Usability Evaluation of a Self-Levelling Robotic Wheelchair for Tip Prevention in Outdoor Environments

by

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Tips and falls are the most prominent causes of wheelchair accidents in the US when driving on uneven terrains and non-accessible environments. The Mobility Enhancement Robotic Wheelchair (MEBot) was designed to tackle these environmental challenges and address the mobility limitations of conventional electric-powered wheelchairs (EPW).

MEBot offers a self-leveling application to maintain a stable seat in uneven terrains with the use of position sensors at each wheel and an attitude sensor to move each wheel accordingly. The self-leveling application can be enabled/disabled via a switch.

The goal of the study was to perform a usability evaluation of MEBot's self-leveling application in terms of the wheelchair's performance and the participant's perception. Ten participants were asked to drive their own EPW and MEBot through a driving course that simulated outdoor environmental obstacles for five times in each device.

The wheelchair's performance hypotheses included MEBot's ability to be safe by maintaining a lower change in seat angle change than participants' EPWs and MEBot's self-leveling time would be within or lower than an average person's walking speed. Additionally, it was hypothesized that participants would score better on the NASA-TLX and QUEST assessment tools for MEBot than their own EPW.

Results showed that MEBot has lower angle change when going up and down a 10° slope; MEBot (5.6° ± 1.6°, 6.6° ± 0.5°) than their own wheelchair (14.6° ± 2.6°, 12.1° ± 2.6°) absolute deviation going up and down the slope, respectively. This contrasts with the participants' EPWs

when ascending and descending both slopes as MEBot required a longer time (7.8 ± 3.0 seconds) with a greater angle change when driving over an obstacle. The participant's perception towards each EPW favored MEBot with respect to the NASA TLX and QUEST than their own wheelchair based upon the interpretation of the written feedback.

The results demonstrated that the self-leveling application can work effectively but it is hindered by mechanical limitations. Future work will involve a redesign with electro-hydraulic actuators to mitigate this mechanical limitation and similar usability evaluation to evaluate MEBot improvements.

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1.0 Introduction

The Electric Powered Wheelchair (EPW) is a vital mobility device used by people with physical limitations (Mortenson WB, Hammell KW, Luts A, Soles C, & Miller WC, 2015). EPWs provide mobility and participation in the community to improve the quality of life (Edwards K & McCluskey A, 2010). The U.S. Census Bureau's Economics and Statistics Administration reported 5.5 million wheelchair users in 2014 (Taylor DM, 2014). Approximately 9-15% of this population benefits from an EPW (Flagg J, 2009). Additionally, aging baby boomers and increasing life expectancy correlate to annual growth of 5% in the EPW market in the US alone (LaPlante MP & Kaye HS, 2010). Further, there has been a sudden influx of veterans (Central US Army, 2018).

1.1 Challenges with Electric Powered Wheelchairs

EPW users are exposed to all types of terrain and conditions if they venture outside of their homes, to be an active member of society. Terrains and conditions may include slippery slopes, uneven surfaces, compound slopes, curbs and steps (Gavin-Dreschnack D et al., 2005). This has an impact on driving performance, possibly leading to tips and falls and consequently hospitalization. Dynamics analysis of tips and falls has shown that shallower approach angles (25^{o}) were the "most significant predicators of tipping for restrained passengers" but not affected by speed (Erickson B et al., 2016).

A study with 95 participants reported that 87% of wheelchair users have at least one tip or fall in the past three years (Chen W-Y et al., 2011) and Xiang H et al reported 65% - 80% of

100,000 wheelchair user accidents accounted for tips and falls across all age groups (Xiang H, Chany AM, & Smith GA, 2006). In 2005, it was estimated that it could cost $25,000-$75,000 including rehabilitation per incident for wheelchair-related falls (Gavin-Dreschnack et al., 2005). Health spending growth from 2005-2010 in the US showed an average growth of 4.3% and 5.3% from 2010-2018 (Sawyer B & Cox C, 2018). Due to this rising healthcare inflation, it was estimated that the cost of wheelchair-related accidents was roughly $27,460 to $82,371 per incident in 2018.

1.2 Alternative EPWs

Conventional EPWs exist in front-, mid-, and rear-wheel drive configurations. A study conducted by Koontz et al found that front wheel drive EPWs are intuitive for maneuverability, mid-wheel drive EPWs are used for maneuverability in confined spaces and rear wheeled drive EPWs are commonly known for driving at higher speeds (Koontz AM, Brindle ED, Kankipati P, Feathers D, & Cooper RA, 2010). A combination of all three wheel- drive positions would be ideal to tackle environmental obstacles, where it is advantageous for the motorized wheel to be in contact with the obstacle, creating traction. Salatin et al reported that intermittent loss of traction on EPW drive wheels can cause users to get stuck or slip thus making the wheelchair unstable (Salatin B, 2011). Figure 1 displays the Mobility Enhancement roBot (MEBot)' s ability to change the drive wheel configuration onto an obstacle for traction.

Figure 1: MEBot 's drive wheel configuration upon obstacles

The EPW user's weight distribution could be adjusting with the seating position whilst driving to maintain stability (Ding D et al., 2008). The self-leveling suspension is readily used in today's world, especially in cars when weight is concentrated to the rear, causing the front of the car to elevate and increasing work done on the brakes, tires and other components on the vehicle. The car could have self-leveling suspension lifts at the rear end in order to keep the chassis level and counter the work done (Fijalkowski B, 2011). A similar concept could be applied to EPWs to shift the center of gravity towards the front of the wheel when going up a hill or towards the back when going down a hill. There are currently devices in Research and Development (R&D) and commercially available devices that apply the same concept towards assistive mobility technology, for example, iBot, Observer Maximus and RT-Mover as shown in Table 1.

