between the two clinicians. The ICC values on the skilled driving tasks (skilled score) were slightly more similar between the clinicians than the scores on structured tasks (structured score). The ICC values of driving trials from the PC screen (CVE) are significantly higher than those from the VR screen (VRE) especially for the Structured tasks. Since the 75% of the total score is from the structured tasks, a similar trend is seen in the ICC values of total score.

Table 6-7: Inter rater reliability for Clinician 1 and Clinician 2. All ICC values are significant at $p<0.05$

Score	Display	ICC	Lower Bound	Higher Bound	Significance
Structured	PC (CVE)	0.916	0.9	1	<0.001
Structured	VR (IVRE)	0.742	0.6	0.8	<0.001
Skilled	PC (CVE)	0.99	0.99	1	<0.001
Skilled	VR (IVRE)	0.992	0.99	1	<0.001
Total	PC (CVE)	0.901	0.8	0.9	<0.001
Total	VR (IVRE)	0.78	0.7	0.9	<0.001

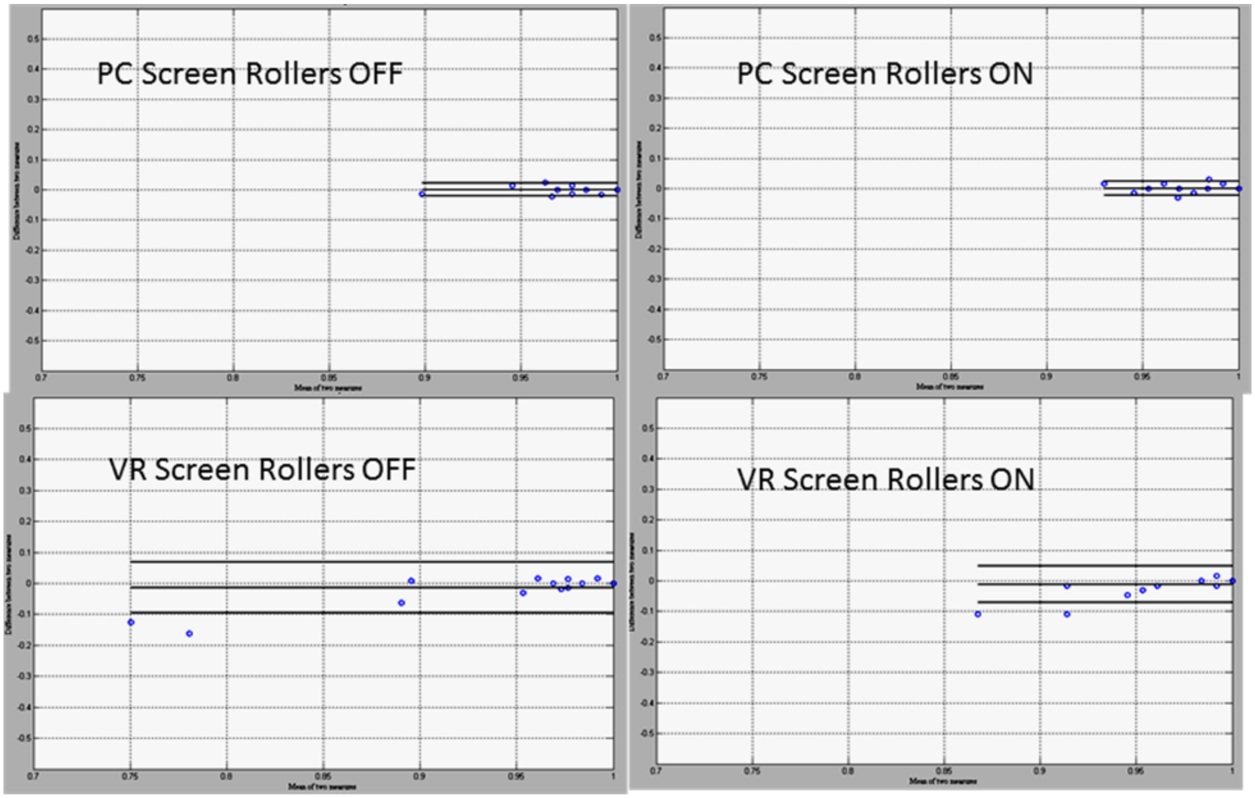

Figure 6-1: Bald Altman plot showing agreement between the TOTAL virtual PMRT scores from Clinician 1 and Clinician 2 for the four driving conditions.

Figure 1 shows Bald Altman plot for the Total composite PMRT scores from clinician 1 and Clinician 2. Bald Altman plot gives a visual representation of agreement between the clinicians. The mean±standard deviations of difference in the ratings of the two clinicians were also computed. For PC screen, for both Rollers off (0.0001 ±-0.011) and Rollers on (0.0007 ±-0.011) the differences and variability were very small. Compare to PC screen the differences of clinicians ratings on the VR screen were significantly larger for both Rollers off (-0.013 ±-0.041) and Rollers on (-0.012 ±-0.03) driving modes.

Kappa statistics were computed to show the level of agreement among Clinician 1 and Clinician 2 for the different tasks. Kappa statistics for tasks 2, 5, 6, 9, 12, and 14 could not be generated since the ratings from one or both of the clinicians were too similar to the ratings from other clinician. One assumption for kappa statistics is that the ratings received for a task must vary, even if by one instance. Clinicians may or may not use all available levels (1-4) of the PMRT scoring. Since all participants recruited for this study could drive the virtual chair, everyone got a '4: Completely independent' rating for tasks 2 (Starting and Stopping the wheelchair at will) and task 9 (Starting and Stopping the wheelchair upon request). Since the PMRT scores did not vary, the kappa statistics was not calculated yet there is 100% agreement between clinicians. A similar issue occurs if one of the raters gave the exact same score to all participants on a single task. Hence, the kappa statistic for tasks 5, 6, 12, and 14 could not be generated. If one clinician used a score value (1-4) that the other clinician did not, the Clinician1 * Clinician2 frequency matrix becomes non symmetric and the statistics cannot be calculated. The NSKAPPA macro accounts for this unequal cell sizes but fails if the cell sizes are too small. Clinician2 scored all participants the same on the 5 while Clinician 1 scored that way only on 3 tasks (two of which were common to both). The task "decreasing hallway" showed a kappa statistic of 76% suggesting a moderately high agreement among the two clinicians.

Table 6-8: Table shows Kappa statistic (a measure of agreement among raters). The reasons for missing coefficients are in comments column. DH: Decreasing Hallway

Task	Kappa	Lower Bound	Upper Bound	pvalue	Comments
1	0.512405	0.328833	0.695977	<0.001	
2	NA				All ratings from both Clinicians same
3	0.428263	0.195276	0.66125	<0.001	
4	0.390805	-0.14809	0.929697	<0.001	
5	NA				All ratings from Clinician2 same
6	NA				All ratings from Clinician1 same
7	0.665625	0.51057	0.82068	<0.001	
8	0.681107	0.420069	0.942145	<0.001	
9	NA				All ratings from both Clinicians same
10	0.470297	0.170823	0.769771	<0.001	
11	0.416667	0.174312	0.659021	<0.001	
12	NA				All ratings from Clinician2 same
13	0.801694	0.645639	0.957749	<0.001	
14	0	0	0.004	0.921	All ratings from Clinician2 same
15	0.520877	0.327944	0.71381	<0.001	
16	1	1	1	<0.001	
DH	0.758215	0.625583	0.890848	<0.001	

Survey results show that Clinician 1 gave higher preference to the "Safety only" criterion while Clinician 2 considered both "Safety only" and "Safety and Accuracy" criteria while assessing virtual wheelchair driving. Another set of reliability analyses was performed to check the reliability between clinicians and the automated PMRT scores derived by the computer algorithm (using their survey responses). The Auto $\text{PMRT}_{\text{Safety}}$ algorithm shows a moderate degree of reliability with PMRT assessments from Clinician 1. The scores are more similar for the structured tasks (structured score) than the assessment scores from the dynamic tasks (skilled score). The PMRT scores predicted by the Auto $\text{PMRT}_{\text{SafetyAccuracy}}$ algorithm showed poor to moderate reliability for Clinician 2's scores. Especially, ICC values for the skilled driving tasks on PC screen had poor reliability.

Table 6-9: Inter Rater Reliability for Clinician 1 and Automated PMRT (Safety)

Score	**Display**	**ICC**	**Lower Bound**	**Upper Bound**	**Significance**
Structured	PC (CVE)	0.696	0.351	0.874	<0.001
Structured	VR (IVRE)	0.772	0.499	0.905	<0.001
Skilled	PC (CVE)	0.431	-0.03	0.741	0.033
Skilled	VR (IVRE)	0.469	0.032	0.756	0.018
Total	PC (CVE)	0.71	0.377	0.881	<0.001
Total	VR (IVRE)	0.904	0.767	0.962	<0.001

Table 6-10: Inter Rater Reliability for Clinician 2 and Automated PMRT (Safety Accuracy)

Score	**Display**	**ICC**	**Lower Bound**	**Upper Bound**	**Significance**
Structured	PC (CVE)	0.59	0.18	0.82	0.004
Structured	VR (IVRE)	0.48	0.05	0.76	0.016
Skilled	PC (CVE)	0.11	-0.4	0.54	0.322
Skilled	VR (IVRE)	0.38	-0.1	0.71	0.048
Total	PC (CVE)	0.56	0.14	0.81	0.007
Total	VR (IVRE)	0.55	0.15	0.8	0.006

6.5 DISCUSSION

The intra rater reliabilities of the two raters were moderate to high for structured driving tasks. The correlations were significant for trials repeated across two driving modes and for the trial repetitions performed for every driving condition. This indicates that overall the clinicians were fairly consistent in their assessments on structured/static tasks. Clinician1 showed higher intra rater reliability than clinician 2. The correlations of driving scores on the unstructured/skilled tasks were poor for clinician 1 and non significant for clinician 2. This was expected since Clinician1 had more direct and "hands on" experience of evaluating wheelchair driving in the real world. Although Clinician 2 was trained to assess real world wheelchair driving, Clinician2 would only oversee such evaluations in a rehabilitation clinic. There was high variability in subjects' performance on skilled driving tasks. Sometimes subjects would accelerate and try to escape the "sharing hallway with walking man" task. Most of the times their virtual speed was not enough to escape the task the virtual wheelchair would eventually have a collision with the walking man. This was especially common near the "wet floor" sign. Also, the other skilled tasks such as bouncing ball were randomly presented in the subjects' paths.

As seen from Table 6-8, the inter rater reliabilities for tasks 2 (Starting and Stopping the wheelchair at will), 5 (Turning around a 90º left hand corner), 6 (Driving straight forward (15 ft) in an open area), 9 (Starting and Stopping the wheelchair upon request), 12 (Maneuver between objects), and 14 (Avoid unexpected obstacles: person entering hallway) could not be generated since one or both clinician's ratings were too similar to each other. The same scores on tasks 2 and 9 were expected since all participants recruited for this study were regular wheelchair users. Other than tasks 2 and 9, Clinician 2 scored all participants the same on one task compared to 3 tasks by Clinician 1. Future studies will ensure that the raters get sufficient training in assessment with the virtual PMRT scoring scheme.

Another interesting observation was that the ICC values from Clinician 1-Clinician 2 inter rater reliability analysis for the structured tasks on VR screen were significantly lower than the than those on the PC screen. One possible reason could be a bias or preference of the clinicians to one or other screen. One clinician expressed of feeling “slight dizziness” from continuously observing participants drive on the VR screens for a long time. Virtual reality displays are known to cause simulator sickness (similar to motion sickness) after prolonged use without a break [13], [14].

The algorithms for Automated PMRT scores generated scores that showed only moderate to poor reliability with the clinician’s PMRT scores. Diving data from a larger cohort of participants will be collected in a recently approved study. People with varying degrees of driving experience will be invited to participate. This data will be helpful in fine tuning the auto PMRT algorithms. In the present analysis the outcome variables root mean squared deviation, task completion time and reaction time were used in building the Auto PMRT algorithms. These variables might not be sufficient to identify certain complex driving behaviors such as impulsive driving. Other outcome measures such as average speed and average acceleration in a task would add more information.

During a wheelchair driving assessment in the real world, the clinician typically walks behind or on the sides of the client. The clinician and also observe the client’s facial expressions and look for signs of panic or stress before an accident is committed. Such multiple points of view are not easily feasible in the current implementation of the VE. The clinician basically sees the virtual world in the same way the user sees it. Due to this locked frame of reference, the clinician might find it hard to estimate certain parameters he/she determines by observation during real world driving. For example, depth perception is typically quite limited in the VE projected on flat screens. Hence the clinician might not be able to accurately estimate is the virtual chair’s drive wheel is one feet or half a feet away from a wall or obstacle. Chances of accident of course increase if the user is driving the wheelchair too close to a wall. In such cases the automated evaluations scores could be a valuable addition to the virtual simulation application. The simulation program can rate the user's driving performance based on the chair's exact distance from wall. It also could warn the user of an impending collision or of erratic driving behaviors. The algorithm will provide a consistent and repeatable wheelchair driving assessment. The scores could be used by clinicians as well as wheelchair users to track their progress in virtual driving environments. For wheelchair candidates who are borderline safe or unsafe drivers, such a training tool could assist in getting an exposure to real world wheelchair driving without ever leaving safety of their home or clinic. The confidence thus gained from training in virtual environments will transfer to their real life wheelchair driving and thus help improve their community participation.

Another potential application could that the entire virtual driving assessment environment could be simulated or integrated into an online virtual world such as Second Life [15]. This will enable potential wheelchair users to benefit from training in virtual environments while exploring places and socializing with friends.

6.6 CONCLUSION

The virtual Power Mobility Road Test shows high inter and intra rater reliability scores. The automated Power Mobility Road Test ratings show moderate to low reliabilities with the clinician's ratings.

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7.0 VRSIM 4.0: VALIDATION OF VIRTUAL POWER MOBILITY ROAD TEST IN AN IMMERSIVE VIRTUAL REALITY ENVIRONMENT

The virtual Power Mobility Road Test (PMRT) protocol that was presented in chapters 5 and 6 was updated with more realistic graphics in the virtual environment. This research protocol is an improvement on the earlier protocol (presented in chapter 5) and designed to include more raters for driving evaluation of a more diverse cross section of wheelchair users. This research study aims to compare the driving performances of this larger cohort of wheelchair users and to establish intra rater reliability and inter rater reliability of the virtual PMRT scores.

Like other tasks that require focused and concentrated attention, performing driving trials in virtual environments is associated with certain physical and cognitive demands/loads. This study aims to compare the overall workloads on users after different virtual driving sessions.

7.1 RESEARCH OBJECTIVES AND SPECIFIC AIMS

7.1.1 Is the Power Mobility Road Test a reliable and valid measure of power wheelchair driving performance?

Specific Aim 1: To establish Inter and Intra rater reliability of the virtual Power Mobility Road Test.

7.1.2 Do experienced wheelchair users perform differently in an IVRE than in a CVE?

Specific Aim 3: To compare the driving performance in IVRE and CVE.

> **Hypothesis 3:** Experienced wheelchair drivers show significantly better driving performance scores in the IVRE compared to that in the CVE.

7.1.3 Do driving trials in IVRE and CVE induce higher workloads compared to driving in real world?

Specific Aim 4: To compare the overall workloads self reported by participants after driving in IVRE and CVE with the workload after driving in real world.

> **Hypothesis 4:** Participants will report to have significantly higher workload after using the IVRE and CVE compared to the real world driving.

7.2 METHODS

7.2.1 Subject Recruitment

The protocol for this research study was approved by the Institutional Review Boards of the Veteran Affairs and the University of Pittsburgh. Subjects were recruited by advertising flyers at the 31st National Veteran Wheelchair Games (NVWG) at Pittsburgh, PA. When interested participants enquired about the research study they were briefed about the study procedures by clinicians and were scheduled for a visit to the research center.

7.2.2 Inclusion Criteria

1. Subjects must be between 18 to 80 years old.
2. Subjects must use a power wheelchair for all or part of their mobility or would be candidates for power wheelchair, or would benefit from a power wheel chair after training.
3. Subjects must be able to provide informed consent.
4. Subjects must have basic cognitive, visual, and motor skills to interact with the virtual driving environments.

7.2.3 Exclusion Criteria

1. Subjects who have active pelvic or thigh wounds. (They may be worsened by prolonged sitting).
2. Subjects who do not pass the screening protocol

7.2.4 Screening Procedures

A written informed consent was obtained from participants before screening. All screening procedures were administered by a trained Occupational Therapist, Physical Therapist, or a physician. The screening criteria were as follows:

1. *Subjects must have sufficient short term memory to recall that interaction with the joystick produces results on the computer screen.* Subjects must be able to move the simulated wheelchair without additional prompting in order to proceed with testing.

2. *Subjects must have the ability to perceive the moving simulated wheelchair on the computer screen.* They may indicate perception with words, sounds, gestures, or other responses.
3. *Subjects must be able to tap or hit the joystick*. They must be able to exert approximately 2N of force on the joystick, which is the typical amount of force it requires for operation[1] and which will result in simulated wheelchair movement on the computer screen.

7.2.5 Experiment Setup

The virtual environment (VE) that implemented the Power Mobility Road Test (PMRT) was modeled using a commercial modeling program (Multigen Paradigm Creator Studio [2]). The base software application, written in C++, interfaced the graphics engine (Multigen Paradigm Vega Prime [3]) Application Programming Interface (API) with National Instruments Measurement Services (NIDAQMx,) [4] API for reading analog voltages from joystick, and US Digital Serial Encoder Interface (SEI) [5] for reading encoders. The virtual simulation software ran on a Dell XPS laptop with 2GHz Intel Core2Duo processor and 4GB of Random Access Memory (RAM).

Participants were seated in their own power wheelchairs all times during this protocol. Participants were asked to park his or her wheelchair on a 33”x33”x6” roller platform. Two sets of dual rollers were instrumented in the roller platform such that each of them interfaced with one drive wheel of the wheelchair. Incremental encoders mounted in the rollers read the wheelchair wheel rotations. Analog voltages from a conventional movement sensing joystick, similar to the participant’s wheelchair joystick, were read into a computer through a National Instruments Data Acquisition (NIDAQ) card 6024E. The rollers and customized joystick were two input mechanisms subjects used to interact with the virtual simulation. The simulation was projected on three 6’x8’ back projected screens or on a single generic 22” widescreen LCD monitor.

7.2.6 Virtual Power Mobility Road Test (VPMRT)

The VPMRT modeled in the simulation was a virtual model of a real office space (Human Engineering Research Laboratories). The virtual tasks were modeled after the rehabilitation clinic where the real world PMRT was developed and validated [6]. The testing scenario consists of a large indoor lab space with a simulated kitchen and living room and a set of hallways lined by offices. The task assigned to the user was to drive the virtual wheelchair along the driving course through certain preset milestones. These sequentially displayed milestones defined the 12 static/structured and 4 dynamic/unstructured tasks of the PMRT. The structured tasks had fixed obstacles while the dynamic tasks had moving obstacles such as a bouncing ball or a person walking in the virtual wheelchair’s driving path. Computer generated audio instructions were played as required by some PMRT task (Starting and Stopping the wheelchair on request, turning right and left upon command, Turning 180 degrees). Participants were instructed to complete these tasks as fast and as accurately as possible. Other than the 16 PMRT tasks, the driving course had hallways of different widths (0.914, 1.067, 1.219, 1.524, 1.676, 1.829, 2.134 meters) in order to simulate different levels of cognitive loads while driving. This section of VPMRT might be useful in identifying driving deficits that distinguish drivers with experience from new or borderline safe wheelchair drivers.

The “actor” in the VE is a person sitting in a power wheelchair (seat width= 0.671m, length/depth= 0.701m) that is controlled by the user. The dimensions of the virtual chair and virtual occupant were selected based on the standard dimension of a commercially available

Permobil C500 wheelchair. The user sees the VE from a “First Person Shooter” (FPS) point of view [7]. The user also sees a virtual joystick that animates in response to the user input the real world joystick. Appendix D shows the driving course from the user’s viewpoint. Tasks are ordered in the PMRT scoring sheet as they appear in the driving course.

