A Quantitative Methodology for Assessment of Wheelchair Controllability

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Changes in wheeled mobility user demographics and technologies over the past 30 years show the need for design guidelines for accessibility to persons with disabilities, including those who use wheelchairs. A key component is wheelchair maneuverability, which determines the clear space needed for travel in the environment. Previous studies have applied rating scales to assess the difficulty when wheelchair users maneuver in a built environment. These need to be complemented by direct maneuverability measurements. Having wheelchair users perform self-paced control tasks, for both lateral and longitudinal tasks is a potential method to meet the requirement. This study validated a methodology of measuring the steering controllability and start/stop controllability of wheelchairs so that further studies can apply this methodology to evaluate either environmental or wheelchair designs. The same speed/accuracy relationships were found for wheelchair users as had been found earlier for a variety of vehicles.

INTRODUCTION

The number of individuals who use wheeled mobility aids has grown considerably over the past 30 years, and may reach over four million in the United States by year 2010 (LaPlante, 2003).

Anthropometric data used by code developers and designers for environmental accessibility is becoming outdated, with many of the data sources and tools developed as many as 30 years ago. Recent guidelines, suggested by the ADA Accessibility Guidelines for Buildings and Facilities, are based on the research data from the study of occupied wheelchairs by Steinfeld, Schroeder & Bishop (1979). As more, and more varied people, require wheeled mobility and use different technologies, more research is needed to improve design guidelines and building codes to address the needs of wheeled mobility device users.

To characterized and/or predict the degree of difficulty wheeled mobility users have while manuvering in built environments, many studies (Steinfeld & Danford, 1999; Stineman, Wechsler, Ross, & Maislin, 2003) utilized ordinal scales for either observers or subjects to rate the difficultly and required assistance. While these types of ratings are useful for generally describing maneuvering performance, they do not characterize differences in the speed and/or errors made during wheeled mobility maneuvering tasks.

One way to view wheeled mobility device maneuvering is as a self-paced control task, requiring the device user to adjust the speed and accuracy of movement as needed while traveling within an environment. As noted by Drury, Montazer, and Karwan (1987), there are two types of self-paced movement control task: Path Control and Terminal Aiming.

Path Control Tasks. The device user must negotiate a path while avoiding lateral barriers, typified by automobile driving. The steering controllability (C) is assessed by measuring the speed chosen as a function of the path width, or tolerance, between the vehicle and the barriers. Drury & Dawson (1974) found there is a linear relationship between chosen speed and lateral tolerance (Equation 1), with the slope of the line characterizing the C ($time^{-1}$) of the vehicle.

$$\text{Speed} = \text{C} \times \text{Tolerance} \qquad \text{Equation (1)}$$

Many studies (Accot & Zhai, 1997; Beggs, Sakstein, & Howarth, 1974; Defazio, Wittman, & Drury, 1992; Drury, Cardwell, & Easterby, 1974; Drury & Dawson, 1974) have shown that speed increases in a linear manner until a critical tolerance is reached. Beyond this tolerance width, the users will not or cannot increase their speed. Equation 1 could help us to define a minimum tolerance that does not interfere with mobility.

Terminal Aiming Tasks. This task, defined by the stopping tolerance required at the termination of the moving path, has the movement distance (A) from a standing start, to stop within a longitudinal stopping tolerance (W). The time taken for such a move is a function of the start/stop controllability (R) and the Index of Difficulty (ID) of the movement, i.e. Fitts' Law. This methodology has been applied successfully to measure the R ($bit \times s^{-1}$) of fork-lift trucks (Drury & Dawson, 1974), to simulations (Drury et al., 1974), and to walking tasks (Drury & Woolley, 1995).

$$\text{Time} = \frac{1}{\text{R}}(\text{ID}) = \frac{1}{\text{R}}\log_2\left(\frac{2\text{A}}{\text{W}}\right) \qquad \text{Equation (2)}$$

Wheelchair usage also contains both path control tasks, when wheelchair users ride their wheelchair through an aisle, and terminal aiming tasks, as they move from a point to another. Therefore, this preliminary study attempted to determine if the methodology used in previous studies of self-paced vehicle control tasks could be used to quantitatively characterize the controllability of wheeled mobility use.