Table 1: Existing examples of Self-levelling wheelchairs

Device	iBot *(Mobility Mobius, 2019)*	Observer Maximus *(Observer Mobility, 2019)*	RT- Mover *(Nakajima Shuro, 2011)*
Drive Mechanism	4- wheel drive with roll actuators on front & back axles	2 drive wheels with 2 front casters	4-wheel drive
R&D / Commercially Available	Commercially Available	Commercially Available	Research & Development
Self-level mechanisms	Seat-based (Pitch only)	Seat-based (Pitch only)	Axle based (Pitch & Roll)
Limitations	Lack of lateral self-levelling Seating system not appropriate for EPW users	Lack of lateral self-levelling Large footprint Limited indoor maneuverability	Large footprint Limited indoor maneuverability

The two commercially available devices; in Table 1 self-level in the pitch direction. On the otherhand, the RT-Mover has range of motion of ± 30° pitch and roll, but has limited indoor mobility due its large footprint.

MEBot was developed by following a participatory action design process involving clinicians, engineers, and end-users (Daveler BJ et al., 2015). The MEBot includes six independent height-adjustable wheels and an interchangeable drive wheel configuration (front-, mid-, and rear-wheel drive). Its footprint is within the dimensions of a conventional EPW and incorporates similar features found on group 4 EPW designs such as tilt-in-space for pressure relief and seat elevation (Dicianno BE et al., 2009). Additionally, MEBot provides advanced mobility applications such as climbing/descending curbs up to 8.0 in. height to enhance accessibility and a self-leveling application to reduce the risk of tips and falls. Most of MEBot' s mass is concentrated in the base of the wheelchair which creates a lower center of gravity, thus increasing its stability. MEBot provides lateral and anterior tilt to keep the seat leveled in uneven terrains, transfers or provide the user the ability to reach for items on shelves.

The first generation of MEBot was a proof-of-concept evolved from design criteria based on a literature review with current EPWs' limitations when driving in everyday environments (Salatin B, 2011). A focus group evaluation with 12 active EPW users showed that 83% of the users would use the MEBot self-leveling application to tackle uneven terrains (Daveler BJ et al., 2015). In this study reported that 34.8% of users had tipped over with their EPW in common outdoor environments. This suggested a mechanical (pitch and roll range of $\pm 20^{o}$) and software re-design of the control system leading to the second generation of MEBot which was tested to comply with ANSI/RESNA engineering stability standards (Candiotti JL et al., 2017). In a survey study, Dicianno et al reported that 50.2% of 500 veterans with disabilities highlighted the need to develop wheelchairs that can self-adjust or can assist with overcoming obstacles (Dicianno BE et al., 2018). Previous MEBot self-leveling research studies were conducted through an engineering perspective but this study entailed additional input from end-users for the self-leveling application. The goal of this study was to perform a usability evaluation of the automated self-leveling application.

1.2.1 Hypotheses

The study presents two objectives: to evaluate the driving performance and the participant's perception towards MEBot in a controlled environment. The hypotheses for this study are formed from these terms; safety, effectiveness, satisfaction, and usability. The wheelchair's driving performance is measured in terms of safety and effectiveness whilst the participant's perception is measured in terms of usability and satisfaction.

1.2.1.1 Wheelchair's Driving Performance

Hypothesis 1: MEBot will have a lower change in seat angle compared to the participant's own wheelchair.

Rationale: Safety is determined by seat angle change from a threshold of ± 2.5°. The threshold region was formed from accounting a safety factor of two for an ADA standard accessible 4.7° ramp ((ADA), 2010).

Hypothesis 2 MEBot's self-leveling time will be within or below the average time walking speed (1.43m/s) when negotiating the obstacle.

Rationale: Effectiveness is the ability of the wheelchair to self-level by the required time taken to travel across the obstacle within the average walking speed of 1.43 m/s (Bohannon RW & Williams AA, 2011).

1.2.1.2 Participant's perception

Hypothesis 3: MEBot will score higher than the participant's own wheelchair through each NASA-TLX subscale score measuring the level of demand required to complete the obstacle course.

Rationale: Usability was described by the International Standardization for Standards (ISO:9241-11:2018), as the extent of a product that could be used by users to achieve specific goals for effectiveness, efficiency, and satisfaction gave a specified context (Standardization, 2018). Usability in this study adopts this concept, where the user would report the ease of use for both wheelchairs by evaluating the overall workload of the obstacle course.

Hypothesis 4: Participants will score higher on QUEST when evaluating the overall impression between MEBot and their own EPW.

Rationale: Satisfaction evaluates the overall impression from the user's perspective between the two wheelchairs of tackling the obstacle course.

2.0 Method

2.1 Self-levelling Algorithm

The self-leveling algorithm incorporated all six independent wheels as an expansion on Sundaram's and Candiotti's work (Candiotti JL et al., 2017; Sundaram SA, Candiotti JL, Wang H, & RA, 2016). The midpoint of the wheelchair frame uses a reference to define the origin of where the center of mass is located. Each of the six wheels provides the x, y, and z coordinates with respect to the center of the wheelchair frame as shown in Figure 2.