Stereo vision in the real world is possible because the two eyes and plays a vital role in perception of depth. In this VE the camera is “fixed” or locked to the virtual chair in a FPS point of view. Multiple textures are added to sections of the driving circuit to aid the depth perception and to enhance the optical flow during motion in VE. Gourhand shading was used with components of the VE to improve depth perception [8]. To give a sense of boundaries of the virtual wheelchair, a red wire frame box was placed around the complete footprint of the virtual wheelchair. This box also aided in detection of collisions of chair with other VE components such as virtual furniture, walls, or moving people. A short beep was sounded to indicate collision with obstacles. After a collision, the virtual chair slightly bounced back to facilitate maneuvering of the chair. Subjects had a limited amount of time to move the virtual wheelchair away from the obstacle, depending on their speed before impact. If the user did not move the chair soon enough after the collision, the program terminated the driving trial. This feature was designed to make the subjects anticipate and avoid accidents/collisions and react promptly by driving themselves away from the collision site.

Unlike real world driving, while driving in the VE the user’s field of view is locked with the virtual wheelchair. In other words the camera looking at the VE is held fixed to the virtual chair at a fixed inclination. Users are required to judge their distance from an obstacle outside of the field of view, especially the sides of the chair. In the FPS view of the virtual environment, a slider bar was displayed to users to indicate their approximate position with respect to the walls of the hallway or obstacles they are navigating through. If the virtual wheelchair was too close to an obstacle, the slider would point to a red region before the chair would make contact with the obstacle. Since the clinicians who evaluated their driving performance saw the same view as the users, this feature gave them a guide they used to determine accuracy in driving. The slider bar turned out to be a less distracting solution to the less than ideal depth perception on the flat display screens.

7.2.7 Real world Power Mobility Road Test

The real world PMRT driving course was designed to be as close as possible to the virtual PMRT course. Just like in the virtual world instructions were given to participants as they drove on the real world course. The real world track had hallways that were comparable in lengths to the virtual hallways. Decreasing hallways section of virtual PMRT was not modeled in the real world track due to space constraints at the research site.

7.2.8 Research Protocol

Subjects performed three driving trials each for the two display screens and one driving trial along the real world obstacle course (Real World mode). A balanced randomization scheme was used to set the sequence of the two display screens and the three driving modes. See Table 7-1. For virtual driving trials, the subject's wheelchair was securely strapped to the roller platform with the drive wheels interfacing with the two rollers. During the two trials for the 'Rollers ON' driving mode, subjects powered on their wheelchair and used their own joystick to move the rollers to interact with the VE. Encoder readings from the two rollers were used by the simulation program to determine the virtual wheelchair’s instantaneous linear and rotational speeds. During one driving trial for the ‘Rollers OFF’ mode, subjects interacted with the VE using a customized joystick. The simulation program read this joystick directly and applied a mathematical model to estimate the virtual wheelchair’s linear and rotational speeds. Subjects performed a few practice trials to familiarize themselves with the experimental setup and driving in the VE. Subjects self selected their acceleration setting for the virtual wheelchair and this value was kept unchanged during the rest of the experiment. A balanced randomization scheme was used to set the sequence of the two display screens and the three driving modes. See Table 7-1. Subjects were allowed to take breaks for a few minutes between driving trials if they felt tired.

Five clinicians (1 Occupational Therapist, 3 Physical Therapists, and 1 Physician) participated in this study of which two clinicians independently assessed the driving performance of participants on every driving trial. Three clinicians had more than 5 years of experience with power wheelchair driving evaluations, were certified Assistive Technology Professionals, and at least one of them was always part of the two clinician evaluation team for every subject. The other two clinicians had moderate level of experience (less than 5 years) with power wheelchair evaluations. The PMRT scoring sheet (Appendix D) lists the scoring criteria used to assess the driving performance on the 12 Structured driving tasks (with static obstacles), 4 Unstructured (with dynamic obstacles), and the decreasing hallway task. Compound scores from these tasks were used to establish intra and inter rater reliability of the PMRT for the VE.

Task components in the driving circuit involved driving between two milestones (indicated by a green balloon (for start) and a blue balloon (for end)) or turning in direction of an arrow. After one milestone was reached, arrows pointed to the next milestone. An ideally expected path for each of these task components was predetermined and deviations from this path were calculated. A root mean squared deviation (RMSD) was recorded for all task components. Also, during every driving trial, the simulation program recorded joystick voltages and encoder inputs, wheelchair speeds, virtual wheelchair position and orientation coordinates, and collisions with static and moving obstacles. These data were post processed to determine the subject's wheelchair driving proficiency. After every change in display screen and driving mode, a Task Load Index developed by the National Aeronautics and Space Administration (NASA TLX) was used to evaluate the physical and cognitive loads on the subjects after completing driving trials [9–11]. After completing all driving trials, subjects were asked for their feedback about individual system components like screen preference, roller systems, and graphics in virtual environment.

Table 7-1: Five experiment test conditions

Test Condition	Driving Mode	Display	User interacts with VE using
1	Rollers ON	PC	Encoders on Rollers
2	Rollers ON	VR	Encoders on Rollers
3	Rollers OFF	PC	Customized joystick + Math Model
4	Rollers OFF	VR	Customized joystick + Math Model
5	Real World	-	Wheelchair joystick

7.2.9 Data Preprocessing and Statistical Analyses

Raw data from the driving trials were processed to derive certain performance metrics for driving performance. These metrics were derived from their equivalents in computer access research [12] and have been used in past research to evaluate wheelchair [13–16] and car driving [17] in virtual environments. Trial completion time was the time it took to complete all components of the driving circuit in the virtual simulation. Reaction time was defined as the time it took for the subject to move the virtual wheelchair 0.01 meters. The length of the actual path taken by the virtual wheelchair and the number of collisions were recorded. Whether the virtual wheelchair took a zig-zag path instead of a straight or single curved path between two milestones, was measured with number of direction changes in chair's heading/orientation in the VE using a custom algorithm [18]. The number of times the wheelchair collided with the virtual world objects was recorded. During the real world driving it is expected that the driver quickly changes directions to avoid collision with the object. If subjects failed to exert any effort to move the virtual chair away from the object after colliding with it, they were assumed to be stuck and the driving trial was restarted. The number of times such events took place was recorded as stuck count.

$$RMSD = \sqrt{\frac{\sum (d_i - \bar{d})}{n-1}}$$

$$ME = \frac{\sum |d_i|}{n}$$

$$MO = \bar{d}$$

Equation 3: Formulae to calculate Root Mean Squared Deviation (RMSD), Movement Error (ME), and Movement Offset (MO)

Root Mean Squared Deviation (RMSD), Movement Error (ME), and Movement Offset (MO) were derived from the trajectory the virtual wheelchair took in relation to the ideally expected path as shown in the following equations. It is expected that ideally the wheelchair will take the shortest path between two milestones. Deviation (d_i) is the perpendicular Cartesian distance of the wheelchair's actual trajectory from the ideally expected trajectory at sampling intervals (*i*). RMSD is the standard deviation in d_i, ME is the average of absolute values of d_i, and MO is the average of d_i. MATLAB (version 7.11) [18] was used for these analyses.

SPSS (version 18.0) [19] was used for all statistical analyses. Significance level was set at 0.05 *a priori*. Researchers, [6] who established reliability and validity of the real world PMRT, used composite scores from individual tasks. Three combined scores were computed from the PMRT ratings given by a clinician to each driving trial. Scores from the structured driving tasks were combined into the "Structured" score while those from the dynamic tasks were combined into the "Skilled" score. A "Total" score was calculated from the scores from all 16 tasks. To address Specific Aim 1, the three combined scores were used to perform Intra Class Correlation (ICC) analyses to establish inter rater reliability in scores from the two clinicians who evaluated every trial. The reliability ranges for ICC values were fixed as follows: ICC less than 0.5 indicated poor reliability, between 0.5 and 0.75 indicated moderate reliability, between 0.75 and 0.9 indicated good reliability, and above 0.90 indicated very good reliability. [20]. Pearson's correlation analyses were also used to check the consistency in clinical evaluations of every clinician and establish intra rater reliability.

The trajectory data was screened and corrected for outliers. Logarithmic transformations were used to normalize the statistical distributions of outcome variables trial completion time, reaction time, path length, number of collisions, and number of direction changes. Inverse transformations were used to normalize distribution of the RMSD and ME while exponential transformation was used for MO. Since trajectory data was only available for virtual driving trials, a 2x2 (2 displays and 2 driving modes) completely within subjects repeated measures Analysis of Variance (ANOVA) was performed to answer hypothesis 3 using the above mentioned driving performance metrics. Additional post hoc analyses were performed if main effects were statistically significant.

A composite score for overall workload was calculated by averaging scores from the six sub scales. A weighting process is suggested to compute relative importance of the six sub scales of NASA TLX [9]. These weights are used to compute a composite score from the sub scales. This scheme requires users to answer 15 additional questions after every change in task type. This would have significantly increased the time allotted for testing one subject. Besides, research has shown that the weighted combined score showed high correlation (r=0.94) with the average score [10], [11]. For purposes of this study, three clinicians graded the relative importance or contribution of each of the subscales to the overall workload on the subjects. Weights for sub scales were derived by averaging the clinician assigned weights. Individual subscale scores, averaged score, and the new weighted average score were used in an ANOVA to compare the effects of screen and driving modes with real world driving.

7.3 RESULTS

A total of twenty one subjects were recruited for this research study after they completed the informed consent process. One subject couldn’t complete the protocol due to excessive intentional tremor in the joystick operating limb. Two subjects experienced significant fatigue during the research protocol and clinicians discontinued the driving sessions. Table 7-2 shows the demographics of all participants.

Table 7-2: Demographics of NVWG study participants

Number of Participants	Completed Protocol	18
	Partially completed protocol	2
	Unable to complete protocol	1
Mean Age (SD) in years		52.38 (11.91)
Number of females		4
Ethnicity	African American	7
	Caucasian	12
	Other	2
Veterans		20
Primary cause of disability	Spinal Cord Injury	12
	Traumatic Brain Injury	1
	Multiple Sclerosis	2
	Amputation	1
	Other	5
Average number of sporting events participated at NVWG		3
Subjects with prior experience with computer games	Never	12
	Sometimes	6
	Frequent	3
Wheelchair type	Front wheel drive	2
	Mid wheel drive	11
	Rear wheel drive	7

Table 7-4 shows the Intra Class Correlation (ICC) coefficients for driving trials in CVE, IVRE, and real world. The structured and total scores of PMRT tasks showed high reliability between the two clinician ratings for all of the three environments. The composite score from skilled driving tasks showed moderate to high reliability for trials in CVE and IVRE and low reliability values from the real world tracks.

Table 7-3: Raw PMRT scores for the four virtual driving conditions and real world

Subject ID	**PC Screen**		**VR screen**		**Real World**
	Rollers OFF	**Rollers ON**	**Rollers OFF**	**Rollers ON**	
1	0.930	0.980	0.891	0.973	1.0
2	0.984	0.981	0.969	0.981	1.0
3	0.992	0.988	1.0	1.0	1.0
4	0.958	0.965	0.914	0.953	1.0
5	0.934	0.961	0.805	0.988	0.977
6	0.867	0.863	NA	0.900	1.0
7	0.938	0.988	0.914	0.951	0.984
8	0.961	0.984	0.984	0.973	0.977
9	0.969	0.963	0.945	0.953	1.0
10	1.0	1.0	0.984	0.981	1.0
11	0.891	0.883	NA	0.814	0.969
12	1.0	0.984	1.0	0.988	1.0
13	0.961	0.996	0.992	0.988	1.0
14	0.953	0.949	0.992	0.981	1.0
15	0.969	0.981	0.914	1.0	0.992
16	0.836	0.910	NA	NA	0.977
17	NA	NA	NA	NA	NA
18	0.969	0.981	1.0	0.977	1.0
19	0.961	1.0	0.977	0.977	1.0
20	0.945	0.844	0.961	0.867	1.0
Average	**0.948**	**0.958**	**0.953**	**0.958**	**0.993**

Table 7-4: Inter rater reliability between the two clinicians: Intra Class Correlation (ICC) coefficients from the two screens and real world driving trials.

Score	Screen	ICC	Lower Bound	Upper Bound	P value
STRUCTURED	PC (CVE)	0.80*	0.69	0.88	<0.001
	VR (IVRE)	0.82*	0.71	0.89	<0.001
	Real World	0.70*	0.37	0.87	<0.001
SKILLED	PC (CVE)	0.72*	0.57	0.82	<0.001
	VR (IVRE)	0.62*	0.43	0.76	<0.001
	Real World	0.15	-0.32	0.56	0.265
TOTAL	PC (CVE)	0.82*	0.72	0.89	<0.001
	VR (IVRE)	0.81*	0.69	0.89	<0.001
	Real World	0.75*	0.45	0.89	<0.001

Two trial repetitions were performed with the Rollers ON driving mode in CVE and IVRE. Test retest intra rater reliability values for the two environments are as shown in Table 7-5. The structured and total PMRT scores show high and significant correlations on both CVE and IVRE. The skilled driving combined scores showed little to low consistency across trial repetitions.

Table 7-5: Intra rater reliability for all clinicians: Pearson Correlation coefficients between the two driving trial repetitions of "Rollers ON" mode from PC and VR screens

Score	Screen	Pearson Correlation	P value
STRUCTURED	PC (CVE)	0.81*	<0.001
	VR (IVRE)	0.75*	<0.001
SKILLED	PC (CVE)	0.05	0.76
	VR (IVRE)	0.4*	0.015
TOTAL	PC (CVE)	0.74*	<0.001
	VR (IVRE)	0.68*	<0.001

The repeated measures ANOVA analysis for driving performance metrics (see Table 7-6) indicated significant main effects of Screen (p value =0.017, partial η^2=0.805) and Driving mode (p value <0.001, partial η^2=0.985) and significant interaction effect (p value =0.006, partial η^2=0.846). Subjects on average took 98 seconds longer to complete the same driving trial in IVRE than in the CVE (p value <0.001, partial η^2=0.75). Subjects overall had 33 significant direction changes more while driving in the IVRE than when driving in the CVE (p value =0.002, partial η^2=0.46).

While comparing the two driving modes the trial repetitions for the Rollers ON mode were averaged. When rollers were used (Rollers ON), subjects took 80 seconds less to complete the driving trials (p value =0.001, partial η^2=0.486), had 0.5 seconds higher reaction time (insignificant), 0.06 m lesser RMSD (p value =0.028, partial η^2=0.269), 0.04 m lesser ME (p value =0.01, partial η^2=0.351), 12.4m shorter path length (p value =0.012, partial η^2=0.335), and 168 more direction changes (p value <0.001, partial η^2=0.93) compared to when rollers were not used. Univariate post-hoc analyses for Screen x Mode interaction effect were insignificant for all outcome variables RMSD (p value =0.013, partial η^2=0.33). Driving trials with Rollers OFF showed an RMSE values around 0.33 m for both CVE and IVRE. However, when rollers were used, trials in CVE showed 0.056m higher error values than trials in IVRE.

When a wall collision took place, subjects were expected to quickly drive away from the object of collision. However 4 subjects had at least four or more instances during the whole experiment when they collided with walls and needed instruction or manual assistance from clinicians to navigate away from the object.

Table 7-6: Results from Repeated measures ANOVA for driving performance metrics from trajectory data.

Mean ± Standard Deviation

Screen	**PC (CVE)**		**VR (IVRE)**	
Mode	**Rollers OFF**	**Rollers ON**	**Rollers OFF**	**Rollers ON**
Trial Time(seconds)*,[a]	403.32 ±1.26	333.14 ±1.34	506.61 ±1.25	414.88 ±1.28
Reaction Time(seconds)	1.3 ±3.58	1.74 ±2.52	1.14 ±1.83	1.73 ±1.8
RMSD(meters) [a]	0.33 ±1.08	0.3 ±0.71	0.33 ±0.85	0.25 ±0.85
MO(meters)	-0.04 ±2.32	-0.06 ±1.87	-0.1 ±1.99	-0.05 ±2.72
ME(meters)[a]	0.22 ±0.79	0.19 ±0.49	0.22 ±0.62	0.17 ±0.61
Path Length(meters) [a]	174.13 ±1.16	167.51 ±1.09	186.5 ±1.13	167.99 ±1.12
Direction Changes*,[a]	80.92 ±1.39	247.09 ±1.45	108.94 ±1.33	276.84 ±1.29
Collisions	6.74 ±2.82	7.17 ±3.19	5.22 ±3.76	5.75 ±3.19

*Significant difference across the two screens; [a] significant difference across the two driving modes.

The NASA TLX values for the individual subscales and overall workloads compared across the screens and driving modes are as shown in

Table 7-8 and Table 7-9. Overall participants reported higher workload values after driving in CVE or IVRE compared to driving on the real world track. These differences were statistically significant for the subscales of Mental Demand and Frustration and both raw and weighted average scores. There were no significant differences in subscale or overall workload values between CVE and IVRE. A low workload score on the real world driving track was expected since all subjects were regular wheelchair users and were used to navigating the tasks modeled on the real world driving track.

After completing driving trials with both Rollers ON and OFF modes, subjects reported much higher workloads than driving on the real world track. Workloads, especially after driving trials with the Rollers ON mode, were significantly higher than real world mode. This difference was significant for the subscales of Mental Demand, Physical Demand, Effort, Frustration, raw average and weighted average. Subjects reported a significantly higher level of frustration with the Rollers ON driving mode than with the Rollers OFF driving mode. For all other scores compared there was no significant difference in Rollers ON and Rollers OFF modes.

Table 7-7: Clinicians' opinion (range 1-10) about relative contribution of the six components of NASA TLX to overall workload. Weights are normalized averages of ratings from 3 clinicians

Clinician	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	10	5	1	10	5	10
2	8	2	4	9	7	5

3	9.5	5	5.5	6	8	8
Weights	**0.92**	**0.4**	**0.35**	**0.83**	**0.67**	**0.77**

Table 7-8: NASA TLX sub scales and composite scores (all mean ± standard deviation) for workloads on CVE and IVRE screens

NASA TLX	PC (CVE)	VR (IVRE)	Real World	P value
Mental Demand	11.87 ±6.44*	11.76 ±6.25*	5.14 ±4.74	0.002
Physical Demand	9.84 ±6.9	9.79 ±7.19	5.07 ±4.8	0.060
Temporal Demand	7.66 ±6.34	7.18 ±6.67	3.43 ±4.22	0.089
Performance	7.39 ±5.3	5.87 ±4.59	4.21 ±3.66	0.090
Effort	11.89 ±7.27	11.84 ±7.08	7.14 ±5.38	0.070
Frustration	10.24 ±6.85*	10.5 ±7.19*	3.21 ±3.87	0.002
Raw Average	9.82 ±4.84*	9.49 ±4.99*	4.7 ±3.62	0.002
Weighted Average	6.57 ±3.09*	6.34 ±3.16*	3.11 ±2.3	0.001

* Significant differences from Real World driving scores

Table 7-9: NASA TLX sub scales and composite scores (all mean ± standard deviation) for workloads after driving trials from Rollers ON and Rollers OFF modes

NASA TLX	Rollers OFF	Rollers ON	Real World	P value
Mental Demand	11.62 ±5.82*	12.03 ±6.85*	5.14 ±4.74	0.001
Physical Demand	9.23 ±6.51	10.43 ±7.52*	5.07 ±4.8	0.044
Temporal Demand	6.69 ±5.75	8.19 ±7.15	3.43 ±4.22	0.054
Performance	6.44 ±4.63	6.84 ±5.39	4.21 ±3.66	0.220
Effort	11.21 ±6.55	12.57 ±7.72*	7.14 ±5.38	0.048
Frustration	8.54 ±6.73*,[a]	12.3 ±6.79*	3.21 ±3.87	<0.001
Raw Average	8.95 ±4.64*	10.39 ±5.1*	4.7 ±3.62	0.001
Weighted Average	6.01 ±2.98*	6.93 ±3.21*	3.11 ±2.3	<0.001

* Significant differences from Real World driving scores; [a] significant difference from "Rollers ON" mode

All subjects reported that a driving simulator could be a clinically useful tool for training power wheelchair driving in marginal or unsafe drivers and they would be willing to recommend or use such a program if it were commercially available. All subjects said that the simulation graphics were realistic enough for them to feel immersion and with some improvements the program had “Good potential as a training tool.” One subject suggested that the program “would be useful as a smooth transition tool from rehab to wheelchair”. Ten subjects preferred the VR screen over the PC screen, and one had no screen preference for potential use in future training simulation application. Those who preferred PC screen also reported that VR screens made them dizzy, and the 180° field of view presented with a lot of information which was overwhelming for them at times. Eight subjects had prior experience with playing computer games, and of them six subjects preferred the VR screen better. Those who preferred PC screen appreciated the video game like appearance of the program and said that the PC screen allowed them to focus better on driving. If they were tired or had a serious collision, subjects were able to disassociate themselves from the virtual environment easier while using the PC screen. This allowed participants to take a small break after which they continued driving. Since the VR screen covered almost all of their central and peripheral vision such breaks were not possible.