METHOD

Participants

Six (4 female, 2 male) manual wheelchair users were recruited from the local community. Each participant and their own wheelchairs were treated as a unit in this research, since participants' wheelchair types and medical history are quite different.

Path Control Experiment

Participants performed self-paced steering between lateral barriers consisting of two cardboard walls. The tolerance was determined as the difference between the width of the course and the participant's minimal lateral width in the posture he/she can ride wheelchairs. Six levels of Tolerance were 50, 150, 250, 350, 450, and 550 mm. In the experiment, participants maneuvered their wheelchairs from a start line to a finish line 6 m away. Two practice trials were given before participants conducted three timed trials for each Tolerance. Time was measured after a 1.5 m acceleration zone and ended 0.5 m before the finish line to avoid transition errors. The errors were determined as the times participants hit the barriers. Participants repeated a certain timed trials while they have more than three errors.

Terminal Aiming Experiment

In the Terminal Aiming Experiment, participants made self-paced terminal control movements defined by the Moving Distance (A) and the Stopping Tolerance (W). Six different Index of Difficulty (ID) values, combinations of three values of A (320, 1280, and 5120 mm) and two values of W (80 and 160 mm), were used. Participants were timed from when they started moving their wheelchairs to stopping with a specific mark point (attached to their wheelchairs) within the stopping tolerance. Participants had to complete each run without error.

Procedure

The participants, first, conducted the Path Control experiment. After a break, they performed the Terminal Aiming Experiment. After every experimental combination, the participants rated the controllability of the task using the Modified Cooper-Harper Scale (MCHS, Wierwille & Casali, 1983).

RESULTS

Participants 1 and 4 did not perform two practice trials before both the experiments due to difficulties with their hands. However, they did a few practice trials to understand the experimental tasks. Except for Participant 1 who finished all experiments in two appointments because of her hand fatigue, all participants completed both of the two experiments in one appointment.

Steering Controllability: Path Control

Analyses of variances of Speed, Error Rate and MCHS rating values were performed using 6 Tolerances X 6 Participants in a Latin Square ANOVA with Tolerance fixed and Participant random. Note that Participant 1 could not perform the narrowest Tolerance (50 mm). Table 1 shows that Participant has highly significant effects for Speed and MCHS. Further, Tolerance has highly significant effect for Speed, Error Rate, and significant effect for MCHS.

Table 1. ANOVA Table for Path Control Experiment

Variables	Speed	Error Rate	MCHS
Participant	$F(5,94) = 193.15$, $p < 0.001$	$F(5,94) = 0.66$, $p = 0.654$	$F(5,25) = 8.02$, $p < 0.001$
Tolerance	$F(5,94) = 26.73$, $p < 0.001$	$F(5,94) = 20.93$, $p < 0.001$	$F(5,25) = 3.99$, $p < 0.05$

In Figure 1, all Speed/Tolerance curves rise in a linear manner at low tolerances and then level out at a certain high Tolerance value (critical tolerance). The only exception is Participant 1 who was uniformly slow throughout. The linear parts of the other five participants' curves were used to calculate C values. Table 2 shows these C values, the related correlation coefficient values (r^2) and the relevant critical tolerance. In Figure 2 and 3, there is a trend in which the participants commit many errors and rated MCHS with high values especially when Tolerance was 50 mm and 150 mm. However, both errors and the MCHS decreased to much lower values as Tolerance increased.