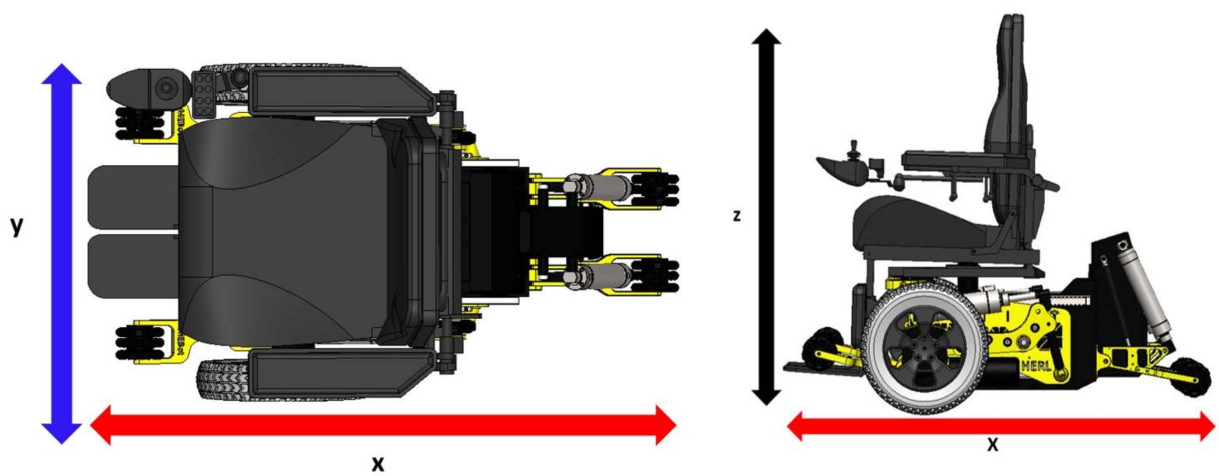


Figure 2: MEBot coordinate reference system

MEBot can be configured in real-time to front-, mid- and rear- wheel drive position. The 'home' position of the self-leveling was set to front-wheel drive for its benefits when driving outdoors (Koontz AM et al., 2010).

The desired positions were obtained by comparing the actual seat orientation to the desired seat orientation from an Inertial Measurement Unit (IMU) with the current seat angle obtained by the positions of the pneumatics. The difference between the angles is sent to a transformation matrix to obtain the desired position of the pneumatics (Candiotti JL et al., 2016). The driving wheel position moves in a geometric arc when elevating the chair and it was determined experimentally that the move in the x-plane was not significant (as it was within the acceptance range) to alter calculations for the desired wheel positions.

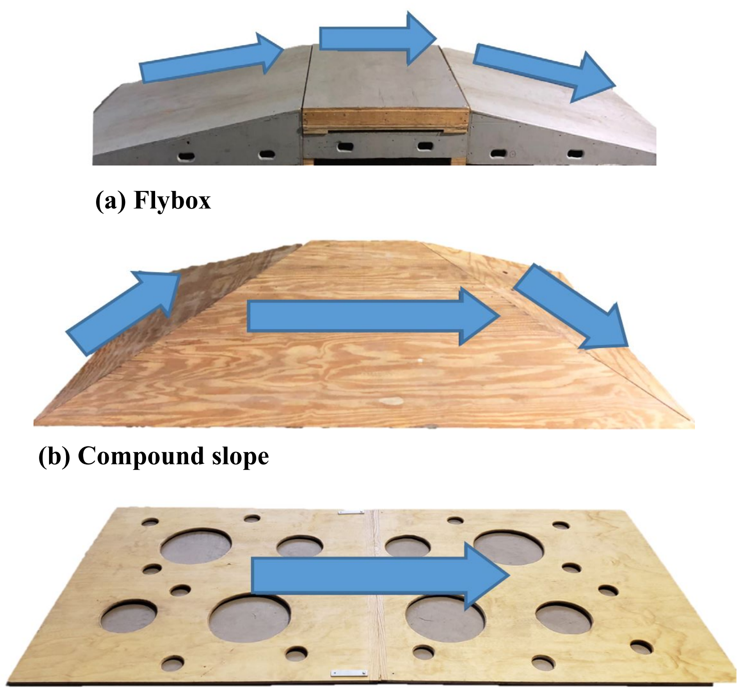
2.2 Inclusion/ Exclusion Criteria

To evaluate the self-leveling application, a usability evaluation was performed with EPW users comparing MEBot versus their own EPW. The inclusion/ exclusion criteria were constructed to ensure participant validity for the study and safe to participate from the National Veteran Wheelchair Games (NVWG) 2018 and at the Human Engineering Research Laboratories (HERL).

Participants who were older than 18 years old, weigh less than 113.4 kg (250 lbs.), able to tolerate sitting for 3 hours, have at least 1 year of experience using a power wheelchair indoor and outdoor environment, able to be properly fitted with the test wheelchair, and free of back, pelvic, or thigh pain limiting his/her sitting tolerance were recruited in the study.

2.3 Experimental Setup

The tasks represented a real-world environment that EPW users encounter daily. The tasks included: 10° fly box ramp, 8° compound slope, and a series of potholes (maximum diameter 12 inches and 1 inch in depth). The fly box ramp simulated conventional incline and decline ramps that were non-compliant with Americans with Disabilities Act (ADA) standards but used for RESNA's wheelchair standards for dynamic stability ((ADA), 2010; Rehabilitation Engineering & Assistive Technology Society of North America (RESNA), 2009). The 8° compound slope with ± 18° transition simulated a combination of compound slopes and curb cuts defined by the Cybathlon competition (Riener R, 2016). The last task simulated a series of potholes based upon a wheelchair skills test and which was 30.48 cm (12 inches) in diameter and 2.54 cm (1 inch) deep (Figure 3) (Rushton PW, Kirby RL, Routhier F, & Smith C, 2016).