For most, the vibrations and sounds from the rollers helped to feel more immersion in the virtual driving tasks. One participant self reported that his wheelchair was not programmed appropriately and so he liked the customized joystick used with the Rollers OFF mode. One other common demand from subjects was to include more realistic and interactive components in the simulation for tasks like outdoor navigation, road crossing in traffic, and simulation inside public transportation.

7.4 DISCUSSION

The primary objective of this study was to establish reliability of virtual Power Mobility Road Test (PMRT). Recruiting athlete participants from the 31st National Veteran Wheelchair Games provided us a cohort of subjects who were experienced, skilled, and possibly more consistent power wheelchair drivers. More than 50% of study subjects competed in one or more sports like power wheelchair soccer, relay race, and slalom which required skilled driving using their power wheelchairs. For most of the power wheelchair sports, the acceleration and speed settings on the subject's wheelchairs were changed to optimize/improve their performance during the sporting event. Thus subjects arrived at the test center with speed and acceleration settings that they could drive with but were not the settings they used during day to day driving. We tried to rectify this by changing the speed and acceleration settings in the virtual environment to a level subjects were comfortable driving with. All subjects who completed the protocol, showed a strong tendency to quickly learn and adapt to changes in driving modes or display screens. Because of the events they participated in earlier in the day, some subjects were already fatigued before starting the protocol. Prior fatigue was a primary reason that one subject was unable to complete the protocol and for another subject who completed only the CVE trials. Trial repetitions on the IVRE had to be limited for two other subjects because they felt fatigued after first few trials in IVRE.

Both Structured and Total composite PMRT scores showed high inter rater reliability in the clinicians evaluating driving trials in CVE, IVRE, and real world. The composite score from the Skilled tasks showed moderate to high inter rater reliability for CVE and IVRE but poor and insignificant ICC values for real world driving trials. During the virtual driving trials, clinicians relied upon the slider bar that displayed closeness to obstacles and the beeps after obstacle detection to make an informed decision about the subject's accuracy in completing the task. However, for real world skilled driving tasks the clinicians probably did not have a consensus on the evaluation metrics such as whether to evaluate the subject's accuracy in completing the skilled driving task or whether to evaluate rash driving maneuvers. In the virtual environments, the people walking in the virtual wheelchair's path travelled at a specific speed and appeared at certain distances along the hallways. Equivalent hallway lengths could not be simulated at the test site due to space constraints. This only applied for the two skilled driving tasks (Avoid unexpected obstacles (person entering hallways) and avoid unexpected obstacles (ball)) which were closer in the real world track than on the virtual world track. The real world structured tasks were simulated equivalent to their virtual world equivalents. Further research testing for this study will continue at the new lab space at Human Engineering Research Laboratories. The virtual driving track is a scaled replica of the real world track in the new lab space.

The inter rater reliability values from the virtual environments (both CVE and IVRE) were slightly higher than the values from the real world driving trials. Before starting subject testing all five clinicians discussed among themselves the criteria to judge individual tasks in the virtual PMRT. They received sufficient amount of training in using the virtual PMRT evaluation criteria before and during the first few subjects. No such consensus building exercise was performed for evaluating the real world PMRT. The less experienced clinicians did not receive adequate training while the more experienced clinicians relied on their individual clinical judgments and interpretations of the PMRT driving evaluation criteria. With sufficient exposure and a standardized training protocol we expect the reliability and validity ratings in scores from novice/less experienced clinicians could be improved to match those of the experienced clinicians.

The order of driving modes and display screens were randomized. We allowed all subjects sufficient training time with virtual driving to get used to changes in driving modes and screens. Thus we expect that subjects had little carry over or learning effects affecting their performances on subsequent driving trials. For the two repetitions of virtual driving trials, clinicians showed high test retest intra rater reliabilities in their structured and total scores. The measured event/performance must repeat closely or exactly to get an honest intra rater reliability estimate of how closely the rater rates the repeated trials [20]. Subjects' performance on the structured tasks was not expected to change significantly with trial repetition. However, there was some amount of randomness programmed in the occurrences of the dynamic obstacles during skilled driving tasks. This could be another reason that the skilled driving tasks showed low intra rater reliability values. The intra rater reliability correlation coefficients were low for skilled driving tasks in IVRE and insignificant for the CVE. Possibly, the higher form factor of the VR screens might have been helpful for clinicians to observe and judge finer motions of the virtual chair with respect to the moving obstacles.

During the Rollers ON driving mode, the users operated their own wheelchair and the virtual environment was fed motion data through a set of wheel rollers. This arrangement might have slightly increased stimulus to response delay as compared to when the joystick was directly connected to the computer running simulation software during the Rollers OFF mode. This could explain the higher trial completion time for the Rollers ON mode. However, the rollers provided subjects with rich audio and a vibro-tactile feedback that they associated with real world driving thus improving their immersion in the VE. Multimodal interaction, including audio and vibro-tactile feedback, is known to improve proprioception [21–23], sense of presence in VEs and task performance [24]. Subjects were able to drive more accurately when using the rollers by staying close to center of hallways. A small number subjects came to the research center with altered speed and acceleration settings on their wheelchairs. They were asked to select a driving profile on their wheelchair they typically used for their day to day indoor driving. If no alternate set of parameters were available, they were accommodated by changing acceleration and speed settings in the simulation software. Although not ideal, this arrangement limited speed of the virtual wheelchair. High rotational accelerations on subjects' wheelchairs sometimes made them drive with hasty motions with frequent stops and required multiple corrections in quick successions. These frequent corrections contributed to more changes in wheelchair direction/headings when rollers were used. On the other hand, when rollers were not used, the simulation software used a mathematical model to simulate kinematic parameters of the virtual chair. In Rollers OFF mode, subjects' motions were smoother and easier to control. Compared to wheelchair on rollers the mathematical model had a slightly higher decay time, so the virtual chair would take little longer to stop compared to the wheelchair on rollers which stopped almost immediately. In some cases this might have contributed to over steering or over compensation applied to the virtual wheelchair, thus causing higher RMSD and MEs in trajectories. All subjects were able to adapt to changes in driving style in the Rollers OFF mode irrespective of whether they used a front wheel, mid wheel or rear wheel drive wheelchair. Overall, after completing the Rollers OFF driving trials, subjects reported lesser frustration, lower mental demand, lesser effort put in, and lower total workload than after the Rollers ON trials.

Further research is required to evaluate the relative importance of the two driving modes and display screens. Future studies would aim at optimizing the mathematical model to closely mimic performance of a real wheelchair. Generic mathematical models can be built for front wheel, mid wheel, and rear wheel drive wheelchairs. These models could be customized to fit the driving profiles of the user's wheelchair. Eventually as data from wheelchairs from different manufacturers are available, the simulation system can have a database of these generic and specific models which the clinicians can use with their potential clients to identify a wheelchair and settings that may work best for the client.

Exploring the use of a mathematical model to simulate the wheelchair's kinematics is important, as it can help in implementing virtual driving environments in clinics where the roller platforms are not available or cannot be afforded. Such a piece of software can be embedded in a joystick software driver, and the user can play any computer or online game as if driving a wheelchair. The roller platform used for this study allowed driving simulation only on a plain floor surface. In future, advanced roller systems can be implemented and used to simulate driving on uneven surfaces, grass, sand, and curb cuts. Actors with artificial intelligence can be implemented to have more lifelike dynamic obstacles in indoor and outdoor settings. The graphics of the virtual environments can be upgraded to create an equally immersive virtual experience on computer and virtual reality screens. In future studies, emphasis will be given on more consistent training of clinical raters. With inputs from more clinicians who have regular experience with wheelchair driving evaluations, clinical rules will be created to evaluate certain simple tasks. These algorithms when embedded in the simulation software will generate a score that can aid the clinical judgment of raters.

7.5 CONCLUSION

The virtual Power Mobility Road Test (PMRT) modeled in the computer based virtual environment and virtual reality environment shows high intra rater and inter rater reliabilities. Subjects had higher workloads while driving on the virtual PMRT track compared to the real world PMRT track. There was no significant difference in the overall workloads after using the two screens and with and without the rollers. The virtual PMRT shows promise to serve as a clinical evaluation tool for power wheelchair driving skills.

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8.0 VRSIM 4.0: PREDICTING REAL WORLD WHEELCHAIR DRIVING PERFORMANCE FROM VIRTUAL DRIVING PERFORMANCE

For a clinical tool to be effective and usable, researchers must ensure that independent evaluators reliably rate measurements using the tool and that the tool truly measures what it is supposed to measure. For the virtual Power Mobility Road Test (PMRT), the former research objective of rater reliability was evaluated in the last 2 chapters while this study aims to explore the latter research objective to evaluate validity of measurements with the Virtual PMRT. There are various types of validity evaluations that are performed before a clinical tool could be widely used [1]. This protocol specifically aims to establish concurrent validity of virtual PMRT with respect to the real world PMRT, considered as a gold standard for this research study.

The ultimate objective of the research studies presented in this dissertation is to develop a clinical tool that could be used by clinicians to train and evaluate potential users with wheelchair driving. Virtual environments (VE) present a safe and customizable medium to develop such training and evaluation protocol. However, we need to ensure that the driving performances of users in the VEs are reflective and comparable to their real world driving performances.

8.1 SPECIFIC AIMS

Specific Aim 1: To establish concurrent validity of the virtual Power Mobility Road Test.

Specific Aim 2: To explore if the virtual driving performance of wheelchair users predicts their real world wheelchair driving performance.

8.2 METHODS

8.2.1 Subject Recruitment

The protocol for this research study was approved by the Institutional Review Boards of the Veteran Affairs and the University of Pittsburgh. Subjects were recruited by advertising flyers at the 31st National Veteran Wheelchair Games (NVWG) at Pittsburgh, PA. When interested participants enquired about the research study they were briefed about the study procedures by clinicians and were scheduled for a visit to the research center.

8.2.2 Inclusion Criteria

1. Subjects must be between 18 to 80 years old.
2. Subjects must use a power wheelchair for all or part of their mobility or would be candidates for power wheelchair, or would benefit from a power wheel chair after training.
3. Subjects must be able to provide informed consent.

4. Subjects must have basic cognitive, visual, and motor skills to interact with the virtual driving environments.

8.2.3 Exclusion Criteria

1. Subjects who have active pelvic or thigh wounds. (They may be worsened by prolonged sitting).
2. Subjects who do not pass the screening protocol.

8.2.4 Research Protocol

The experimental protocol is the same as explained in Chapter 7. Subjects performed virtual driving trials along 16 standardized tasks during each of the test conditions in two VEs: Immersive Virtual Reality Environment (IVRE) and Computer Based Virtual Environment (CVE) with and without Rollers. See Table 1. A team of two clinicians, out of five, independently assessed every driving trial using the PMRT rating scale (see Appendix D). The same clinicians also evaluated the driving performance on subjects on a real world PMRT track.

The VE for virtual driving tasks was modeled based on a real world office space. Individual driving tasks were marked using a series of balloons to indicate milestones subjects were supposed to cross and arrows to point in direction of turns. The software program running the simulation reads the predetermined coordinates of these milestones and turns. Along a straight driving task, the program defines ideal path as a straight line joining two milestones. Along a turn, ideal path was defined as a smooth curve along the turn arrow. During every frame update, the program saved several state measures, such as root mean squared deviation from the ideal path, virtual wheelchair position and speed, and collisions with walls or virtual objects.

Table 8-1: Five experiment test conditions

Test Condition	Driving Mode	Display	User interacts with VE using
1	Rollers ON	PC (CVE)	Encoders on Rollers
2	Rollers ON	VR (IVRE)	Encoders on Rollers
3	Rollers OFF	PC (CVE)	Customized joystick + Math Model
4	Rollers OFF	VR (IVRE)	Customized joystick + Math Model
5	Real World	-	Wheelchair joystick

8.2.5 Data Processing and Statistics

The state variables recorded by the simulation program were post processed to get driving performance measures like total time to complete a driving trial (TT), Average Speed (AS), Root Mean Squared Deviation (RMSD), and number of collision (NC). During the real world driving it is expected that the driver quickly changes directions to avoid collision with the object. If subjects failed to exert any effort to move the virtual chair away from the object after colliding with it, they were assumed to be stuck and the driving trial was restarted. The number of times such events took place was recorded as stuck count (SC). The number of times the chair changed its orientation was recorded as significant direction changes (DC) [2].

Scores from the real world PMRT were considered the gold standard for purposes of this study and were correlated with scores on the virtual PMRT. Since the real world PMRT track was designed to be as close as possible to the virtual driving track, subjects were expected to have similar driving performance on both. Pearson's correlation analysis was performed to establish concurrent validity of the virtual PMRT.

Regression analysis was used to evaluate if the virtual driving performance measures can predict subject's real world PMRT scores. However, the virtual driving performance measures derived above showed significant correlation with each other. Because of these correlation effects, it is inappropriate to use conventional least squares based linear regression methods since it generates highly biased regression estimates. Ridge regression is recommended in such cases. In ridge regression a bias (lambda) is added to the model to shrink regression coefficients [3]. It is also recommended that regression models without constant term be used to select ridge regression parameter, lambda and those with a constant term be used for prediction [4]. The variables TT, RMD, NC, SC, DC, and AS were added as regressors since they were the most significant and relevant to predicting real world PMRT in this regression. Ridge regression models were built for different values of lambda for the four virtual driving conditions. Diagnostic statistics Variance Inflation Factors (VIF) were computed for all regressors from each of these models and plotted against lambda values. The regression coefficients (β) were also plotted against lambda values. The lambda value optimum for building the model was selected based on certain rules of thumb criteria recommended by Marquardt [4], [5] and McDonald [6]. VIF values less than one make the model unstable and values above 10 contribute to violation of multicollinearity [3]. The criteria followed for selecting lambda were: The least VIF should be closer and greater than one, the maximum VIF should be between one and ten, regression coefficients should not change much.

Leave one out cross validation was used for validating the regression models that were built for the four driving conditions. Data from nineteen subjects were used to build models and one was used for validation. This process was repeated 20 times and R squared values were recorded from the validation process.

8.3 RESULTS

Of the five clinicians who participated in this study three were more experienced (more than 5 years) with wheelchair evaluations while two had moderate experience. Every subject was evaluated by a team with at least one experienced clinician. It was expected that all clinicians would have strong correlations in their scores on real world PMRT and virtual PMRT. However, the clinicians with less experience showed poor and insignificant correlations in all scores for trials on both screens. The experienced clinicians group showed strong correlations in their structured composite scores and total scores, especially in the IVRE. Their skilled driving scores showed poor correlations. These results indicate that the structured and total PMRT scores of virtual PMRT show good concurrent validity with scores from real world PMRT (gold standard for this research study). No differences were seen in validity scores from the two driving modes. The virtual PMRT composite scores by experienced clinicians explain about 13.7% to 33.6% of variances in the real world PMRT scores. The validity ratings from the experienced clinicians group were further separated by driving modes. The real world PMRT scores by experienced clinicians show strong concurrent validity correlation correlations with virtual PMRT scores measured during the Rollers OFF driving mode. The coefficients indicated weak correlations with virtual PMRT scores from Rollers ON driving mode.

Table 8-2: Concurrent validity of driving in CVE and IVRE with real world driving: Pearson's correlations coefficients for less and more experienced clinician groups

Score	**Screen**	**Clinical Experience = Less**		**Clinical Experience = More**	
		Pearson Correlation	P value	Pearson Correlation	P value
STRUCTURED	PC (CVE)	0.16	0.33	0.26	0.1
	VR (IVRE)	0.1	0.58	0.58*	<0.001
SKILLED	PC (CVE)	0.2	0.25	0.16	0.32
	VR (IVRE)	-0.5	0.77	-0.08	0.67
TOTAL	PC (CVE)	0.27	0.11	0.37*	0.01
	VR (IVRE)	0.27	0.11	0.5*	0.003

Table 8-3: Concurrent Validity of virtual driving modes and real world driving from the more experienced group

Score	**Screen**	**Mode = Rollers OFF**		**Mode = Rollers ON**	
		Pearson Correlation	P value	Pearson Correlation	P value
STRUCTURED	PC (CVE)	0.28	0.17	0.01	0.71
	VR (IVRE)	0.71*	<0.001	-0.09	0.75
SKILLED	PC (CVE)	0.24	0.25	-0.08	0.78
	VR (IVRE)	0	-	-0.13	0.64
TOTAL	PC (CVE)	0.55*	0.005	-0.02	0.92
	VR (IVRE)	0.74*	<0.001	0.03	0.91

Table 8-4: Means and Standard Deviations of difference between real and virtual PMRT ratings

Driving Conditions	Mean Difference (real PMRT & virtual PMRT)	Standard Deviation
PC screen Rollers OFF	0.0405	0.042
PC screen Rollers ON	0.0389	0.0514
VR screen Rollers OFF	0.0368	0.0398
VR screen Rollers ON	0.0331	0.0469

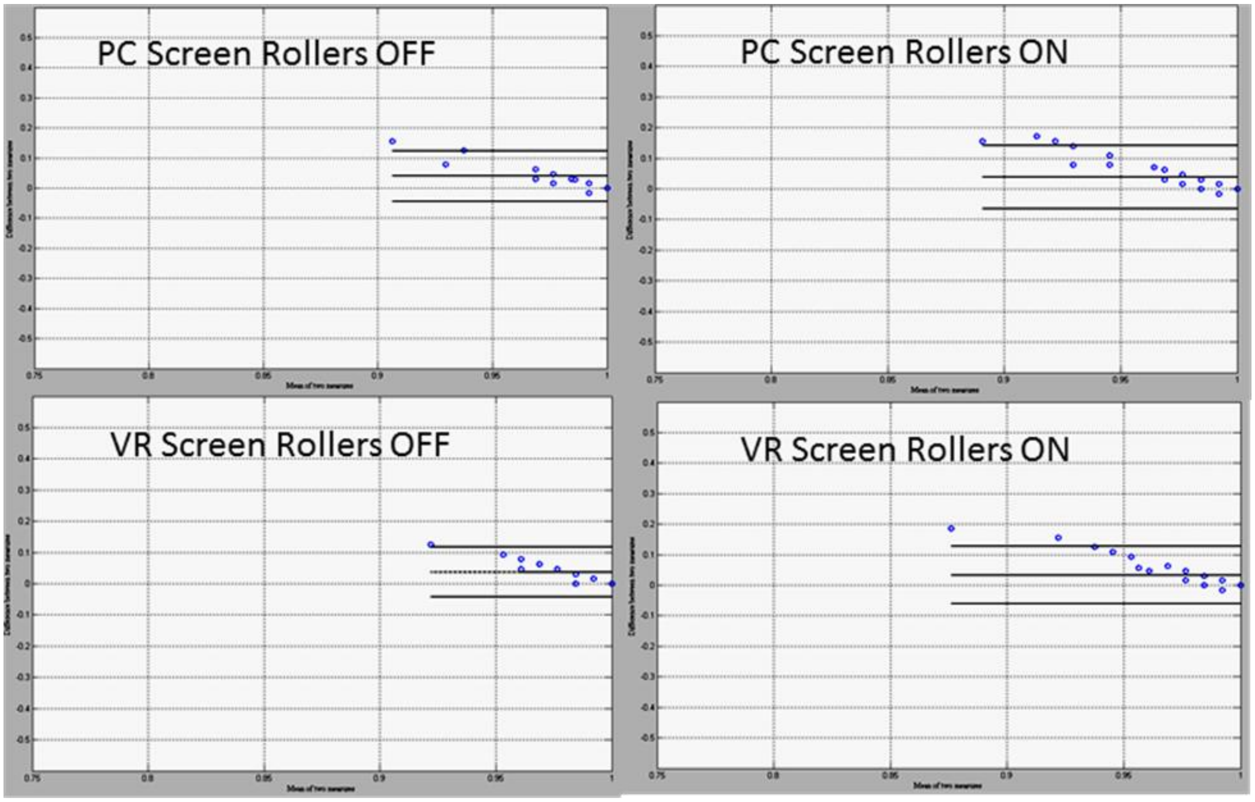

Figure 8-1: Bland Altman Plots showing agreement between Virtual and Real PMRT ratings of experienced clinicians for the four driving conditions.