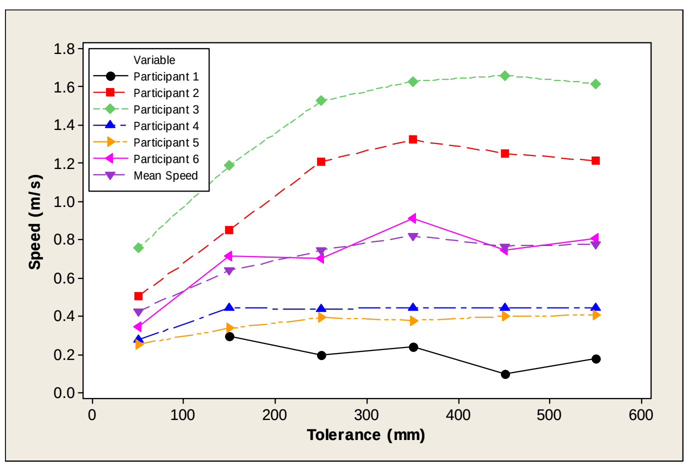

Figure 1. Speed / Tolerance relationship for each Participant

Table 2. Steering Controllability Values

Participant	C(s^{-1})	r^2	Critical Tolerance (mm)
1	---	---	---
2	3.35	98.8%	250
3	3.85	89.4%	250
4	1.67	96.5%	150
5	0.70	95.0%	250
6	1.68	66.2%	350

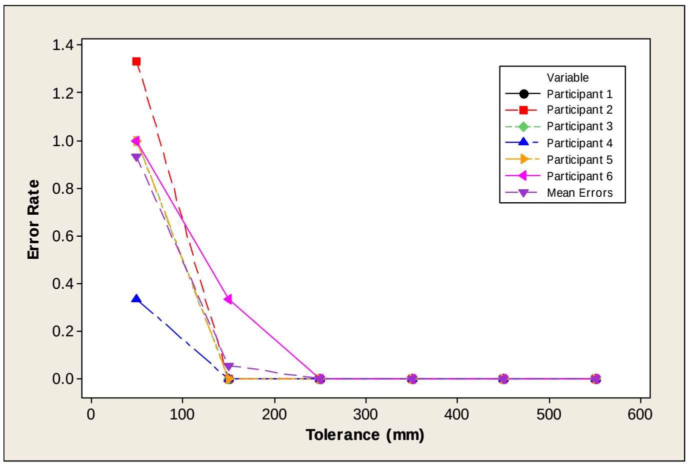

Figure 2. Error Rate/Tolerance Relationship for Each Participant

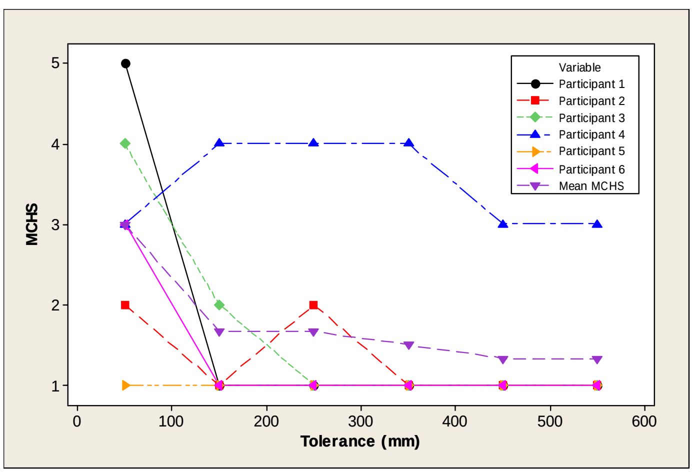

Figure 3. MCHS/Tolerance Relationship for Each Participant

Start/Stop Controllability: Terminal Aiming

Times in seconds for each movement and MCHS rating values were analyzed similar to the Path Control Experiment. Table 3 below shows that differences among participants were significant for Time and highly significant for MCHS. However, ID has a highly significant effect for Time, but no significant effect for MCHS. Further, the interaction effect of Participant and ID was highly significant for Time. Figure 4 shows that before ID value 5, there is a linear relationship between Time and ID. This represents how Time increased according to the increase of ID for each participant. Table 4 shows the R values calculated without ID value 6 and 7 (see Discussion).