(a) Flybox

(b) Compound slope

(c) Pot hole Obstacle

Figure 3: Outdoor environmental Obstacles

2.4 Protocol

The usability study was approved by the Institutional Review Board of Veteran Affairs (VA) Pittsburgh Healthcare System. The researcher first briefed and screened each participant to ensure that they consented with the study and satisfied the eligibility criteria. All participants were required to complete a demographics questionnaire. The order of which wheelchair was used first, was randomized prior to the protocol, to reduce bias. If MEBot was selected first, participants received training with MEBot. Participants were asked to drive MEBot during the training period until participants and researchers were comfortable with the participant's driving skills. Participants were asked to attempt each of the three obstacles over 5 trials (Figure 4). Participants were asked to complete the QUEST (Quebec User Evaluation of Satisfaction of Assistive Technology) prior and post executing the tasks with each wheelchair. At the end of the study, participants were asked to rate each wheelchair using the NASA-TLX (NASA Task Load Index).

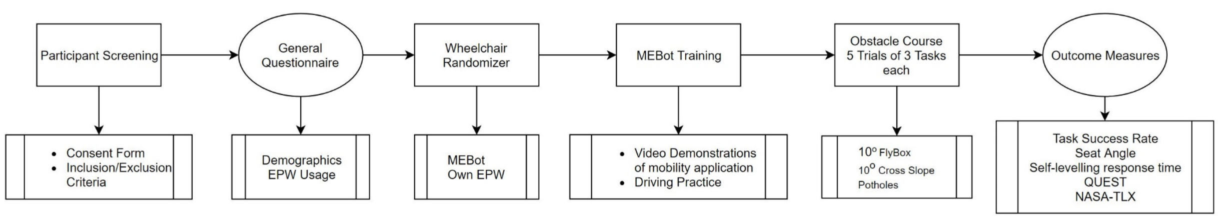


Figure 4: Self-Levelling Protocol

2.5 Variables

To analyze driving performance the seat angles (pitch and roll) were measured with the IMU sensor placed on MEBot and the participant's own EPW. The IMU sensor was placed on the base of the wheelchair as this was the most stable position. The IMU's pitch and roll values show the maximum seat angle's deviation from zero, the IMU was calibrated prior to starting the protocol. The IMU sampling rate was at 100 Hz and a complementary filter was used to evaluate the results.The response time was defined as how long it takes for the seat angle to come back within the threshold region of 2.5°. The participant's perception variables were the results obtained from NASA-TLX and QUEST.

2.5.1 NASA-TLX

The NASA-TLX is a workload measurement tool based on 6 subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart SG, 1986). These can be clustered into three categories; objective demand, behavior and psychological impact (Hart SG & Stavenland LE, 1988). This usability evaluation will analyze the 6 subscales individually and compared against the participant's own wheelchair.

The overall workload score is calculated by multiplying each raw value by the weight given to that factor by the participant. The sum of the weighted scores is then divided by 15 (total weights) to give an absolute workload score, which ranges between 0 and 100 (Noyes JM & Bruneau DPJ, 2007). Participants are also able to add further open-ended comments to each of the subscales and do not factor in the quantitative score.

The objective demand category is related to physical, mental, and temporal demand questions for the tasks. Behavior related questions such as 'performance' and 'effort' reflected the individual's subjective evaluation of the task. 'Frustration' measured the psychological impact on the individual. Higher scores do not necessarily coordinate to positive results, as questions were structured to make participants think about their response.

2.5.2 QUEST

QUEST is an assessment tool to measure user satisfaction with assistive technology (Demers L, Weiss-Lambrou R, & Ska B, 1996) ranking 8 questions in a 5-point Likert scale from "Not Satisfied at all", "Not very satisfied", "More or less satisfied", "Satisfied" to "Very Satisfied". QUEST can also be measured with respect to service delivery however this component of the assessment tool is irrelevant to the study. Scores on QUEST subdomains were calculated individually. These subdomains are dimensions, weight, ease of adjustment, safety, durability, ease of use, comfort, and if the device was effective for the participant's needs. The assessment tool was used for both wheelchairs and completed prior and post executing each task. Completing QUEST in this format allowed for differences to be highlighted between the participant's initial perception of the wheelchair and their actual experience. The QUEST assessment tool also contained a comments section for participants to add further detail to each of the subdomains.

2.6 Data Analysis

The study collected quantitative data (data obtained from the IMU and task completion rate) and qualitative data (Questionnaires). SPSS (IBM, Chicago, IL) was used to analyze all statistical data and Microsoft Excel to tabulate data. The demographics and participant wheelchair usage data were collated to observe against the usability analysis. Descriptive analysis included mean, standard deviation, median, interquartile (IRQ) ranges, and graphical representations such as box plots.

Hypothesis 1 tested the MEBot's safety by analyzing comparing the seat angle changes. Three measurement points (going up, over and down) allowed the absolute values of the seat angle to be used as reference points for both fly box and compound slope. For the pothole obstacle, the minimum and maximum of the maximum seat angle change were recorded. The analysis of maximum pitch and roll provides the extreme seat angle measurements to prevent such a case in future iterations of MEBot, thus the use of absolute deviations means and minimum to maximum ranges. A t-test was conducted to obtain p-values between the wheelchairs to verify if the results were statistically significant.