Figure 1 above shows Bland Altman [7] plots for the virtual an real world PMRT scores for the four driving conditions. The plots present a graphical representation of agreements between a gold standard and an experimental clinical measure. The difference between real PMRT and virtual PMRT is positive for subjects with poor driving performance while it is close to zero for subjects with good driving performance. Table 4 shows that the differences between real and virtual PMRT ratings are small.

The plots show that the clinician ratings show a tendency towards ceiling effect. Real world PMRT data only from the experienced clinicians were used to build and validate the ridge regression models. Table 5 shows the composite PMRT scores from the 16 tasks of the PMRT. Tables 6 to 9 show the VIF for every regressor computed for different values of ridge regression parameter lambda. The optimum lambda values selected are as highlighted in the tables.

Table 8-5: Real PMRT scores from the experienced clinicians

Subject ID	REAL PMRT Score
1	1.000
2	1.000
3	1.000
4	1.000
5	0.984
6	1.000
7	0.984
8	0.984
9	1.000
10	1.000
11	0.969
12	1.000
13	1.000
14	1.000
15	0.984
16	0.984
17	Incomplete
18	1.000
19	1.000
20	1.000
21	1.000

Table 8-6: Display: PC Rollers: OFF; Models to select optimum lambda

Lambda	R^2	VIF_{SC}	VIF_{NC}	VIF_{RMSD}	VIF_{AS}	VIF_{TT}	VIF_{DC}	MSE	P value
0	0.476	2.857	4.720	4.246	7.435	14.015	8.175	6.40E-05	0.1438
0.01	0.549	2.637	4.437	4.238	5.098	10.090	7.559	4.81E-05	0.0670
0.02	0.576	2.511	4.276	4.233	3.765	7.851	7.207	4.34E-05	0.0484
0.03	0.593	2.433	4.175	4.231	2.933	6.454	6.987	4.06E-05	0.0389
0.04	0.605	2.381	4.108	4.229	2.380	5.525	6.841	3.87E-05	0.0329
0.05	0.615	2.344	4.061	4.227	1.993	4.876	6.739	3.72E-05	0.0288
0.06	0.623	2.318	4.027	4.226	1.712	4.404	6.665	3.60E-05	0.0257
0.07	0.629	2.298	4.002	4.226	1.502	4.051	6.610	3.50E-05	0.0232
0.08	0.635	2.283	3.982	4.225	1.340	3.779	6.567	3.41E-05	0.0213
0.09	0.641	2.271	3.967	4.225	1.214	3.566	6.534	3.33E-05	0.0196
0.1	0.645	2.261	3.955	4.224	1.112	3.396	6.507	3.26E-05	0.0182
0.11	0.650	**2.254**	**3.945**	**4.224**	**1.030**	**3.258**	**6.485**	3.20E-05	0.0169
0.12	0.654	2.247	3.937	4.224	0.962	3.144	6.467	3.14E-05	0.0159
0.13	0.658	2.242	3.930	4.224	0.906	3.049	6.452	3.08E-05	0.0149
0.14	0.661	2.237	3.924	4.223	0.858	2.970	6.440	3.03E-05	0.0140

Table 8-7: Display: PC Rollers: ON; Models to select optimum lambda

Lambda	**R^2**	**VIF_{SC}**	**VIF_{NC}**	**VIF_{RMSD}**	**VIF_{AS}**	**VIF_{TT}**	**VIF_{DC}**	**MSE**	**P value**
0	0.434	1.634	2.193	1.758	7.127	8.107	1.792	3.82E-05	0.0030
0.01	0.489	1.611	2.172	1.643	5.216	6.491	1.746	3.07E-05	<0.001
0.02	0.507	1.598	2.159	1.574	4.077	5.528	1.719	2.85E-05	<0.001
0.03	0.518	1.589	2.151	1.530	3.344	4.909	1.701	2.72E-05	<0.001
0.04	0.525	1.584	2.145	1.500	2.845	4.487	1.689	2.64E-05	<0.001
0.05	0.531	1.579	2.142	1.478	2.490	4.187	1.681	2.57E-05	<0.001
0.06	0.536	1.576	2.139	1.463	2.228	3.965	1.675	2.52E-05	<0.001
0.07	0.540	1.574	2.136	1.451	2.030	3.798	1.670	2.47E-05	<0.001
0.08	0.543	1.572	2.135	1.441	1.876	3.668	1.666	2.43E-05	<0.001
0.09	0.547	1.571	2.133	1.434	1.754	3.565	1.663	2.39E-05	<0.001
0.1	0.550	1.570	2.132	1.428	1.656	3.482	1.661	2.35E-05	<0.001
0.11	0.552	1.569	2.131	1.423	1.576	3.414	1.659	2.32E-05	<0.001
0.12	0.555	1.568	2.131	1.419	1.509	3.358	1.657	2.29E-05	<0.001
0.13	0.558	1.567	2.130	1.416	1.454	3.311	1.656	2.26E-05	<0.001
0.14	0.560	1.567	2.130	1.413	1.407	3.271	1.655	2.23E-05	<0.001
0.15	0.563	1.566	2.129	1.411	1.367	3.238	1.654	2.20E-05	<0.001
0.16	0.565	1.566	2.129	1.409	1.333	3.208	1.653	2.17E-05	<0.001
0.17	0.567	1.566	2.128	1.407	1.303	3.183	1.652	2.15E-05	<0.001
0.18	0.569	1.565	2.128	1.405	1.277	3.161	1.652	2.12E-05	<0.001
0.19	0.572	1.565	2.128	1.404	1.254	3.142	1.651	2.10E-05	<0.001
0.2	0.574	1.565	2.128	1.403	1.234	3.125	1.651	2.07E-05	<0.001
0.21	0.576	1.565	2.127	1.402	1.216	3.110	1.650	2.05E-05	<0.001
0.22	0.578	1.564	2.127	1.401	1.201	3.097	1.650	2.03E-05	<0.001
0.23	0.580	1.564	2.127	1.400	1.186	3.085	1.650	2.01E-05	<0.001
0.24	0.582	1.564	2.127	1.399	1.174	3.074	1.649	1.99E-05	<0.001
0.25	0.583	1.564	2.127	1.398	1.162	3.064	1.649	1.96E-05	<0.001
0.26	0.585	1.564	2.127	1.398	1.152	3.056	1.649	1.94E-05	<0.001
0.27	0.587	1.564	2.127	1.397	1.142	3.048	1.649	1.92E-05	<0.001
0.28	0.589	1.564	2.127	1.397	1.134	3.040	1.648	1.90E-05	<0.001
0.29	0.591	1.563	2.126	1.396	1.126	3.034	1.648	1.89E-05	<0.001
0.3	0.592	1.563	2.126	1.396	1.119	3.028	1.648	1.87E-05	<0.001
0.31	0.594	1.563	2.126	1.395	1.112	3.022	1.648	1.85E-05	<0.001
0.32	0.596	1.563	2.126	1.395	1.106	3.017	1.648	1.83E-05	<0.001
0.33	0.598	1.563	2.126	1.395	1.101	3.012	1.648	1.81E-05	<0.001
0.34	0.599	**1.563**	**2.126**	**1.394**	**1.096**	**3.008**	**1.647**	1.80E-05	<0.001
0.35	0.601	1.563	2.126	1.394	1.091	3.004	1.647	1.78E-05	<0.001
0.36	0.602	1.563	2.126	1.394	1.086	3.000	1.647	1.76E-05	<0.001
0.37	0.604	1.563	2.126	1.394	1.082	2.997	1.647	1.75E-05	<0.001
0.38	0.606	1.563	2.126	1.393	1.079	2.994	1.647	1.73E-05	<0.001
0.39	0.607	1.563	2.126	1.393	1.075	2.991	1.647	1.71E-05	<0.001

Table 8-8: Display: VR Rollers: OFF; Models to select optimum lambda

Lambda	R^2	VIF_{SC}	VIF_{NC}	VIF_{RMSD}	VIF_{AS}	VIF_{TT}	VIF_{DC}	MSE	P value
0	0.488	10.223	7.913	10.122	67.408	114.403	4.288	3.82E-05	0.2467
0.01	0.656	4.136	6.697	5.867	8.391	15.823	3.038	1.91E-05	0.0516
0.02	0.676	3.625	6.596	5.511	3.445	7.561	2.933	1.76E-05	0.0403
0.03	0.687	3.483	6.567	5.412	2.068	5.261	2.904	1.66E-05	0.0344
0.04	0.696	3.425	6.555	5.371	1.498	4.310	2.892	1.60E-05	0.0303
0.05	0.704	3.395	6.550	5.350	1.209	3.827	2.886	1.54E-05	0.0273
0.06	0.710	**3.378**	**6.546**	**5.338**	**1.043**	**3.549**	**2.883**	1.50E-05	0.0248
0.07	0.716	3.367	6.544	5.330	0.938	3.374	2.880	1.46E-05	0.0228
0.08	0.721	3.360	6.543	5.325	0.868	3.257	2.879	1.42E-05	0.0211
0.09	0.725	3.355	6.542	5.322	0.819	3.175	2.878	1.39E-05	0.0195
0.1	0.730	3.351	6.541	5.319	0.783	3.115	2.877	1.36E-05	0.0182
0.11	0.734	3.348	6.540	5.317	0.757	3.070	2.876	1.33E-05	0.0170
0.12	0.738	3.346	6.540	5.316	0.736	3.036	2.876	1.31E-05	0.0160
0.13	0.741	3.344	6.539	5.314	0.720	3.008	2.876	1.28E-05	0.0150
0.14	0.745	3.343	6.539	5.314	0.707	2.987	2.875	1.26E-05	0.0141

Table 8-9: Display: VR Rollers: ON; Models to select optimum lambda

Lambda	R^2	VIF_{SC}	VIF_{NC}	VIF_{RMSD}	VIF_{AS}	VIF_{TT}	VIF_{DC}	MSE	P value
0	0.660	2.088	2.559	2.783	2.601	4.707	1.726	2.92E-05	<0.001
0.01	0.819	2.081	2.555	2.783	2.268	4.475	1.703	1.25E-05	<0.001
0.02	0.839	2.076	2.553	2.783	2.010	4.295	1.685	1.08E-05	<0.001
0.03	0.850	2.071	2.551	2.783	1.805	4.152	1.672	9.97E-06	<0.001
0.04	0.856	2.068	2.549	2.783	1.641	4.038	1.660	9.47E-06	<0.001
0.05	0.861	2.065	2.548	2.783	1.507	3.944	1.651	9.13E-06	<0.001
0.06	0.864	2.063	2.546	2.783	1.397	3.867	1.644	8.87E-06	<0.001
0.07	0.866	2.061	2.546	2.783	1.304	3.802	1.637	8.68E-06	<0.001
0.08	0.869	2.059	2.545	2.783	1.226	3.748	1.632	8.52E-06	<0.001
0.09	0.870	2.058	2.544	2.783	1.159	3.701	1.627	8.39E-06	<0.001
0.1	0.872	2.056	2.543	2.783	1.102	3.661	1.623	8.27E-06	<0.001
0.11	0.873	2.055	2.543	2.783	1.052	3.626	1.620	8.18E-06	<0.001
0.12	0.874	**2.054**	**2.543**	**2.783**	**1.009**	**3.596**	**1.617**	8.09E-06	<0.001
0.13	0.875	2.054	2.542	2.783	0.971	3.570	1.614	8.02E-06	<0.001
0.14	0.876	2.053	2.542	2.783	0.938	3.547	1.612	7.95E-06	<0.001

The following figure (Figure 8-2) shows the regression traces of regression coefficients for the different values of lambda. The optimum lambda selected in where the regression traces is just starting to plateau. Table 9 shows the regression coefficients from optimum lambda selected from the four driving conditions. Table 10 shows the regression coefficients for the optimum lambda selected for the different driving conditions. Tables 11 and 12 show the results from leave one out cross validation of the models with data from 20 subjects. The R squares values from the cross validation trials were averaged. The averaged R squared values of the models on VR screens were higher than the models on PC screen. This indicates that the driving trials in IVRE are must better in predicting the real world PMRT scores.

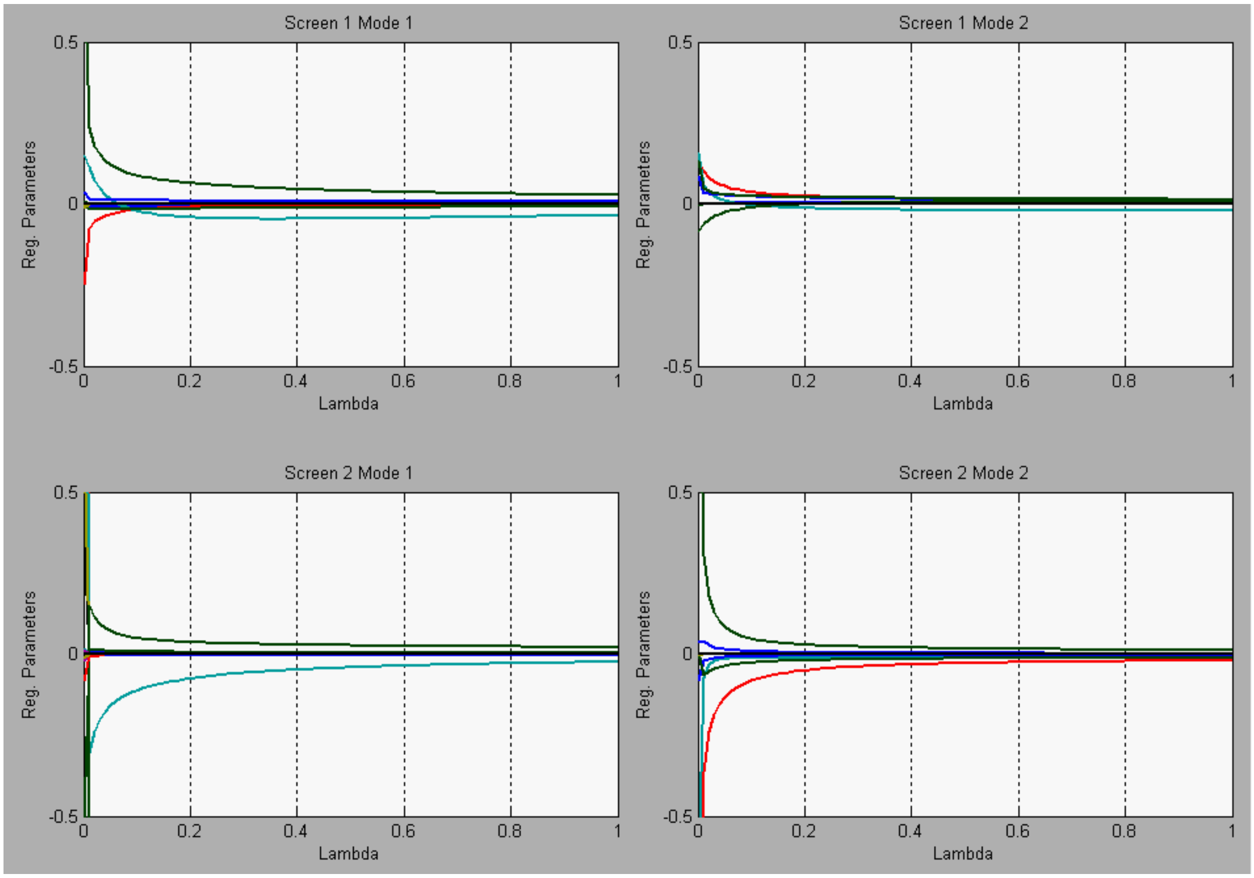

Figure 8-2: Regression traces for the regression parameters for the four driving conditions. Screen 1: PC, Screen 2: VR, Mode 1: Rollers OFF, Mode 2: Rollers ON.

Table 8-10: Regression coefficients for models with optimum lambda

Modes	**Lambda**	β_{SC}	β_{NC}	β_{RMSD}	β_{AS}	β_{TT}	β_{DC}	β_{SC}
PC Screen Rollers OFF	0.11	1.0178	-0.0070	-2.87E-05	-0.0164	-0.0241	4.76E-05	3.20E-05
PC Screen Rollers ON	0.34	1.0363	0.0028	-2.03E-05	0.0180	-0.0175	-5.07E-05	3.47E-05
VR Screen Rollers OFF	0.06	0.9943	0.0034	-0.00024	-0.0012	-0.1453	-5.21E-05	4.43E-06
VR Screen Rollers ON	0.12	0.9960	0.0075	-2.87E-05	-0.0726	-0.0120	2.85E-06	4.73E-07

Table 8-11: Cross Validation results for PC screen models

Cross Validation	**PC Screen Rollers OFF**			**PC Screen Rollers ON**		
	R squared	**MSE**	**P value**	**R squared**	**MSE**	**P value**
1	0.663	3.23E-05	0.021	0.593	1.85E-05	<0.001
2	0.645	3.43E-05	0.027	0.573	2.00E-05	<0.001
3	0.644	3.48E-05	0.027	0.635	1.72E-05	<0.001
4	0.687	3.33E-05	0.014	0.596	1.89E-05	<0.001
5	0.564	4.50E-05	0.076	0.672	1.64E-05	<0.001
6	0.710	2.86E-05	0.009	0.668	1.64E-05	<0.001
7	0.898	9.63E-06	<0.001	0.567	2.10E-05	<0.001
8	0.795	2.10E-05	0.001	0.657	1.73E-05	<0.001
9	0.664	3.23E-05	0.021	0.603	1.83E-05	<0.001
10	0.647	3.39E-05	0.026	0.601	1.89E-05	<0.001
11	0.883	5.25E-06	0.000	0.519	6.58E-06	<0.001
12	0.646	3.41E-05	0.027	0.608	1.82E-05	<0.001
13	0.654	3.32E-05	0.024	0.628	1.76E-05	<0.001
14	0.629	3.66E-05	0.034	0.638	1.85E-05	<0.001
15	0.643	3.28E-05	0.028	0.716	1.39E-05	<0.001
16	0.788	2.05E-05	0.002	0.667	1.52E-05	<0.001
17	0.715	2.79E-05	0.009	0.624	1.77E-05	<0.001
18	0.643	3.56E-05	0.028	0.551	2.20E-05	<0.001
19	0.650	3.36E-05	0.025	0.660	1.63E-05	<0.001
20	0.659	3.31E-05	0.022	0.595	1.87E-05	<0.001
Average	**0.691**	**2.99E-05**		**0.619**	**1.74E-05**	

Table 8-12: Cross Validation results for VR screen models

Cross Validation	**VR Screen Rollers OFF**			**VR Screen Rollers ON**		
	R squared	**MSE**	**P value**	**R squared**	**MSE**	**P value**
1	0.705	1.65E-05	0.042	0.880	8.31E-06	<0.001
2	0.683	1.83E-05	0.056	0.870	8.70E-06	<0.001
3	0.704	1.65E-05	0.043	0.875	8.48E-06	<0.001
4	0.760	1.34E-05	0.019	0.875	8.52E-06	<0.001
5	0.835	7.03E-06	0.004	0.833	1.14E-05	<0.001
6	0.710	1.50E-05	0.025	0.873	8.50E-06	<0.001
7	0.873	6.03E-06	0.001	0.869	9.36E-06	<0.001
8	0.826	9.98E-06	0.005	0.935	4.62E-06	<0.001
9	0.638	2.31E-05	0.092	0.877	8.33E-06	<0.001
10	0.707	1.64E-05	0.041	0.882	7.83E-06	<0.001
11	0.710	1.50E-05	0.025	0.679	8.35E-06	<0.001
12	0.693	1.73E-05	0.049	0.874	8.40E-06	<0.001
13	0.705	1.64E-05	0.042	0.881	8.03E-06	<0.001
14	0.703	1.65E-05	0.044	0.882	7.87E-06	<0.001
15	0.694	1.29E-05	0.049	0.821	1.15E-05	<0.001
16	0.710	1.50E-05	0.025	0.914	5.37E-06	<0.001
17	0.905	5.34E-06	<0.001	0.909	6.11E-06	<0.001
18	0.726	1.59E-05	0.032	0.882	8.38E-06	<0.001
19	0.719	1.57E-05	0.035	0.884	7.81E-06	<0.001
20	0.730	1.51E-05	0.030	0.885	8.18E-06	<0.001
Average	**0.737**	**1.44E-05**		**0.869**	**8.21E-06**	

8.4 DISCUSSION

Virtual PMRT scores on the IVRE showed high concurrent validity with real world PMRT scores. Possibly, the higher form factor of the VR screens might have been helpful for clinicians to observe and judge finer motions of the virtual chair with respect to the moving obstacles. Significant differences were seen in the concurrent validity estimates between real and virtual PMRTs from the less and more experienced clinician groups. The less experienced group showed weak and statistically insignificant correlations between their real PMRT and virtual PMRT scores on equivalent tasks. The experienced clinicians group showed much better concurrent validity correlation coefficients with the IVRE driving trials than with the CVE driving trials. This difference in IVRE and CVE validity scores was more pronounced for the Rollers OFF driving mode. With sufficient exposure and a standardized training protocol we expect the reliability and validity ratings in scores from novice/less experienced clinicians could be improved to match those of the experienced clinicians. The results from ridge regression are promising. All models were able to predict more than 60% of variation in the real world PMRT scores. The models built from data from IVRE show higher R square values than the models from the CVE. Using the rollers significantly improved the prediction only for the VR screen. For the PC screen, better prediction accuracy was achieved when rollers were not used.