Table 3. ANOVA Table for Terminal Aiming Experiment

Variables	Time	MCHS
Participant	$F(5,72) = 3.30$, $p < 0.05$	$F(5,25) = 29.00$, $p < 0.001$
ID	$F(5,72) = 6.62$, $p < 0.001$	$F(5,25) = 1.00$, $p = 0.438$
Participant * ID	$F(25,72) = 14.76$, $p < 0.001$	---

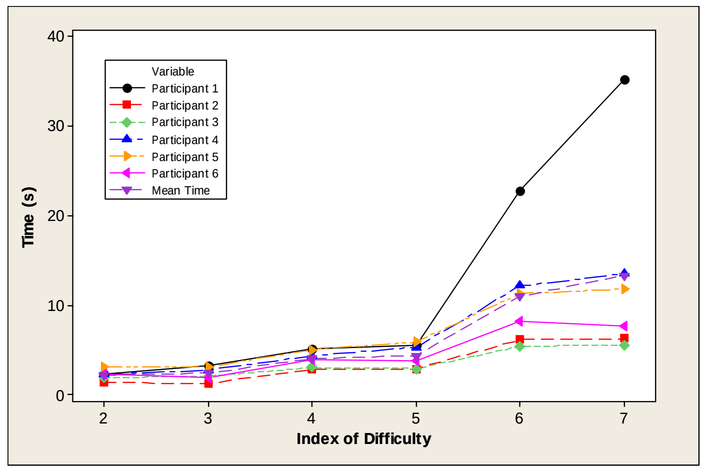

Figure 4. Time/ID Relationship for Each Participant

Table 4. Start/Stop Controllability Values

Participant	R($bit \times s^{-1}$)	r^2
1	0.88	86.1%
2	1.59	76.6%
3	2.52	70.4%
4	0.93	92.9%
5	0.99	63.1%
6	1.57	66.0%

DISCUSSION

In the Path Control Experiment, there was a Speed/Tolerance effect, leveling off at the certain high tolerance values for all participants, except for Participant 1. From Figure 1, the maximum speeds for six participants were different. However, before achieving the maximum speeds, it was clear that the more Tolerance the participants had, the more Speed they could achieve in their wheelchairs.

The results of the Terminal Aiming Experiment showed that Fitts' Law worked as well. Below an ID value of 5, the linear relationship between Time and ID represented how Time increased according to the increase of ID values. Participant 1, again, conducted the tasks much slower than the other participants particularly for the long distance ones (Figure 4). There was a highly significant interaction effect of the Participant X ID (Table 3) for Time. This was primarily due to long moving distance (5120 mm). The participants reached the maximum speeds and continued a certain distance at this speed before they began to decrease the speed for the stopping targets. This was different from the typical Fitts' Law, indicating that the acceleration changes in a parabolic curve. Therefore, in future studies, the moving distance (A) should be limited so that participants will not have so many trials at maximum speeds.

The MCHS results showed that the factor, Participant, was highly significant in both experiments. This might imply the effects of individual subjective opinions and individual health differences. However, from Figure 3, we know that most of the participants felt high difficulty only in the extreme narrow Tolerance (50 mm and 150 mm). This could also provide a baseline for designing environments.

CONCLUSION

The purpose of this study was to assess whether model-based measurements, both path control tasks and terminal aiming tasks, could be used to measure wheelchair controllability. The results of the Path Control Experiment showed that there was a Speed / Tolerance effect. Further, the results of the Terminal Aiming Experiment showed that Fitts' Law worked for assessing wheelchair as well. Therefore, we can measure both steering controllability and start/stop controllability of wheelchair usage by applying the same methodology utilized by other previous vehicles and even walking studies.

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