Hypothesis 2 explored the average time taken throughout all the trials for all participants for each obstacle. The same reference points to determine the seat angle change are used and compared to the average walking speed of 1.43m/s (Bohannon RW & Williams AA, 2011). The average walking time for each of the reference points was calculated with respect to 1.43m/s (Bohannon RW & Williams AA, 2011), which was then compared to against the self-leveling time of MEBot.

Hypothesis 3 used NASA-TLX subscales which were classed and independently scored to perform a t-test analysis and a cross subscale analysis for each of the subscales. The medians, quartile ranges were used to provide a fair representation of the collected data as the sample size would be small.

Hypothesis 4 used a Wilcoxon Signed Rank test (non-parametric) for QUEST if it did not satisfy a normality test. QUEST was completed by participants before and after completing the tasks in both wheelchairs, to test satisfaction over the course of the protocol. The significance level was set at 5%.

3.0 Results

3.1.1 Demographics & EPW Usage

Ten participants completed the study; there were 8 males and 2 females with an average age of 59.3 ± 12.6 years (Appendix A). Participants reported using EPWs for an average usage of 11.6 ± 7.3 years and their current EPW for an average usage of 4.6 ± 4.5 years. Additionally, participants reported an average wheelchair usage of 11.1 ± 5.6 hours per day in total and nearly 6 days per week outdoors (Table 2). Seventy percent of the participants had a mid-wheel drive chair, whereas MEBot was operated in front-wheel drive for these obstacles. All participants operated both their own EPW and MEBot with constant speed throughout the tasks.

Table 2: Participant Electric Powered Wheelchair Usage

Participant ID	Usage of a power wheelchair (yrs.)	Usage of current power wheelchair (yrs.)	Usage of wheelchair per day (hrs)	Usage of a wheelchair outside the home (days/week)	Wheelchair	Model	Drive Configuration
1	7	1	9	6	Quantum	Q Edge 2.0	Mid-wheel
2	4	4	8	7	Quickie	QM-710	Mid-wheel
3	20	1	6	5	Permobil	M400	Mid-wheel
4	8	5	15	7	Permobil	M300	Mid-wheel
5	6	1	18	7	Quickie	QM-710	Mid-wheel
6	25	16	12	7	Quickie	S-646	Rear-wheel
7	18	6	8	2	Invacare	FDX	Front-wheel
8	4	2	1	1	Permobil	M300	Mid-wheel
9	13	5	18	7	Permobil	M300	Mid-wheel
10	11	5	16	7	Permobil	C400	Front-wheel
Mean ± Std	11.6 ± 7.3	4.6 ± 4.5	11.1 ± 5.6	5.6 ± 2.3			

3.2 Wheelchair Driving Performance

3.2.1 Safety- Seat Angle Comparison

All participants completed all the required tasks for MEBot and the participant's own wheelchair. The maximum pitch and roll were measured for all three obstacles and trials. A condensed version results of the mean, standard deviation and p-values are displayed in Table 3. A detailed version of the seat angle comparison including ranges is included in Appendix B.

The absolute deviations for the participant's own wheelchair were higher than MEBot notably when going down the compound slope (Pitch = 14.2° ± 4.0°, Range: -26.06° to -3.87°). MEBot experienced a greater degree in roll angle change when settling over the compound slope (Roll = 6.8° ± 1.3°, Range: -12.9° to 11.8°).

The participants' own wheelchairs had a larger absolute change in deviation in the pitch direction than MEBot when going up and down the slope; MEBot (5.6° ± 1.6°, 6.6° ± 0.5°) and own wheelchair (14.6° ± 2.6°, 12.1° ± 2.6°).

The mean and standard deviation results obtained for both wheelchairs had similar pitch and roll pothole obstacle outcomes, but the participant's own wheelchair had a smaller roll range. MEBot showed average minimum and maximum roll angles of -3.6° ± 1.1° and 3.9° ± 1.6°, respectively compared to participant's own wheelchair -1.6° ± 0.5° to 1.9° ± 0.4°. All p-values apart from the two highlighted rows were under the 5% significance level.

Table 3: Seat Angle comparison

Obstacle	Axis	Direction	MEBot	OWN	P-Value
Compound Slope	Pitch	Up	6.1° ± 2.5°	18.0° ± 3.9°	0.000
		Over	6.9° ± 1.6°	2.8° ± 0.95°	0.000
		Down	8.5° ± 2.0°	14.2° ± 4.0°	0.001
	Roll	Up	4.2° ± 2.9°	2.5° ± 1.3°	0.140
		Over	6.8° ± 1.3°	8.8° ± 0.7°	0.001
		Down	6.9° ± 1.5°	2.5° ± 1.2°	0.000
FlyBox	Pitch	Up	5.6° ± 1.6°	14.6° ± 2.6°	0.000
		Over	8.2° ± 1.3°	3.0° ± 0.75°	0.000
		Down	6.6° ± 0.5°	12.1° ± 2.6°	0.000
	Roll	Up	2.6° ± 0.9°	1.3° ± 0.5°	0.001
		Over	2.4° ± 0.6°	0.4° ± 0.2°	0.000
		Down	3.9° ± 1.2°	1.1°± 0.5°	0.000