As discussed in Chapter 7, more research is required to determine the relative significance of the two display screens and the rollers. The subjects tested in this research protocol were experienced wheelchair users. In future, data from novice wheelchair users and potential wheelchair candidates will help in exploring the limitations of customization capability of the experimental platform, the processing algorithms and regression models. With this cohort of experienced users, the PMRT scores showed a ceiling effect. Although ridge regression gave moderate to high prediction scores, including data from subjects with diverse levels of driving experience will give us more confidence in using the regression models for clinical applications.

8.5 CONCLUSION

The virtual PMRT also shows strong concurrent validity with its real world counterpart when rated by experienced clinicians. The driving performance measures from the virtual PMRT show moderate to high prediction scores for the subjects’ real world driving performance.

8.6 BIBLIOGRAPHY

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9.0 FUTURE WORK

The virtual driving simulator system could be developed further for two distinct set of users. A “basic” version with limited customization features can be developed as a training tool for potential wheelchair users or for those who need to improve on certain driving skills. This version of the virtual environment will be like a computer game that could be easily downloaded by potential users. A joystick interface box will read inputs from a standard gaming joystick of the user’s wheelchair joystick. A software driver will interface with the joystick and apply the mathematical model to simulate wheelchair motion. A physical or occupational therapist would perform the initial customization of the mathematical model according to the user’s requirements. For example, the mathematical model could be customized to simulate a mid wheel driver wheelchair of a specific manufacturer. The user can then practice driving along multiple pre-loaded virtual worlds or use the joystick driver to play computer games of their choice. The program will generate and track automated performance scores that the clients and clinicians can use for check improvement.

In addition to the features of the client’s version, the clinician’s version of the simulator will be highly customizable and programmable to simulate multiple driving scenarios and can interface with different wheelchair input interfaces like joysticks, switches, and head/eye trackers. Clinicians can conveniently develop or modify virtual environments to match the user’s community settings. The client’s wheelchair driving performance can be evaluated and they could be trained on driving scenarios that the clinician thinks would be critical in the client's daily wheelchair driving. Clients can not only get training in the clinic but also take home some of these virtual environments for regular practice. In the clinic, depending on their tolerance and preference the client can interact with virtual environment on a computer screen, virtual reality screens, or with highly immersive head mounted displays. For clients with severe physical or cognitive issues, clinicians can customize different input interfaces to best use the residual capabilities of their clients. The quantitative driving performance metrics generated by the program could be used by the clinicians to validate their clinical intuition about selecting an input interface or about certain driving parameter setting. Because of portability of the software clinicians can also remotely monitor their clients driving using the system at home and suggest changes. Using some of the popular Massively Multiplayer Online Role Playing Game platforms like SecondLife, an online power wheelchair clinic could be set up. Here experienced clinicians can assist and train novice clinicians in remote locations with wheelchair driving evaluations.

More research is required with the Power Mobility Road Test (PMRT) and its use as a driving evaluation tool. PMRT scale, in its present form, shows a tendency of ceiling effect. Some of PMRT tasks seem to be redundant for a majority of potential wheelchair users. Also, the test does not consider outdoor driving tasks and complicated driving maneuvers, like navigating in a tight office spaces or in public transportation. More research is also required to evaluate the system with potential wheelchair users with varying levels of driving skills. This will help the researchers to discover limits to the customizability of the system to the needs of those with severe disabilities. Overall, the virtual driving simulator system shows great promise as a clinical tool to assist clinicians in wheelchair driving training and assessment.

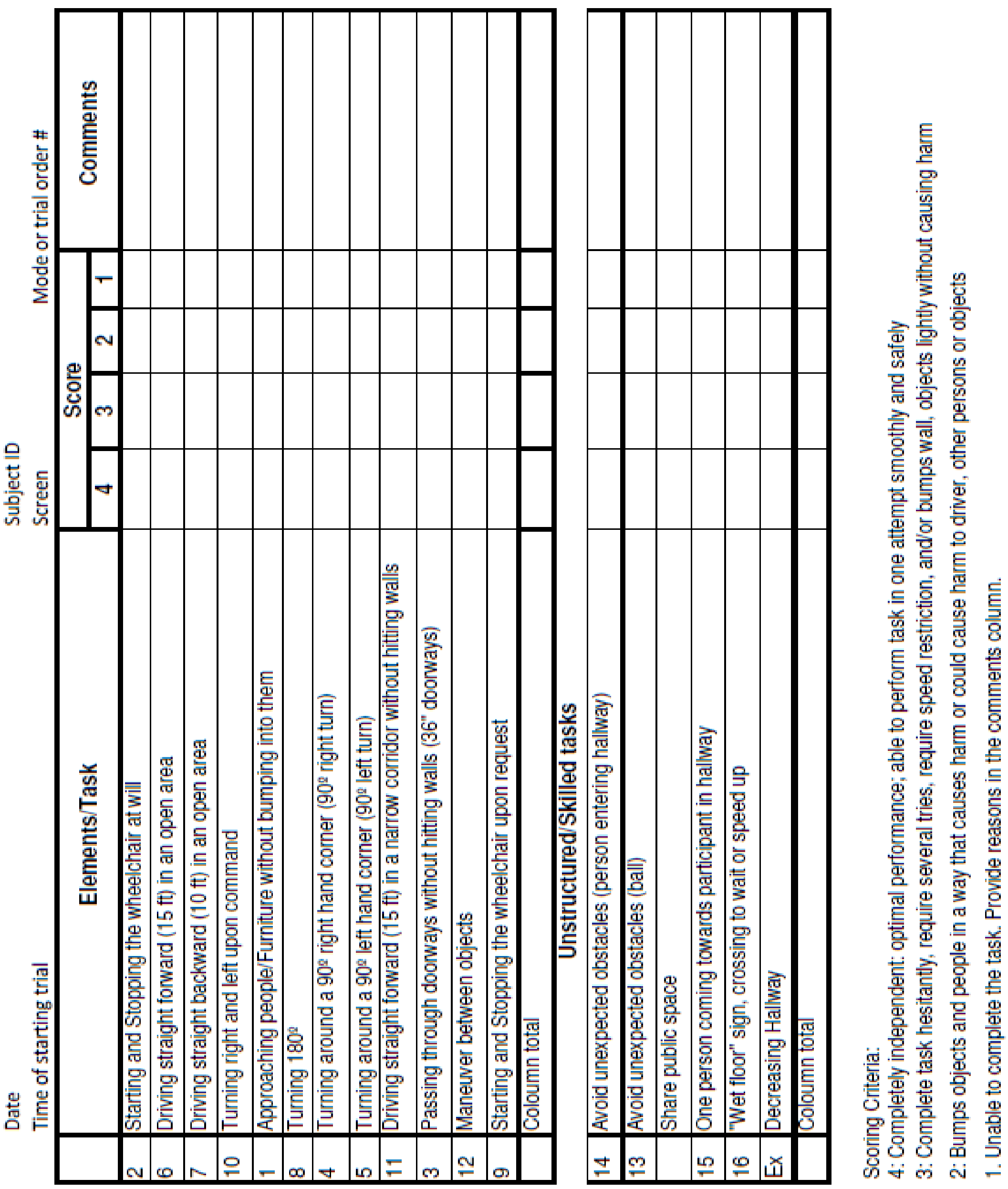
APPENDIX A

POWER MOBILITY ROAD TEST

The Power Mobility Road Test (PMRT) scoring sheet [1] used for this study is shown in Figure A.1. The task items in the scoring sheet are ordered in the sequence these tasks appear in the virtual environment. All task items were scored on a 1(unable to complete) to 4(completely independent) scale. Equation A. 1 was used to compute composite scores subsections of the PMRT. Tasks 1 -12 are “static tasks” and they have non-moving obstacles/components. The “Element score” is calculated from scores from these tasks. Tasks 13-16 are “Unstructured/skilled tasks” and they have moving obstacles/components such as a ball bounding in wheelchair’s path and sharing hallways with a walking person. The “Skilled Score” is calculated from scores from the skilled driving tasks while a “Total Score” is calculated from scores from all tasks. The task “decreasing hallway” is added to the original PMRT to evaluate certain driving deficits. This task is not used in any of the composite scores.

$$Composite\ Score = \frac{Sum\ of\ scores\ from\ all\ tasks\ completed}{4 * Number\ of\ tasks\ completed}$$

Equation A. 1: Composite scores for PMRT components



Date
Time of starting trial

Subject ID
Screen

Mode or trial order #

	Elements/Task	Score				Comments
		4	3	2	1	
2	Starting and Stopping the wheelchair at will					
6	Driving straight forward (15 ft) in an open area					
7	Driving straight backward (10 ft) in an open area					
10	Turning right and left upon command					
1	Approaching people/Furniture without bumping into them					
8	Turning 180º					
4	Turning around a 90º right hand corner (90º right turn)					
5	Turning around a 90º left hand corner (90º left turn)					
11	Driving straight forward (15 ft) in a narrow corridor without hitting walls					
3	Passing through doorways without hitting walls (36" doorways)					
12	Maneuver between objects					
9	Starting and Stopping the wheelchair upon request					
	Coloumn total					

Unstructured/Skilled tasks

14	Avoid unexpected obstacles (person entering hallway)					
13	Avoid unexpected obstacles (ball)					
	Share public space					
15	One person coming towards participant in hallway					
16	"Wet floor" sign, crossing to wait or speed up					
Ex	Decreasing Hallway					
	Coloumn total					

Scoring Criteria:
4: Completely independent: optimal performance; able to perform task in one attempt smoothly and safely
3: Complete task hesitantly, require several tries, require speed restriction, and/or bumps wall, objects lightly without causing harm
2: Bumps objects and people in a way that causes harm or could cause harm to driver, other persons or objects
1. Unable to complete the task. Provide reasons in the comments column.

Figure A. 1: Power Mobility Road Test scoring sheet. Tasks are ordered in the sequence they appear in the virtual environment

[1] S. Massengale, D. Folden, P. McConnell, L. Stratton, and V. Whitehead, "Effect of visual perception, visual function, cognition, and personality on power wheelchair use in adults," *Assistive Technology: The Official Journal of RESNA*, vol. 17, no. 2, pp. 108-121, 2005.

APPENDIX B

POWER MOBILITY ROAD TEST IN VIRTUAL ENVIRONMENT FOR CHAPTERS 5 AND 6

Following section shows the Static (Tasks 1-12), Unstructured/Skilled (Tasks 13-16), and decreasing hallway in the virtual Power Mobility Road Test (PMRT).

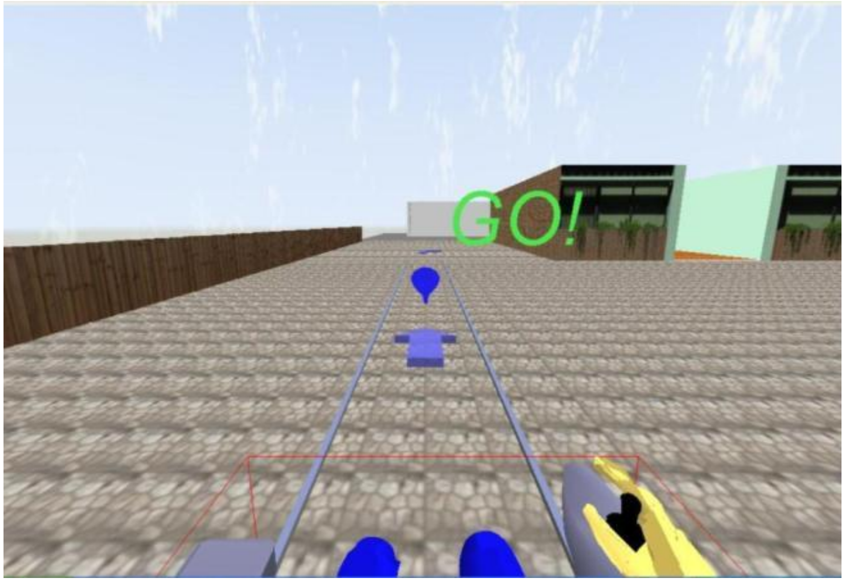


Figure B. 1: Driving circuit begins with a 3-2-GO! Prompt. Also includes part of Task 9 Starting the wheelchair upon request

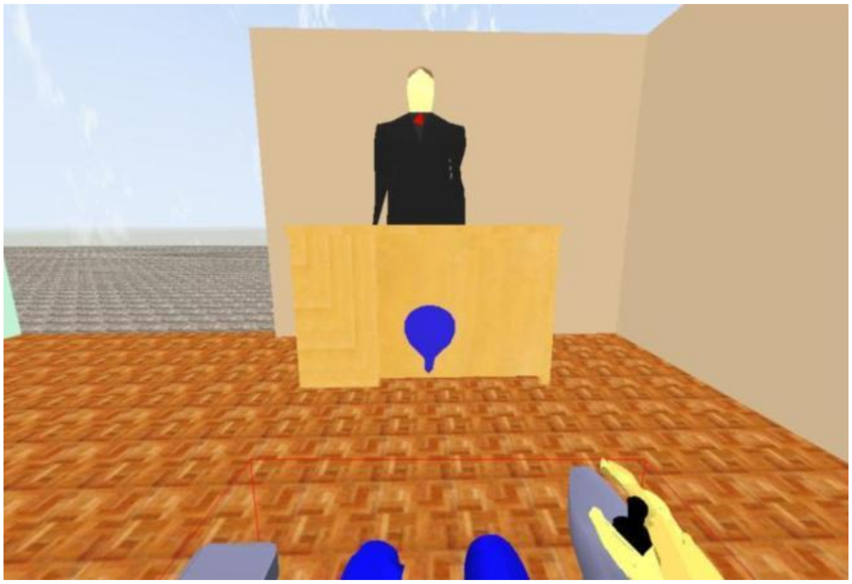


Figure B. 2: Task 1-Approaching people/Furniture without bumping into them

Figure B. 3: Task 3-Passing through 36" doorways without hitting walls

Figure B. 4: Task 4-Turning around a 90º right hand corner (90º right turn)

Figure B. 5: Task 5-Turning around a 90º left hand corner (90º left turn)

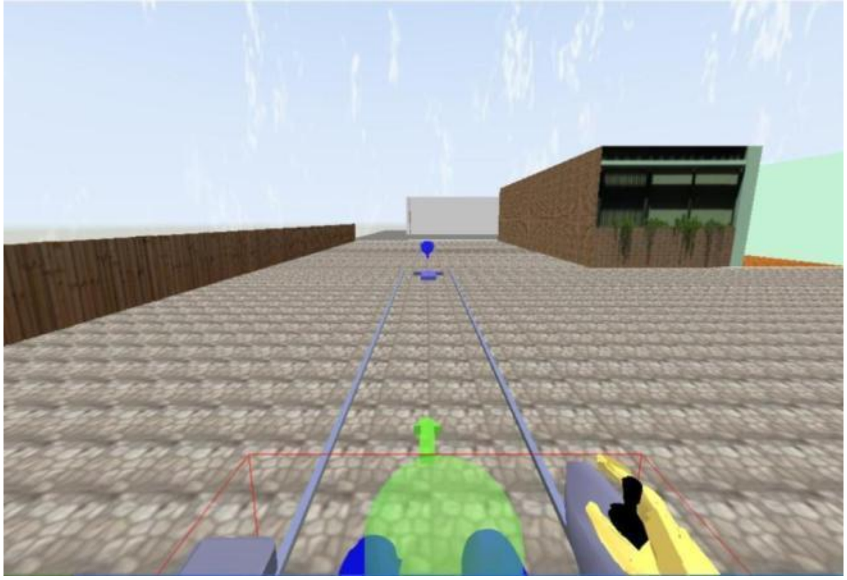


Figure B. 6: Task 6-Driving straight forward (15 ft) in an open area

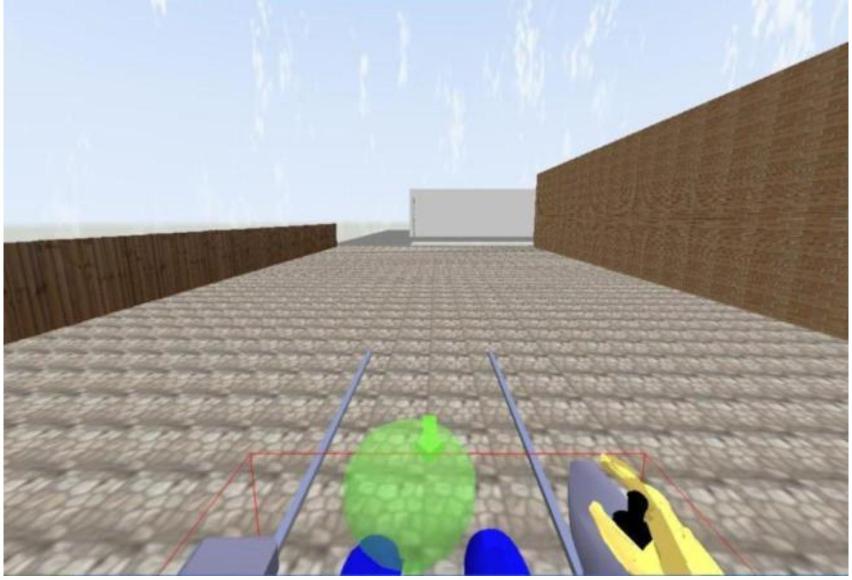


Figure B. 7: Task 7- Driving straight backward (10 ft) in an open area

Figure B. 8: Task 8-Turning around 180 degrees

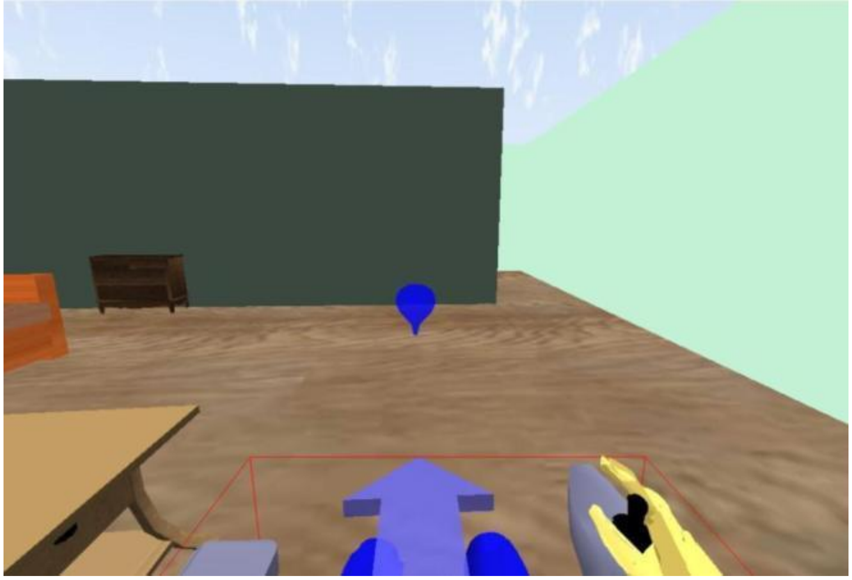


Figure B. 9: Part of Task 9 Stopping the wheelchair upon request

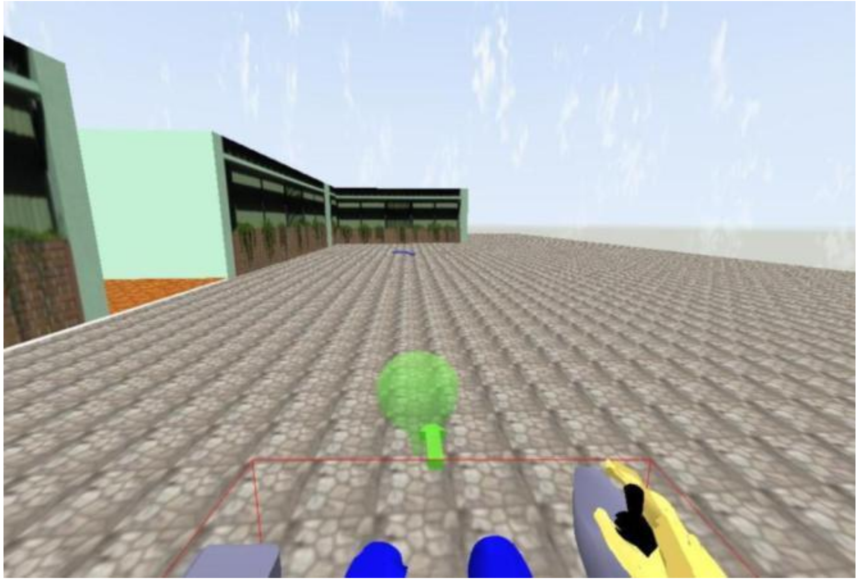


Figure B. 10: Part of Task 10-Turning left in an open area on command

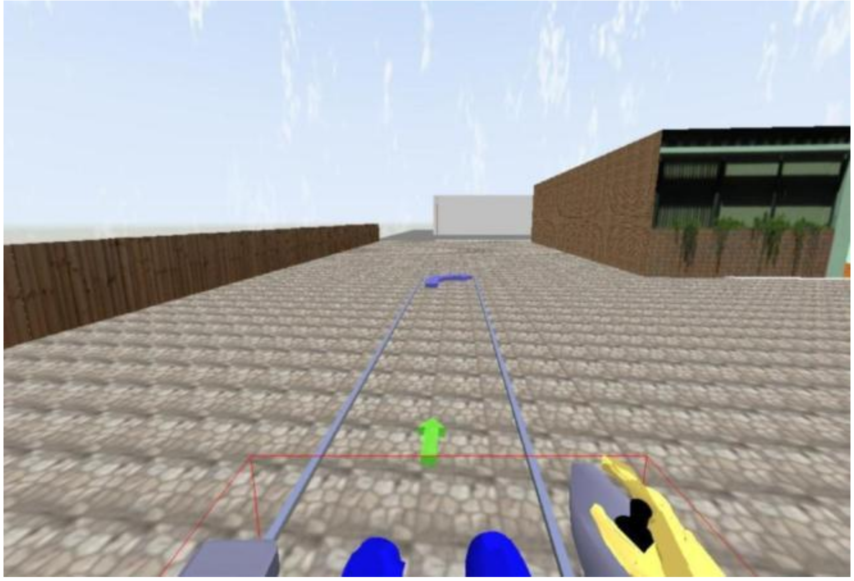


Figure B. 11: Part of Task 10-Turning right in an open area on command

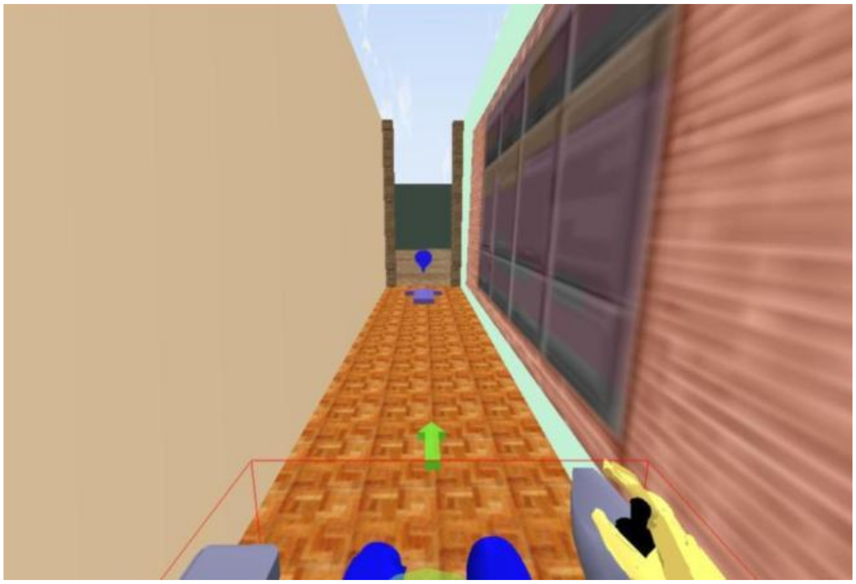


Figure B. 12: Task 11- Driving straight forward (15 ft) in a narrow corridor without hitting walls

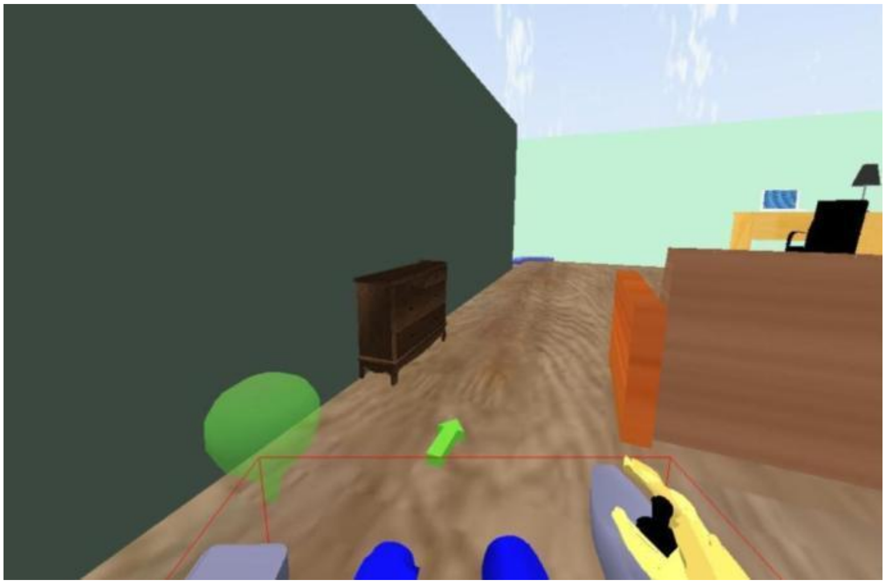


Figure B. 13: Part of Task 12- Maneuver between objects

Figure B. 14: Part of Task 12- Maneuver between objects

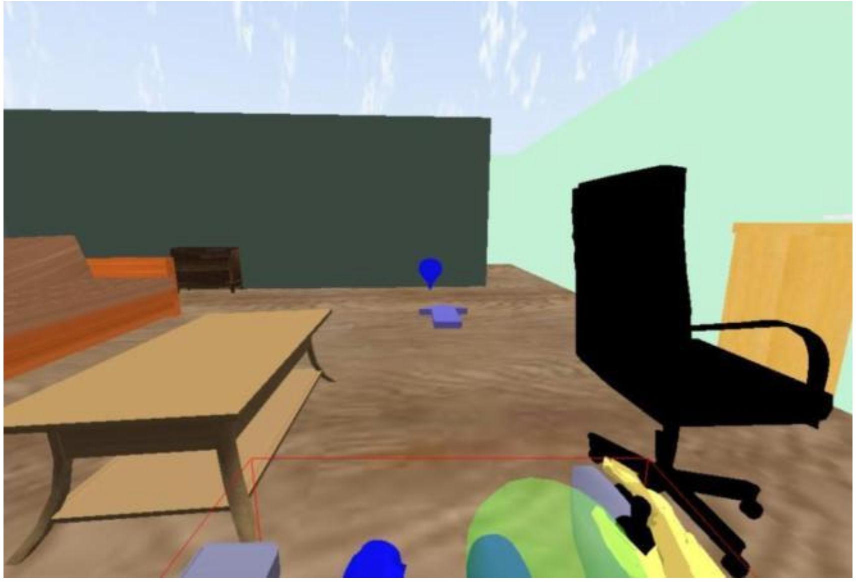


Figure B. 15: Part of Task 12- Maneuver between objects

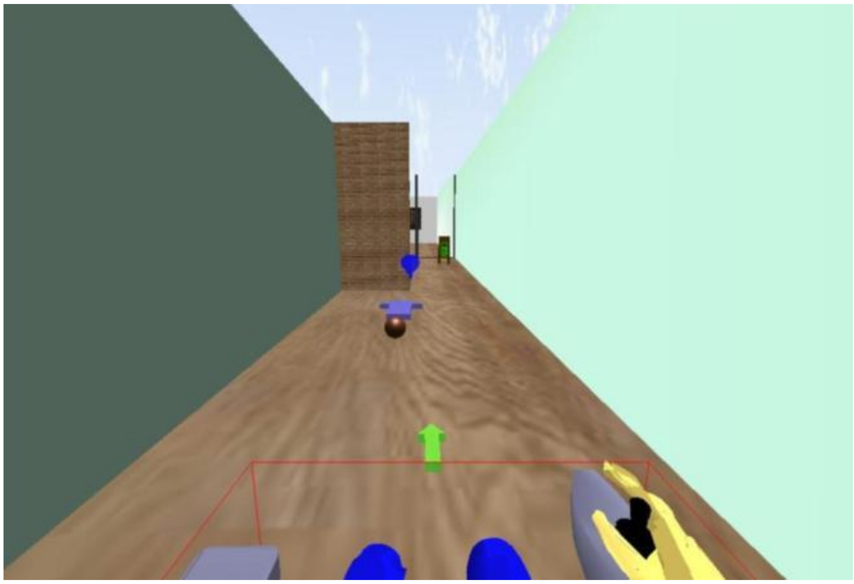


Figure B. 16: Task 13- Avoid unexpected obstacles (bouncing ball)

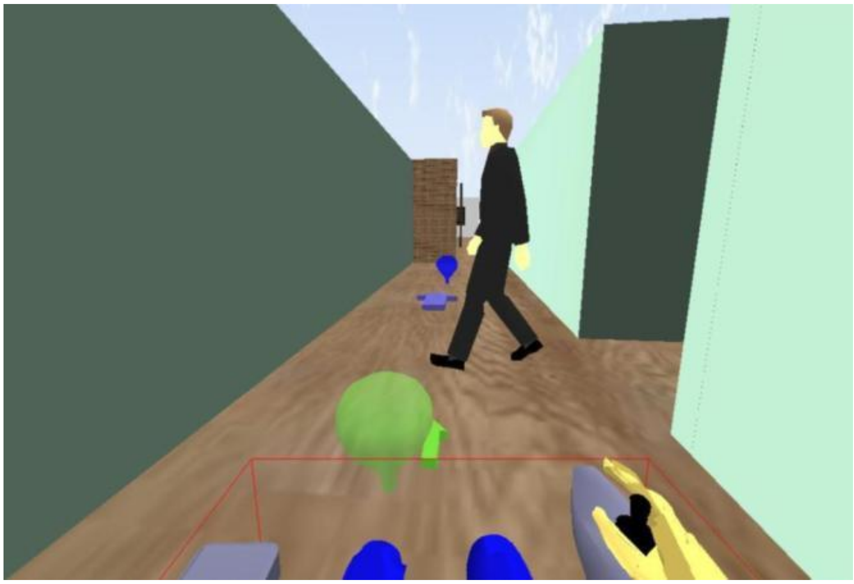


Figure B. 17: Task 14-Avoid unexpected obstacles (person entering hallway)

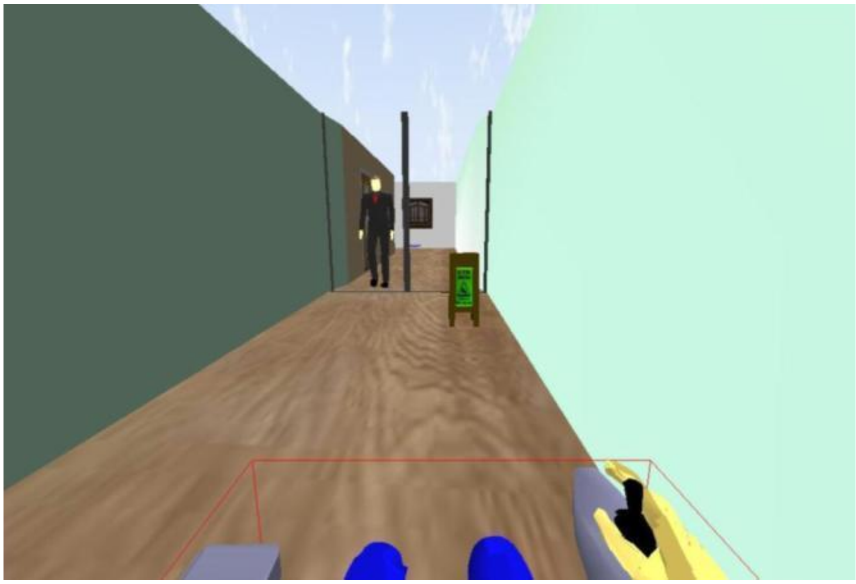


Figure B. 18: Sharing public space with (Task 15) One person coming towards participant in hallway and (Task 16) "Wet floor" sign, crossing to wait or speed up