Obstacle	Axis	Direction	MEBot	Own EPW	P-Value
Potholes	Pitch	Min	-4.3° ± 2.6°	-2.5° ± 1.1°	0.074
		Max	2.0° ± 0.5°	4.9°± 2.2°	0.002
	Roll	Min	-3.6° ± 1.1°	-1.6° ± 0.5°	0.000
		Max	3.9° ± 1.6°	1.9° ± 0.4°	0.003

3.2.2 Effectiveness- MEBot Self-levelling Time

The self-level time was measured to evaluate the MEBot application's effectiveness. Table 4 showed the results of the compound slope and flybox tasks. MEBot's self-leveling algorithm had a threshold of ± 2.5° for the pneumatic actuators, therefore the time was calculated for the self-leveling to maintain this threshold. Table 4 shows the average time to self-level at each stage of the obstacle for each participant and the overall average for all the participants with respect to the standard deviation. The flybox obstacle 10° decline with an average of 8.1 ± 2.8 seconds proved to be the greatest fluctuation and longest time to self-level. The time taken for MEBot to settle over the compound yielded a time average and standard deviation of (7.8 ± 3.0 seconds).

All the times taken for MEBot to self-level were higher than the average walking time for the distance on reference point to each obstacle.

Table 4: MEBot Self-levelling Time

MEBot	Compound slopes (seconds)			FlyBox (seconds)		
Participant	Up	Over	Down	Up	Over	Down
S1	n/a	1.2	3.5	2.5	4.6	14.5
S2	n/a	7.8	11	1.9	4.6	9.6
S3	n/a	13.8	8.5	2.3	6.5	9
S4	n/a	6.4	4.1	2.2	3.9	5.6
S5	n/a	8.1	5.3	2.6	4.5	6.5
S6	n/a	8.1	7.1	2.7	5.6	9.5
S7	n/a	8.7	5.3	2	6.9	6.3
S8	n/a	7	5.9	2.1	5.5	6
S9	n/a	8.5	8.5	2.6	2.6	8.4
S10	n/a	8.1	5.6	2.5	2.7	5.4
Mean ± Std	n/a	7.8 ± 3.0	6.5 ± 2.3	2.3 ± 0.3	4.7 ± 1.5	8.1 ± 2.8
Average Walking Time (Seconds)	n/a	0.89	0.89	1.33	0.85	1.33

3.3 Participant's perception of both wheelchairs

3.3.1 Usability- NASA-TLX

The NASA-TLX results were not statistically significant as seen in Table 5. The NASA-TLX overall weighted score averages favored the participant's own wheelchair (45.70 ± 25.15) than MEBot (35.28 ± 9.44). The large disparity in the standard deviations and small sample size means that these results cannot be statistically concluded.

The median values for MEBot showed it was less physically demanding (1.64, 4.60) but more mentally (2.84, 1.90) and temporal demanding (1.30, 0.20) than the participant's own wheelchair.

The calculation to determine the weighted workload value for the frustration subscale had equated to zero for all the participants except for one participant (medians values 16.67 and 22.33) for MEBot and the participant's own wheelchair. The disparity of the data can be seen in Figure 5, which excludes the NASA TLX overall score.

Table 5: NASA-TLX Subscale Descriptive Analysis

NASA- TLX	p	Mean ± Std Dev	Median	Percentile		
				25th	IQR	75th
TLX Score (MEBot)	0.14	35.28 ± 9.44	38.04	26.12	14.85	40.97
TLX Score (OWN)		45.70 ± 25.15	40.94	25.10	50.90	76.00
Mental (MEBot)	0.84	4.06 ± 4.86	2.84	1.17	3.63	4.80
Mental (OWN)		6.05 ± 9.02	1.90	0.30	10.55	10.85
Physical (MEBot)	0.2	2.72 ± 3.26	1.64	0.77	2.73	3.50
Physical (OWN)		8.17 ± 10.53	4.60	0.30	13.04	13.34
Temporal (MEBot)	0.5	2.13 ± 2.55	1.30	0.00	4.33	4.33
Temporal (OWN)		2.25 ± 4.95	0.20	0.00	18	1.88
Performance (MEBot)	0.44	20.09 ± 9.21	18.70	10.30	20.12	30.42
Performance (OWN)		18.20 ± 8.41	21.34	10.05	15.62	25.67
Effort (MEBot)	0.14	2.49 ± 1.03	2.54	1.59	1.46	3.05
Effort (OWN)		8.79 ± 10.25	3.60	0.50	19.50	20.00
Frustration (MEBot)	0.27	3.80 ± 6.18	0.00	0.00	9.80	9.80
Frustration (OWN)		2.23 ± 7.06	0.00	0.00	0.00	0.00