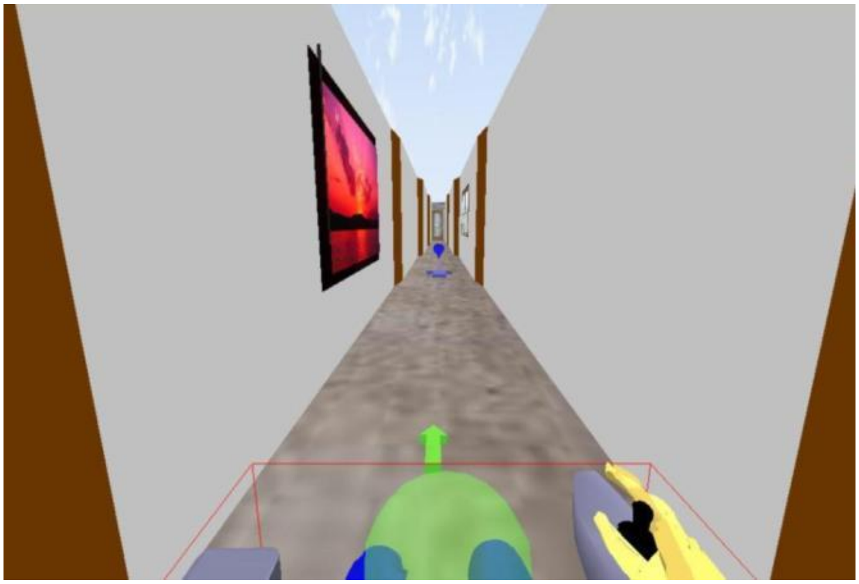


Figure B. 19: Decreasing hallway

APPENDIX C

MATLAB CODE TO DERIVE AUTOMATED PMRT SCORES

```
function [sc_Safety sc_AccuracySafety] = autoPMRT(dat, mstones,vWClen,
header, reactTime)
%dat: Raw data read from trial file. Has following fields
% gets part of raw data and milestones from VRsimdata
%Fields in dat: DeltaT  JstkX   JstkY   ModelAngVel ModelSpeed  ...
%               RealWCAngVel    RealWCspeed ChairX  ChairY  ChairTh ...
%               ClosestX    ClosestY    Deviation   WalkerX WalkerY ...
%               GaveInstruction Collision   Milestone#  EncLeft EncRight
% mstones: Has x,y coordinates of all 35 milestones part of the VRSim PMRT
driving circuit.
% vWClen: width of the virtual wheelchair (meters)
% header: header from the trial file
% reactTime: Reaction time derived when the trial starts

METER2FEET= 3.2808;
sc_Safety = zeros(20,1); %20 for the 20 tasks of interest
sc_AccuracySafety = zeros(20,1); %20 for the 20 tasks of interest
collPerTask = zeros(17,1); %Number of collisions for all tasks.
taskIndex = zeros(17,2); %Index of beginning(coloumn1) and end(coloumn2) of
every task
currms = 1;
msIndex = 1; % Index in data where milestone change occurs for all 35
milestones
for i=2:1:length(dat(:,18))
    if dat(i,18)== currms+1
        msIndex(end+1) = i;
        currms = currms+1;
    end;
end;
%Structured Tasks
taskIndex(1,:) = [msIndex(9) msIndex(11)-1]; %Approaching people/furniture
without bumping into them
taskIndex(2,:) = [1 1]; %Starting and stopping the WC at will
taskIndex(3,:) = [msIndex(16) msIndex(17)-1];%Passing through 36" doorway
without hitting walls
taskIndex(4,:) = [msIndex(10) msIndex(12)-1]; %Turning right around a 90deg
corner
```

```
taskIndex(5,:) = [msIndex(13) msIndex(15)-1]; %Turning left around a 90deg
corner
taskIndex(6,:) = [msIndex(2) msIndex(3)-1]; %Driving straight forward 15ft in
open area
taskIndex(7,:) = [msIndex(3) msIndex(4)-1]; %Driving straight backward 10ft
in open area
taskIndex(8,:) = [msIndex(10) msIndex(11)-1]; %Turning around 180deg
taskIndex(9,:) = [msIndex(21) msIndex(23)-1]; %Starting and stopping upon
request- Index only for "STOP"."MS23" is required
taskIndex(10,:) = [msIndex(4) msIndex(8)-1]; %Turning right and left upon
command- Contains both left and right turns
taskIndex(11,:) = [msIndex(15) msIndex(16)-1]; %Driving straight forward 15ft
in narrow corridor without hitting walls-actually 12ft
taskIndex(12,:) = [msIndex(17) msIndex(22)-1];%Maneuver between objects
%Dynamic Tasks
taskIndex(13,:) = [msIndex(25) msIndex(26)-1]; %Avoid unexpected obstacles --
bouncing ball
taskIndex(14,:) = [msIndex(24) msIndex(25)-1]; %Avoid unexpected obstacles --
person entering hallway
%Sharing public space
taskIndex(15,:) = [msIndex(27) msIndex(28)-1]; %One person coming towards
participant in a hallway
taskIndex(16,:) = [msIndex(27) msIndex(28)-1]; %"Wet floor" sign, crossing to
wait or speed up
taskIndex(17,:) = [msIndex(30) msIndex(35)]; %Decreasing Hallway

door = [45.5 -73.5]/METER2FEET; %Check door coordinates
flag = false;
for i=msIndex(16):1:msIndex(17)-1
     if(~flag)
         if fDist(door, dat(i,11:12)) <= vWClen
            flag = true;
            startDoor = i;
         end
     end;
    if (flag)
        if fDist(door, dat(i,11:12)) > vWClen
            endDoor = i;
            break;
        end;
    end;
end;
collPerTask(1) = sum(dat(msIndex(17):msIndex(18)-1,17));
%This is done to add another section of trajectory to Task1: Approaching
furniture
collPerTask(3) = sum(dat(startDoor: endDoor,17));
for i = 1:1:length(taskIndex)
    if i~= 3
        collPerTask(i) = collPerTask(i)+
sum(dat(taskIndex(i,1):taskIndex(i,2),17));
    end;
    if collPerTask(i)> 4
        sc_Safety(i) = 1;          %Lowest safety rating
        sc_AccuracySafety(i) = 0.125;
    else
        if collPerTask(i)> 2  %3 or 4
            sc_Safety(i) = 2;
```

```
            sc_AccuracySafety(i) = 0.25;
        else
            if collPerTask(i)> 0 %1 or 2
                sc_Safety(i) = 3;
                sc_AccuracySafety(i) = 0.375;
            else
                sc_Safety(i) = 4;                    %Highest safety rating
                sc_AccuracySafety(i) = 0.5;
            end;
        end;
    end;
end;
%No tolerance if there is a collision with walking person
if collPerTask(14) ==1
    sc_Safety(14) = 2;
    sc_AccuracySafety(14) = 0.25;
else if collPerTask(14) >=2
    sc_Safety(14) = 1;
    sc_AccuracySafety(14) = 0.125;
    end;
end;
if collPerTask(15) ==1
    sc_Safety(15) = 2;
    sc_AccuracySafety(15) = 0.25;
else if collPerTask(15) >=2
    sc_Safety(15) = 1;
    sc_AccuracySafety(15) = 0.125;
    end;
end;
%Task 1:Approaching people/furniture without bumping into them
fur = [45.6 -26.5; 45.6 -34.5]/METER2FEET; %furniture coordinates (45.6,-
33.2) and (45.6,-27.8)
%for subjects 1 and 2 detection radius was much smaller for this task and
%this milestone was less intuitive. Hence compensating
if header.id <=2
    fur(:,1) = fur(:,1) - 0.5/METER2FEET;
end;
furdx = fur(1,1) -fur(2,1);
furdy = fur(1,2) -fur(2,2);
%Neglecting first 30 points to remove a turn in trajectory
dist = zeros (taskIndex(1,2)- taskIndex(1,1)-30+ 1,1);
for i=taskIndex(1,1)+30 :1:taskIndex(1,2)
    dist(i-taskIndex(1,1)-30 +1,1) = abs(furdy*(fur(1,1)- dat(i,8))-
furdx*(fur(1,2)- dat(i,9)))...
        /sqrt(furdx*furdx + furdy*furdy);
end;
%Smallest threshold will be 0.8*vWClen from furniture edge consider a front
%impact with WC % dist = sortrows(dist,1); %sort distances
if find(dist(:,1)<= 0.8*vWClen) | collPerTask(1) == 1
    sc_AccuracySafety(1) = sc_AccuracySafety(1)+ 0.125;
else if find(dist(:,1)< vWClen)
        sc_AccuracySafety(1) = sc_AccuracySafety(1)+ 0.25;
    else if find(dist(:,1)< 1.3*vWClen)
        sc_AccuracySafety(1) = sc_AccuracySafety(1)+ 0.375;
        else
            sc_AccuracySafety(1) = sc_AccuracySafety(1)+ 0.5;
        end;
```

```
    end;
end;
clear dist;
%Task2: Starting and stopping the WC at will
sc_AccuracySafety(2) = sc_AccuracySafety(2)+ 0.5;
%Task3: Passing through 36" doorway without hitting walls
%Door between startDoor and endDoor
%Mean Absolute Deviation; max allowable = (3-vWClen)/2
dist = mean(abs(dat(startDoor:endDoor,13)));
if sum(dat(startDoor:endDoor,17)) >=2
    sc_AccuracySafety(3) = sc_AccuracySafety(3)+ 0.125;
else if sum(dat(startDoor:endDoor,17)) ==1
        sc_AccuracySafety(3) = sc_AccuracySafety(3)+ 0.25;
    else if dist >= (3/METER2FEET-vWClen)/4
            sc_AccuracySafety(3) = sc_AccuracySafety(3)+ 0.375;
        else    sc_AccuracySafety(3) = sc_AccuracySafety(3)+ 0.5;
        end;
    end;
end;

%Task4: Turning right around a 90deg corner
sc_AccuracySafety(4) = sc_AccuracySafety(4)+ evalTurn(dat, taskIndex(4,1:2),
mstones(10,2:3),vWClen, -90);

%Task5: Turning left around a 90deg corner
sc_AccuracySafety(5) = sc_AccuracySafety(5)+ evalTurn(dat, taskIndex(5,1:2),
mstones(13,2:3),vWClen, 90);

%Task 6: Driving straight forward 15ft in an open area
[numDirChange, numLoops] =
getDirnChange(dat(taskIndex(6,1):taskIndex(6,2),10),5,0.1, '');
%half of accuracy score comes from "Deviation" and half from number of
direction changes
clear dist;
%Mean Absolute Deviation
dist = mean(abs(dat(taskIndex(6,1):taskIndex(6,2),13)));
if (dist<= vWClen/2)
    sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.25;
else if(dist <= vWClen)
        sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.375/2;
    else if (dist <= 2*vWClen)
        sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.25/2;
        else
            sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.125/2;
        end;
    end;
end;
if (numDirChange<= 5)
    sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.25;
else if(numDirChange <= 10)
        sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.375/2;
    else if (numDirChange <= 15)
        sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.25/2;
        else
            sc_AccuracySafety(6) = sc_AccuracySafety(6)+ 0.125/2;
        end;
```

```
    end;
end;

%Task 7: Driving straight backwards 10ft in an open area
[numDirChange, numLoops] =
getDirnChange(dat(taskIndex(7,1):taskIndex(7,2),10),5,0.1, '');
dist = mean(abs(dat(taskIndex(7,1):taskIndex(7,2),13))); %mean absolute
deviation

if (dist<= vWClen/2)
    sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.25;
else if(dist <= vWClen)
        sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.375/2;
    else if (dist <= 2*vWClen)
        sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.25/2;
        else
            sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.125/2;
        end;
    end;
end;
if (numDirChange<= 5)
    sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.25;
else if(numDirChange <= 10)
        sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.375/2;
    else if (numDirChange <= 15)
        sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.25/2;
        else
            sc_AccuracySafety(7) = sc_AccuracySafety(7)+ 0.125/2;
        end;
    end;
end;

%Task8: Turning around 180deg
clear dtheta;
dtheta = mean(dat(taskIndex(8,1):taskIndex(8,1)+5,10))-
mean(dat(taskIndex(8,2)-5:taskIndex(8,2),10)); %this angle is +ve
dtheta = round(wrapTo180(dtheta));
%Best is if angle is more than 135deg
if dtheta>135
    sc_AccuracySafety(8) = sc_AccuracySafety(8)+ 0.5;
else if ismember(dtheta, 90:135)
        sc_AccuracySafety(8) = sc_AccuracySafety(8)+ 0.375;
    else if ismember(dtheta, 45:90)
            sc_AccuracySafety(8) = sc_AccuracySafety(8)+ 0.25;
        else
            sc_AccuracySafety(8) = sc_AccuracySafety(8)+ 0.125;
        end;
    end;
end;
%Task 9: %Starting and stopping upon request- Index only for "STOP"
if reactTime < 3
    sc_AccuracySafety(9) = sc_AccuracySafety(9)+ 0.25;
else
    sc_AccuracySafety(9) = sc_AccuracySafety(9)+ 0.125;%0.25 for starting WC
end;
    %Determines the "center" time instant while giving "STOP" instruction
```

```
instr = taskIndex(9,1) + find(dat(taskIndex(9,1):taskIndex(9,2),16))-1; %Last
point where instruction
instr = round(mean(instr));
%Detects where the chair stops after the "STOP" instruction: Speed < 0.05
switch(header.mode)
    case {1,2}
        if(find(dat(instr:taskIndex(9,2),5)<0.05))    sc_AccuracySafety(9) =
sc_AccuracySafety(9)+ 0.25;
        end;
    case 3
        if(find(dat(instr:taskIndex(9,2),7)<0.05))     sc_AccuracySafety(9) =
sc_AccuracySafety(9)+ 0.125;
        end;
end;
%task10: Turning right and left upon command- Contains both left and right
turns
scoreR  = evalTurn(dat, taskIndex(10,1:2), mstones(4,2:3),vWClen, -
90);%[scoreR dtl]
scoreL  = evalTurn(dat, taskIndex(10,1:2), mstones(6,2:3),vWClen, 90);
%[scoreL dtr]
sc_AccuracySafety(10) = sc_AccuracySafety(10)+ (scoreL + scoreR)/2;

%Task11: Driving straight forward 15ft in narrow corridor without hitting
walls-actually 12ft
[numDirChange, numLoops] =
getDirnChange(dat(taskIndex(11,1):taskIndex(11,2),10),1,0.1, '');
%half of accuracy score comes from "Deviation" and half from number of
direction changes
clear dist;
dist = mean(abs(dat(taskIndex(11,1):taskIndex(11,2),13)));
if (dist<= vWClen/4)
    sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.5/2;
else if(dist <= vWClen/2)
        sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.375/2;
    else if (dist <= vWClen*0.75)
        sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.25/2;
        else
            sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.125/2;
        end;
    end;
end;
if (numDirChange<= 5)
    sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.25;
else if(numDirChange <= 10)
        sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.375/2;
    else if (numDirChange <= 15)
        sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.25/2;
        else
            sc_AccuracySafety(11) = sc_AccuracySafety(11)+ 0.125/2;
        end;
    end;
end;

%Task 12: Maneuver in crowded office space
[numDirChange, numLoops] =
getDirnChange(dat(taskIndex(12,1):taskIndex(12,2),10),5, 0.1,'');
```

```
if (numDirChange<= 10)
    sc_AccuracySafety(12) = sc_AccuracySafety(12)+ 0.5;
else if(numDirChange <= 20)
        sc_AccuracySafety(12) = sc_AccuracySafety(12)+ 0.375;
    else if (numDirChange <= 30)
        sc_AccuracySafety(12) = sc_AccuracySafety(12)+ 0.25;
        else
            sc_AccuracySafety(12) = sc_AccuracySafety(12)+ 0.125;
        end;
    end;
end;

%Task13: Avoid unexpected obstacles -- bouncing ball
%This task takes place in a 8ft wide hallway. Ball bounces in center of
%hallway with
%Take the average deviation from centerline between wall and ball
%while chair is crossing the bouncing ball. Approx +/- 3*vWClen around ball
BBx = mstones(24,2) + (1+ header.ballRand)*(mstones(25,2)-
mstones(24,2))/3/METER2FEET;
BBy = mstones(24,3);
dist =0;%dist = [0 0 0];
for i=taskIndex(13,1):1:taskIndex(13,2)
    if abs(BBx - dat(i,8)) <= vWClen
        dist(end+1,:) = fDist(dat(i,8:9), [BBx, BBy]);
    end;
end;
dist(1) = [];

dist = dist-(0.5+(4 - 0.5)/2)/METER2FEET;
dist = abs(mean(dist));
%Note this is deviation from centerline between ball and wall; Hence lower
the better.
%The "wiggle room" is just 1.2ft = 0.522*vWC!
if collPerTask(13) sc_AccuracySafety(13) = sc_AccuracySafety(13)+ 0.125;
else
    if (dist<= vWClen*0.25)
        sc_AccuracySafety(13) = sc_AccuracySafety(13)+ 0.5;
    else if(dist <= vWClen*0.375)
            sc_AccuracySafety(13) = sc_AccuracySafety(13)+ 0.375;
        else if (dist <= vWClen*0.5)
            sc_AccuracySafety(13) = sc_AccuracySafety(13)+ 0.25;
            else
                sc_AccuracySafety(13) = sc_AccuracySafety(13)+ 0.125;
            end;
        end;
    end;
end;
%Task14: Avoid unexpected obstacles -- person entering hallway
%0.2 is the half of the shoulder to shoulder width of WalkingMan
clear dist;
for i=taskIndex(14,1):1:taskIndex(14,2)
    dist(i-taskIndex(14,1)+1) = fDist(dat(i,8:9), dat(i,14:15));
end;
dist = sort(dist,'ascend');
dist = dist(1,1); %The smallest distance WC is away from walking man
%for diagonal impact WC center is 0.8*vWC away from vertex of bounding rect
```

```
%0.5 is half of WalkingMan's bounding volume
if (dist<= vWClen*0.9 +0.5) | collPerTask(14)
    sc_AccuracySafety(14) = sc_AccuracySafety(14)+ 0.125;
else if(dist <= vWClen*1.5 +0.5)
        sc_AccuracySafety(14) = sc_AccuracySafety(14)+ 0.25;
    else if (dist <= vWClen*2 +0.5)
        sc_AccuracySafety(14) = sc_AccuracySafety(14)+ 0.375;
        else
            sc_AccuracySafety(14) = sc_AccuracySafety(14)+ 0.5;
        end;
    end;
end;

%Task15: One person coming towards participant in a hallway
clear dist;
for i=taskIndex(15,1):1:taskIndex(15,2)
    dist(i-taskIndex(15,1)+1) = fDist(dat(i,8:9), dat(i,14:15));
end;
dist = sort(dist,'ascend');
dist = dist(1,1); %The smallest distance WC is away from walking man
%0.5 is half of WalkingMan's bounding volume, 0.25 is half of shoulder to
%shoulder distance; talking average here
if (dist<= vWClen*0.5 + 0.375) | collPerTask(15)
    sc_AccuracySafety(15) = sc_AccuracySafety(15)+ 0.125;
else if(dist <= vWClen*0.75 + 0.375)
        sc_AccuracySafety(15) = sc_AccuracySafety(15)+ 0.25;
    else if (dist <= vWClen + 0.375)
        sc_AccuracySafety(15) = sc_AccuracySafety(15)+ 0.375;
        else
            sc_AccuracySafety(15) = sc_AccuracySafety(15)+ 0.5;
        end;
    end;
end;

%Task16: "Wet floor" sign, crossing to wait or speed up
%This is a 8ft wide hallway
SignX = 68/METER2FEET; SignY = -109/METER2FEET;
%Edge coordinates of sign (68, -108.5) (68, -109.5)
clear dist;
for i=taskIndex(16,1):1:taskIndex(16,2)
    dist(i-taskIndex(16,1)+1) = fDist(dat(i,8:9), [SignX SignY]);
end;
dist = abs(mean(dist));
%0.5 is the half of width of the "Wet floor" sign
if (dist<= vWClen + 0.5) | collPerTask(16)
    sc_AccuracySafety(16) = sc_AccuracySafety(16)+ 0.125;
else if(dist <= vWClen*1.5 + 0.5)
        sc_AccuracySafety(16) = sc_AccuracySafety(16)+ 0.25;
    else if (dist <= vWClen*2 + 0.5)
        sc_AccuracySafety(16) = sc_AccuracySafety(16)+ 0.375;
        else
            sc_AccuracySafety(16) = sc_AccuracySafety(16)+ 0.5;
        end;
    end;
end;
```

```
%Task 17: Decreasing Hallway
clear dist;
dist = mean(abs(dat(taskIndex(17,1):taskIndex(17,2),13)));
if (dist<= vWClen/4)
    sc_AccuracySafety(17) = sc_AccuracySafety(17)+ 0.5;
else if(dist <= vWClen/2)
        sc_AccuracySafety(17) = sc_AccuracySafety(17)+ 0.375;
    else if (dist <= vWClen*0.75)
        sc_AccuracySafety(17) = sc_AccuracySafety(17)+ 0.25;
        else
            sc_AccuracySafety(17) = sc_AccuracySafety(17)+ 0.125;
        end;
    end;
end;

sc_AccuracySafety = sc_AccuracySafety*4;
sc_Safety(18) =  sum(sc_Safety(1:12))/48; %Element score
sc_Safety(19) =  sum(sc_Safety(13:16))/16; %Skilled score
sc_Safety(20) =  sum(sc_Safety(1:16))/64; %Total score
sc_AccuracySafety(18) =  sum(sc_AccuracySafety(1:12))/48; %Element score
sc_AccuracySafety(19) =  sum(sc_AccuracySafety(13:16))/16; %Skilled score
sc_AccuracySafety(20) =  sum(sc_AccuracySafety(1:16))/64; %Total score
end
```

APPENDIX D

VIRTUAL POWER MOBILITY ROAD TEST TASKS FROM THE USER'S PERSPECTIVE (FOR CHAPTER 7)