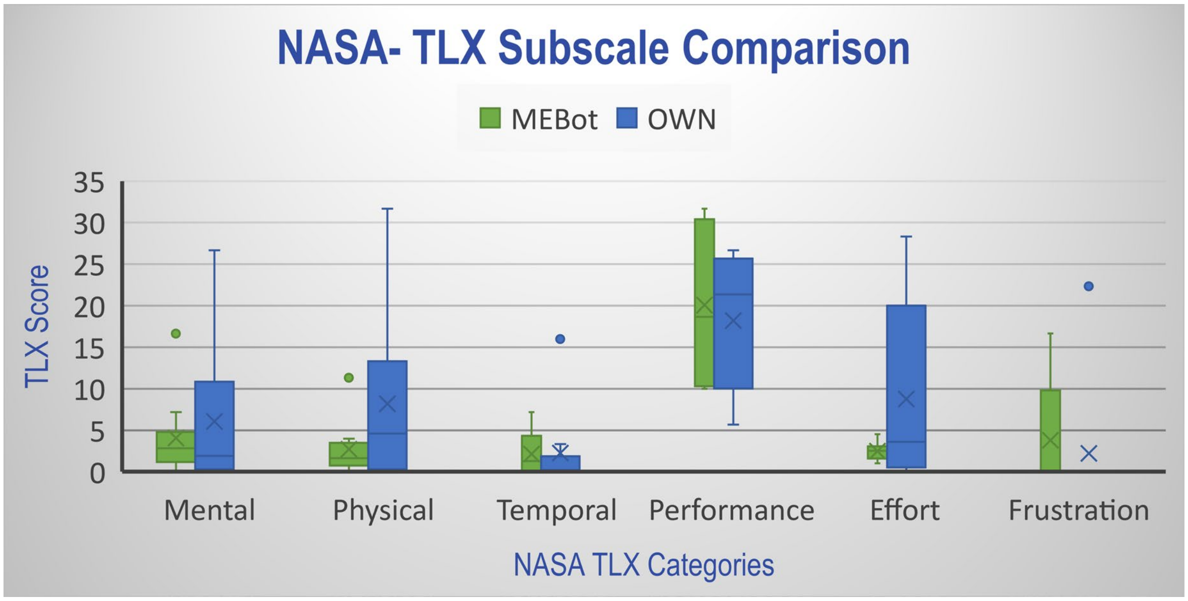


Figure 5: NASA-TLX Subscale Comparison

3.3.2 Satisfaction- QUEST

The comparison between the wheelchairs after the participant completed the obstacle course created the pooled ranking between the two dependent variables to provide the p-value (p). Table 6 and Table 7 show that the p-values are not statistically significant.

Table 6: QUEST Wheelchair Comparison

QUEST	MEBot vs OWN EPW
	P-value
Dimension	0.89
Weight	0.19
Adjustment	0.16
Safe	0.52
Durability	0.52
Easy	0.10
Comfort	0.48
Effective	0.75

Table 7: QUEST Subscale Comparison

QUEST	MEBot		Own EPW	
	Mean ± Std Dev	p	Mean ± Std Dev	p
Dimensions (PRE)	4.4 ± 0.7	1.00	4 ± 1.3	0.79
Dimensions (POST)	4.2 ± 0.9		4.2 ± 0.8	
Weight (PRE)	4.4 ± 0.7	0.32	4.3 ± 1.1	0.45
Weight (POST)	4.5 ± 0.5		4 ± 1.2	
Adjustment (PRE)	3.6 ± 0.9	0.48	4.2 ± 1.3	0.71
Adjustment (POST)	4 ± 0.9		4.4 ± 0.5	
Safe (PRE)	3.4 ± 0.7	0.66	4.4 ± 0.7	0.24
Safe (POST)	3.5 ± 1.4		3.9 ± 1.2	
Durability (PRE)	3.7 ± 1.2	0.78	4.1 ± 1	0.71
Durability (POST)	3.7 ± 0.9		4 ± 1.3	
Easy (PRE)	4 ± 0.7	0.74	4.6 ± 0.5	0.66
Easy (POST)	4 ± 0.7		4.5 ± 0.5	
Comfort (PRE)	3.3 ± 0.9	0.85	4 ± 1.3	0.28
Comfort (POST)	3.5 ± 0.7		3.6 ± 1.3	
Effective (PRE)	3.9 ± 0.8	0.58	4.1 ± 1.3	0.06
Effective (POST)	3.7 ± 1		3.5 ± 0.9	

4.0 Discussion

Seventy percent of the participants were mid-wheel drive EPW users and MEBot was configured to front- wheel drive, which could cause a fishtailing effect (power oversteer) when driving at high speed (Tsiotras P & Cowlagi RV, 2008).

MEBot met the design criterion of its ability to self-level and adjust the seat angle with 87.5% of the data adhering to the significance level. MEBot has satisfied the first hypothesis of safety to self-level but due to mechanical hinderances it was not successful when traversing over the compound slope (Pitch direction), settling over the flybox and potholes (Pitch & Roll) direction. The self-leveling time reflected the adverse seat angle changes and did not meet the second hypothesis forecast to self-level within the average walking speed. The driving performance although successful in MEBot's ability to self-level did have a long settling time (e.g. 7.8 ± 3.0 seconds) for the pneumatic system.

The NASA-TLX subscale scores were not statistically significant therefore the third hypothesis could not be concluded based upon these results. However, participants had the option of adding their own comments when evaluating each of the subscales. Participants had only made comments about their own EPW such as "Frustrated when driving through the compound slope," temporally demanding due lack of space to do the task and "potholes were physically demanding." This contrasts with the mental and temporal demand median scores as participants had scored their own EPW than MEBot.

The QUEST subscale comparison results in Table 7 predominately show a ceiling effect; whereby it is challenging to detect a conclusive statistical verdict to the fourth hypothesis. The comments stated by participants on each of the subdomains were balanced but more critical to their own EPW than MEBot. MEBot comments included: “too much movement,” “Easy to use buttons,” “Noise from the pneumatics adjusting,” “Safe and comfortable on the slopes”. Other comments included, “Not comfortable on potholes,” “Unsafe when driving through compound slopes” and “Slopes were harder to tackle than the potholes.” A research study suggested that 80% of the usability problems are detected with just 4 or 5 participants (Virzi RA, 1992). This study has been able to identify the usability problems with ten participants.

Potential Limitations

The study limitations include the limited number of responses recorded to undertake reliable statistical tests, but a power analysis was not performed prior to the study. A normality test would be usually used to conclude if the data is somewhat normally distributed, however, due to a small sample size it is likely that it would pass the normality tests, thus having little power to reject the null hypothesis (Ghasemi Asghar & Zahediasl Saleh, 2012). There were limitations of using the Likert scale questionnaires like QUEST due to the likelihood of a ceiling effect, making it difficult to derrentiate between the each score. The evaluation of MEBot highlighted the mechanical and software changes that could be addressed such as the “jerkiness” of the pneumatics as quoted by a participant and the long settling time of the pneumatics that affected the seat angle change and self-leveling time for MEBot.

5.0 Conclusion & Future Work

The self-leveling application enhanced the driving performance by reducing the seat angle change to ensure that it was effective and safe for participants. The participant's perception of both wheelchairs objective of analyzing usability and satisfaction slightly favored MEBot than their own wheelchair, based upon the participant's comments than their own wheelchair.

This iteration titiled MEBot 2.5 was developed for curb climbing and now adapted with automatic self-leveling, where all the user is required to do is drive. The use of pneumatics throughout the previous and current iteration enlighten the fact that it is quite volatile to control and maintain consistency as the pressure in the tank decreases.

This had led to the third generation of MEBot, titled MEBot 3.0. MEBot 3.0 will contain Electro-Hydraulic Actuators (EHAs) instead of the pneumatic actuators on the previous iterations. The feedback about MEBot 2.5 and the automatic ability to self-level has led to using EHAs, as they enable better control and smoother ability to self-level. This would allow creating a concept wheelchair enabling us to purely evaluate the self-leveling ability without a potential mechanical hinderance.

Evolving the protocol of the study will allow a more enhanced evaluation of MEBot, such as increasing the sample size and experimenting participants' driving skills in real-world environmental conditions. An active vs passive suspension comparison can be used to test the effectiveness and efficiency of the self-leveling application in addition to a cross-comparison of measuring wheelchair vibrations with user feedback questionnaires. The length and depth of the potholes could also be increased to gain a substantial analysis over a longer period.

Terrain pre-planning would allow algorithm and mechanical efficiency for self-leveling. Potentially, using a combination of Light Detection and Ranging (LIDAR) sensor and a fisheye camera to map the terrain in advance of travel would provide the means to efficiently utilize the mechanics of MEBot.

Appendix A Demographics

Demographics	Participant Number
Gender	
Male	8
Female	2
Age	59.3 ± 12.6 yrs.
30-49	1
50-64	5
65+	4
Ethnic Origin	
Hispanic or Latino	2
Black or African-American	5
White or Caucasian	3
Highest Degree	
High School Grad/ Vocational Technical School or less	3
Bachelor's/ Associates Degree	3
Master's Degree	3
PhD or higher	1
Diagnosis	
SCI C3- C5	4
SCI T3-T7	2
SCI L4	1
Hemiplegia	1
Paraplegia, Post-polio	1
Multiple Sclerosis	1
Work Status	
Retired, but not because of disability	1
Retired because of disability	3
Unemployed	2
Working full-time, outside the home	2
Working part-time, outside the home	1
Unable to work because of disability	1
Marital Status	
Single	6
Married	4

Appendix B : Seat Angle Comparison Complete Table

Change in Seat Angle	Max Pitch & Roll		MEBot			OWN		
			Minimum	|Mean| ± Std Dev	Maximum	Minimum	|Mean| ± Std Dev	Maximum
8° Compound slopes ±18° Transition	Pitch	Up	1.5°	6.1° ± 2.5°	13.5°	10.38°	18° ± 3.9°	30.94°
		Over	-12.4°	6.9° ± 1.6°	-2°	-5.88°	2.8° ± 0.95°	5.62°
		Down	-14°	8.5° ± 2.0°	-2.4°	-26.06°	14.2° ± 4.0°	-3.87°
	Roll	Up	-14°	4.2° ± 2.9°	13.5°	-5.94°	2.5° ± 1.3°	10.31°
		Over	-12.9°	6.8° ± 1.3°	11.8°	-1.81°	8.8° ± 0.7°	13°
		Down	-12.3°	6.9° ± 1.5°	12.4°	-6.81°	2.5° ± 1.2°	8°
± 10° Flybox ramp	Pitch	Up	2.1°	5.6° ± 1.6°	9.1°	10.75°	14.6° ± 2.6°	23.37°
		Over	-11°	8.2° ± 1.3°	-3.2°	-6.19°	3.0° ± 0.75°	5.19°
		Down	-10.4°	6.6° ± 0.5°	5.7°	-18.06°	12.1° ± 2.6°	-8.25°
	Roll	Up	-5°	2.6° ± 0.9°	6.4°	-1.56°	1.3° ± 0.5°	3.19°
		Over	-4.3°	2.4° ± 0.6°	6.1°	-1.69°	0.4° ± 0.2°	1°
		Down	-7.6°	3.9° ± 1.2°	10.6°	-2.44°	1.1° ± 0.5°	3.56°

Change in Seat Angle	Axis		MEBot	OWN
			Mean ± Std Dev	Mean ± Std Dev
Potholes	Pitch	Min	-4.3° ± 2.6°	-2.5° ± 1.1°
		Max	2.0° ± 0.5°	4.9° ± 2.2°
	Roll	Min	-3.6° ± 1.1°	-1.6° ± 0.5°
		Max	3.9° ± 1.6°	1.9° ± 0.4°

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