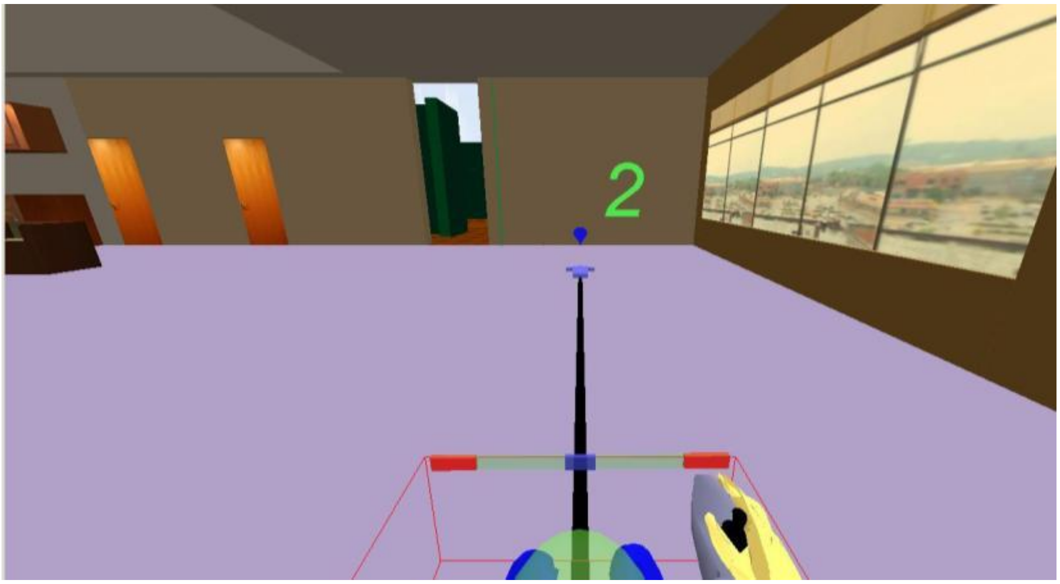


Figure D. 1: Starting the wheelchair upon request

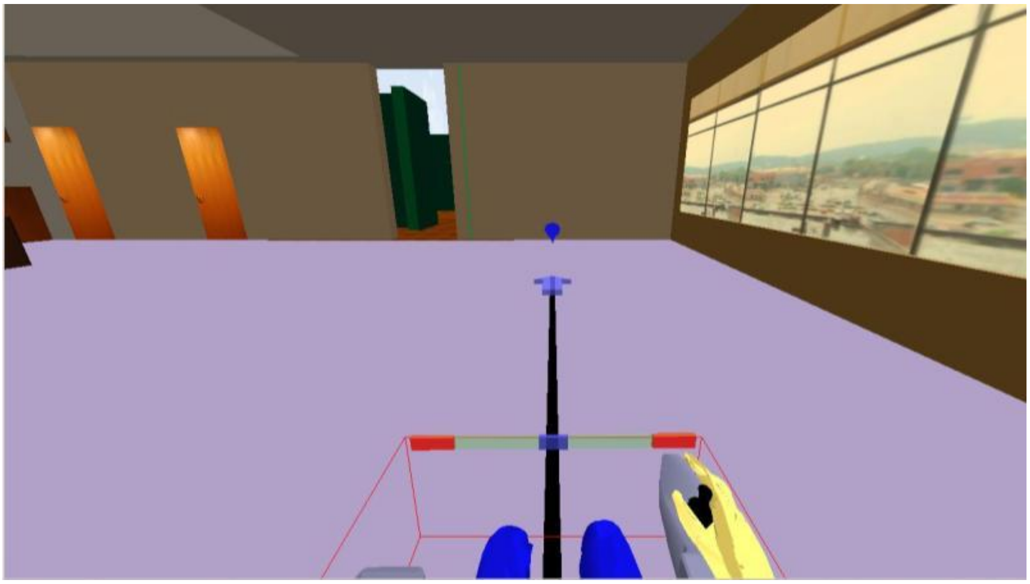


Figure D. 2: Driving straight forward (15 ft) in an open area

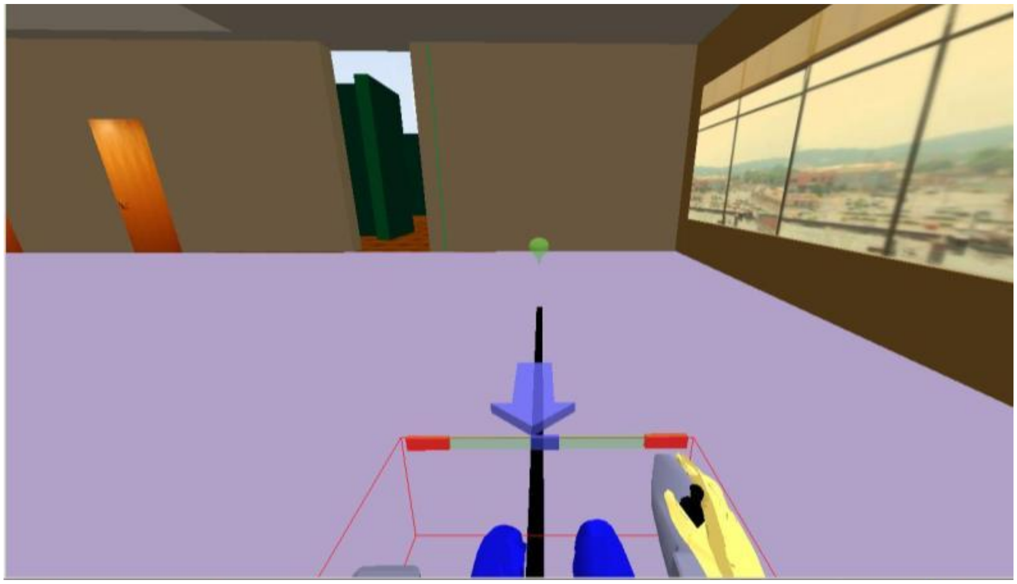


Figure D. 3: Driving straight backward (10 ft) in an open area

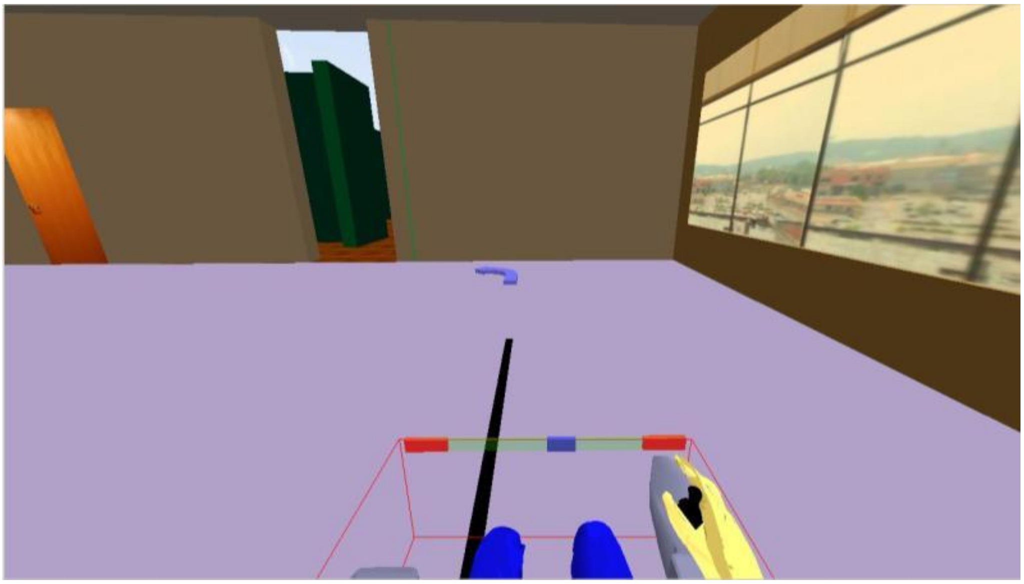


Figure D. 4: Turning left upon command

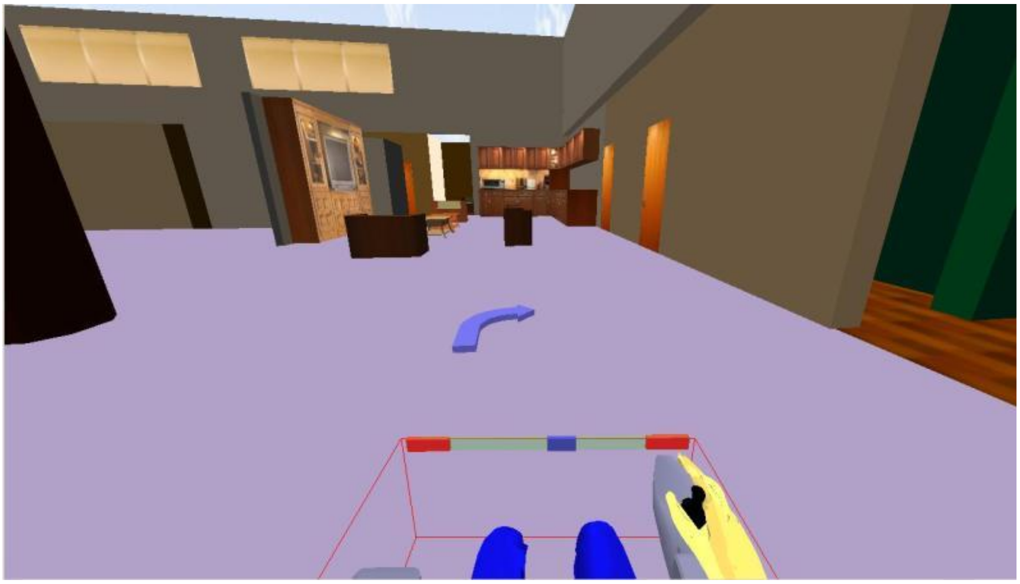


Figure D. 5: Turning right upon command

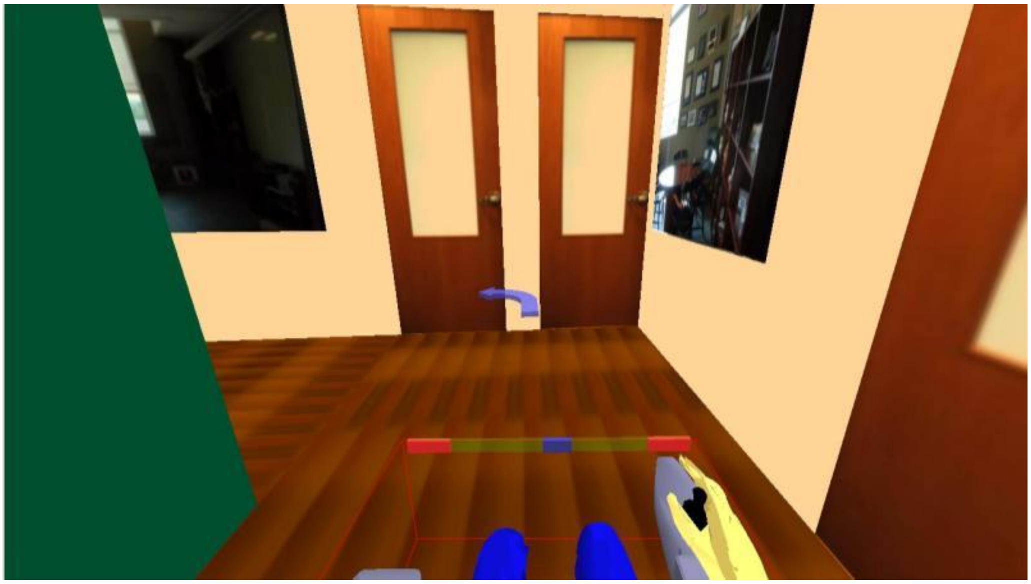


Figure D. 6: Completes a 90° left hand turn

Figure D. 7: Driving straight forward (15 ft) in a narrow corridor without hitting

Figure D. 8: Stop the wheelchair upon command

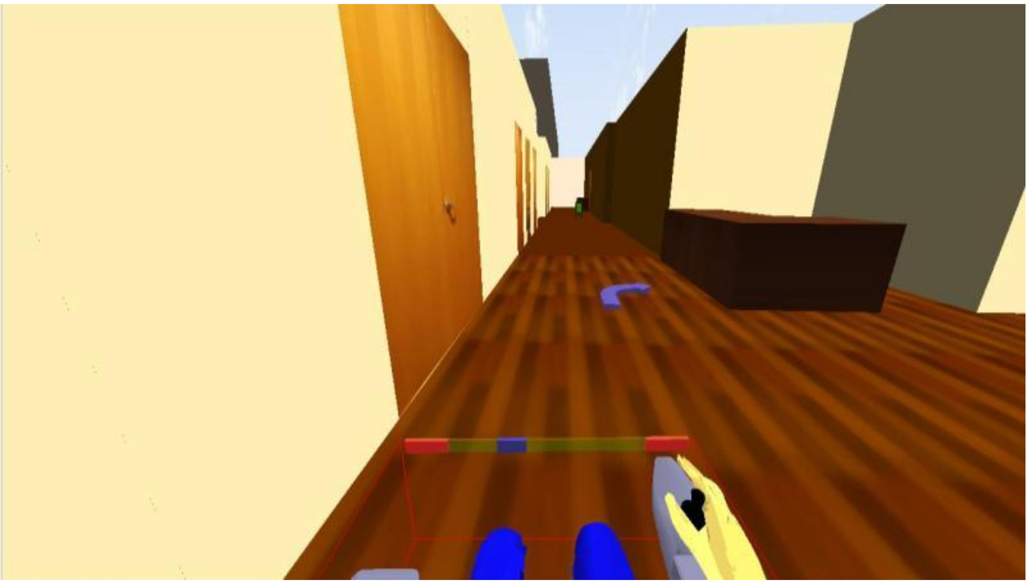


Figure D. 9: Completes a 90° right hand turn

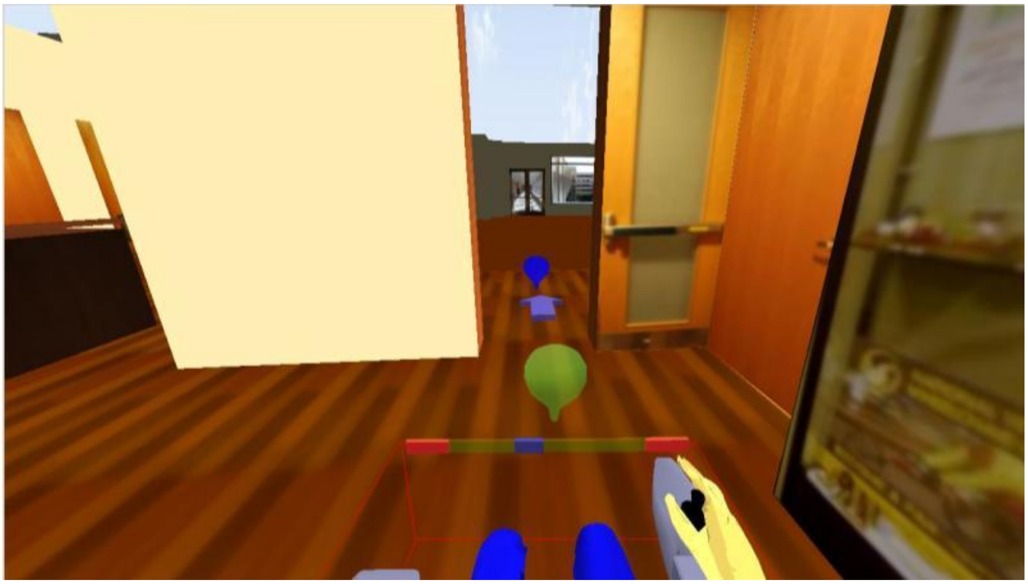


Figure D. 10: Passing through doorways without hitting walls (36" doorways)

Figure D. 11: Safely completes 180° turn

Figure D. 12: Approaching people/Furniture without bumping into them

Figure D. 13: Avoid unexpected obstacles (person entering hallway)

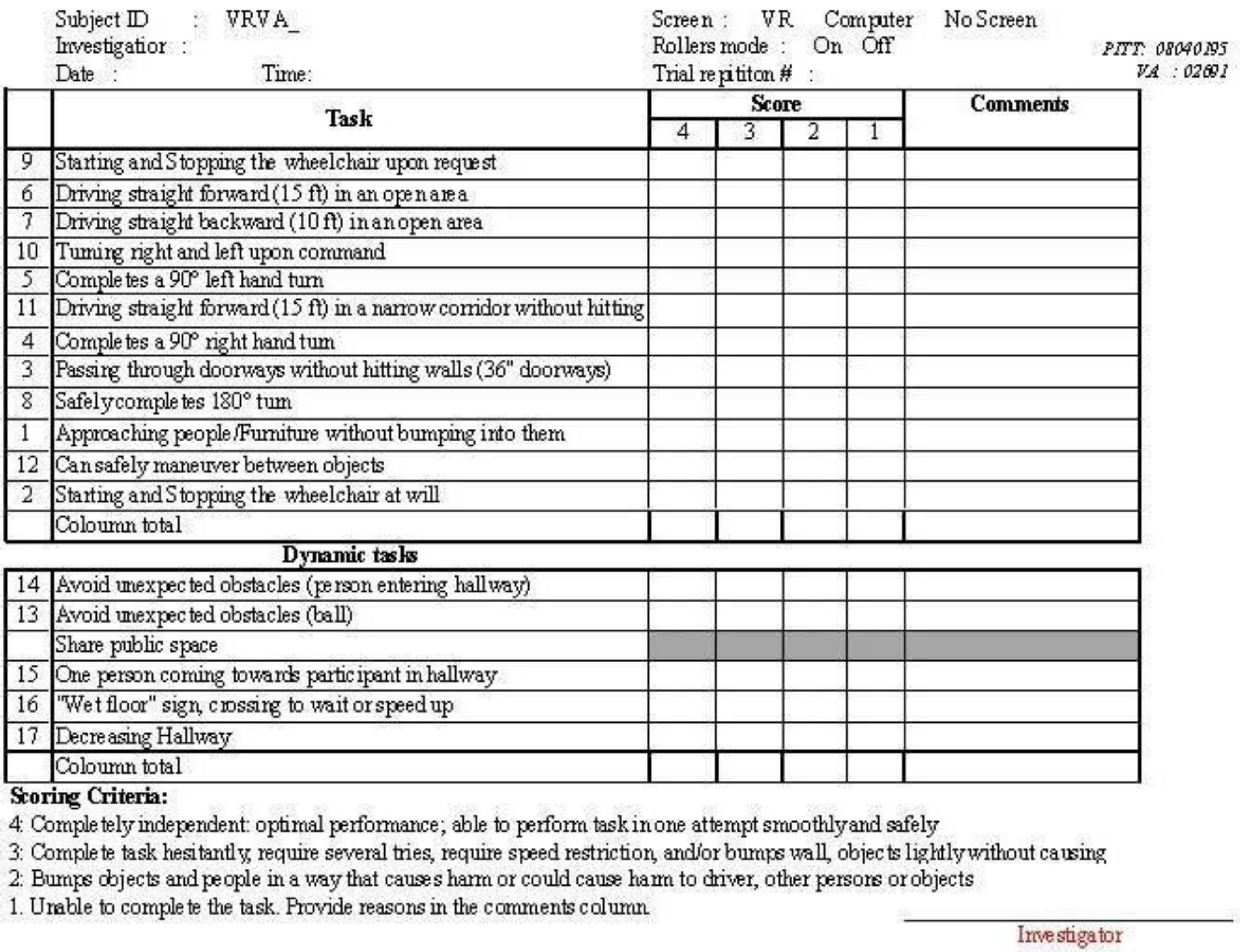
Figure D. 14: Avoid unexpected obstacles (ball)

Figure D. 15: Share public space. Wet floor sign and person walking towards the subject

Figure D. 16: Can safely maneuver between objects

Figure D. 17: Can safely maneuver between objects

Figure D. 18: Decreasing Hallway



Subject ID : VRVA_
Investigatior :
Date : Time:

Screen : VR Computer No Screen
Rollers mode : On Off
Trial repititon # :

PITT: 08040195
VA : 02691

	Task	Score				Comments
		4	3	2	1	
9	Starting and Stopping the wheelchair upon request					
6	Driving straight forward (15 ft) in an open area					
7	Driving straight backward (10 ft) in an open area					
10	Turning right and left upon command					
5	Completes a 90° left hand turn					
11	Driving straight forward (15 ft) in a narrow corridor without hitting					
4	Completes a 90° right hand turn					
3	Passing through doorways without hitting walls (36" doorways)					
8	Safely completes 180° turn					
1	Approaching people/Furniture without bumping into them					
12	Can safely maneuver between objects					
2	Starting and Stopping the wheelchair at will					
	Coloumn total					

Dynamic tasks

14	Avoid unexpected obstacles (person entering hallway)					
13	Avoid unexpected obstacles (ball)					
	Share public space					
15	One person coming towards participant in hallway					
16	"Wet floor" sign, crossing to wait or speed up					
17	Decreasing Hallway					
	Coloumn total					

Scoring Criteria:

4: Completely independent: optimal performance; able to perform task in one attempt smoothly and safely
3: Complete task hesitantly, require several tries, require speed restriction, and/or bumps wall, objects lightly without causing
2: Bumps objects and people in a way that causes harm or could cause harm to driver, other persons or objects
1. Unable to complete the task. Provide reasons in the comments column

Investigator

Figure D. 19Virtual Power Mobility Road Test scoring sheet

APPENDIX E

FEW PICURES FROM REAL WORLD POWER MOBILITY ROAD TEST TRACK

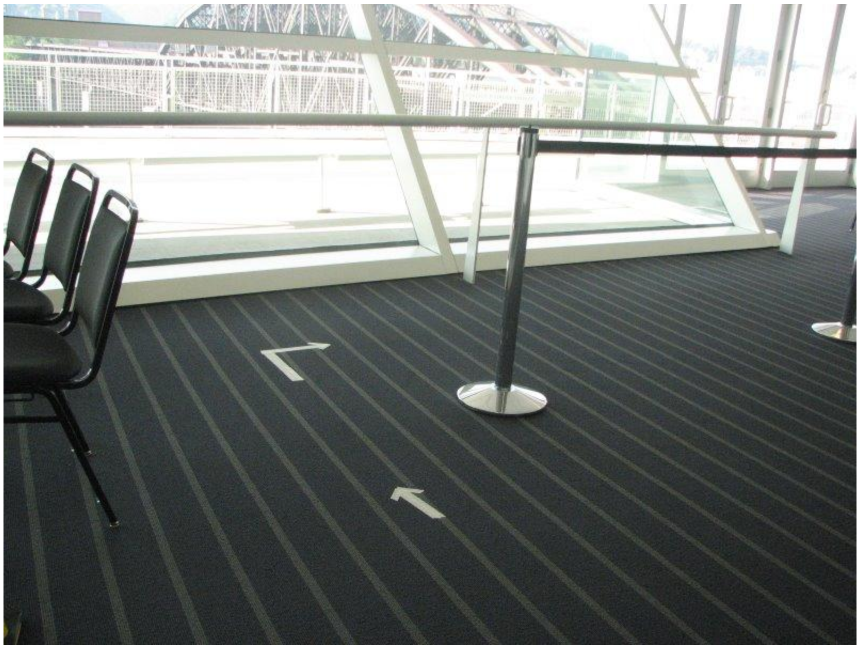


Figure E. 1: Arrows placed on floor to show direction of travel

Figure E. 2: Task to turn around 180 degrees

Figure E. 3: Task to turn right

Figure E. 4: Task to navigate between obstacles. Subject is asked to navigate chair around each cone. Rest of the space is used to complete open space tasks such as drive straight and reverse, turn left and right on command.

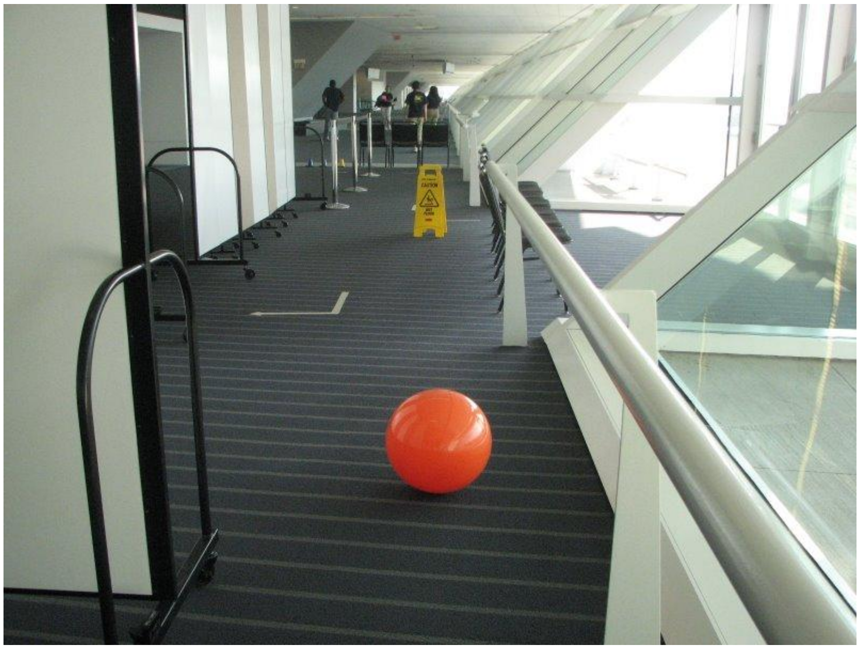


Figure E. 5: Hallway used to complete the skilled driving tasks such as sharing hallway with a walking man and avoid unexpected obstacles.