

## Controllability of Manual and Powered Wheelchairs for Spinal Cord Injury Users

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This study investigates wheelchair maneuvering control for persons with a spinal cord injury across two protocols, path control and terminal aiming. Thirty-one participants using either a manual or powered wheelchair, performed self-paced longitudinal movements (path control) as well as self-paced stopping actions (terminal aiming) across multiple trials. Results show performance differences across both protocols for manual and power wheelchair user groups. This study exemplifies the use of model-based data for clinical applications. Further research using this approach may help to identify individual control settings for optimal maneuvering performance.

### Introduction

The Americans with Disabilities Act (ADA) Accessibility Guidelines for Buildings and Facilities (ADAAGs) are intended to aid the design of public buildings and facilities for improved accessibility to persons with disabilities including those who use wheelchairs (U.S. Architectural and Transportation Barriers Compliance Board, 2002). The space required for wheelchair users in a built facility is an important area of concern for achieving ease of movement and maneuverability for the wheelchair users. The ADAAG dimensions are based on ANSI 117.1 (1980) standards, which in turn are based on the research data on the study of occupied wheelchairs by Steinfeld et al. (1979).

The number of wheeled mobility device users has grown considerably since 1980. Based on the National Health Interview Survey (NHIS) in 1995, as cited in Kaye et al. 2000, there are 1.7 million wheeled mobility device users, with the large majority using manual wheelchairs. There has also been a large expansion in design and configuration of wheelchairs in the last two decades (Cooper

and Cooper, 2003). Manual chairs, powered chairs and scooters all vary considerably in terms of weight carrying capacities, drive and handling characteristics, adjustments and attachments, and appearances. Because of this, it is likely that the existing ADAAG standards may in some case not be as accommodating as intended. For example, Cooper and Cooper (2003) report that there is an alarming growth of people with obesity in North America, led which has to a significant increase in the demand for bariatric wheelchairs that may not fit easily through standard sized doorways and passageways. Additionally, as the number of individuals and different types of wheeled mobility technologies increase, it is likely that there will be greater diversity in terms of wheelchair controllability, which is likely to be a function of an individual's abilities, the design characteristics of the maneuvering controls and the drive and handling characteristics of the mobility device.

The number of wheeled mobility users is expected to grow significantly in the years to come and may reach over four million by the

year 2010 (LaPlante, 2003). Therefore, it is likely that the space requirements for maneuvering wheelchairs within built environments will also continue to change. As a result, it is evident that human performance modeling-based approaches that predict the level of accommodation that an environment might afford would be very useful for informing building regulations such as ADAAG.

Good models that can be applied to wheelchair maneuvering control (controllability) for lateral (Drury, 1971) and longitudinal control movements (Fitts, 1959) do exist. These were tested in a pilot test reported earlier with promising results (Lin, et al., 2006). As a result, a new protocol was developed as part of a larger study to compare wheelchair controllability models across a variety of different wheelchair and disability conditions. This paper compares wheelchair controllability between manual and powered wheelchair users having spinal cord injuries.

## Methodology

Participants were asked to perform two protocols, path control and terminal aiming, using their wheeled mobility device. For the path control protocol, participants performed self-paced steering movements in a six-meter course consisting of one side of cardboard boxes and one side of wall. The lateral width of the course was normalized to the maximum width of each participant/wheelchair combination in a representative posture of travel (for example, lateral width of manual chair users were measured with their hands gripped on the pushrims). For each path control condition, four tolerances were added to the normalized width: +50, +150, +250, and +350 mm. The timed trials were measured over a 4 m course 1.5 m after start line and 0.5 m before end line to eliminate acceleration and deceleration effects.

For the terminal aiming protocol,

participants conducted self-paced terminal aiming movements defined by the two distance parameters (320 mm and 1280 mm) and two stopping tolerances, within a clearly marked zone for the anterior-most portion of the wheelchair to stop (either 80 mm or 160 mm in length). These two different moving distances (amplitude) and two stopping tolerances (target width) defined the independent variable, the Index of Difficulty (ID) of movement at four levels: 2, 3, 4 or 5.

For both protocols, each participant was given two practice trials for each experimental condition before they conducted two timed trials. The order of trials changed across participants using a Latin square design. After finishing each experimental combination set, participants provided a subjective rating of controllability using the Modified Cooper-Harper Scale (MCHS). Participants were asked to move as quickly as they could without error: if an error did occur, the participant repeated the trial.

Static strength for grip and pinch was collected for participants. Two power grip measurements were taken using a hand grip dynamometer (Jamar) with the elbow a zero and ninety degrees flexion. Two pinch grip measurements, thumb-forefinger and lateral pinch were taken using a pinch dynamometer (Jamar). Participants were excluded if they could not sustain the required hand position for the grip or pinch measurement. Participants were given three trials and the average was used in this analysis. Participants also performed four turning tasks with the dependent variable being the lateral tolerance needed to perform each task without error. These grip and turning measures were used as potential correlates of performance, as was participant age.

The controllability data were analyzed with analysis of variance (ANOVA). For the path control protocol, time data was converted to speed in  $\text{ms}^{-1}$  for analysis, primarily to fit the

model (Drury, 1971) but also to help normalize the residuals. A mixed model GLM ANOVA was performed with type of wheelchair (Manual, Powered), participants nested under type of wheelchair, and with path width as the within-participants factor. For the terminal aiming task, the time/move data were analyzed using a mixed model ANOVA, with the difference being that ID value replaced Width. As expected the residuals were not normally distributed, so the analysis was repeated with  $\ln(\text{time})$  resulting in much improved normalization.

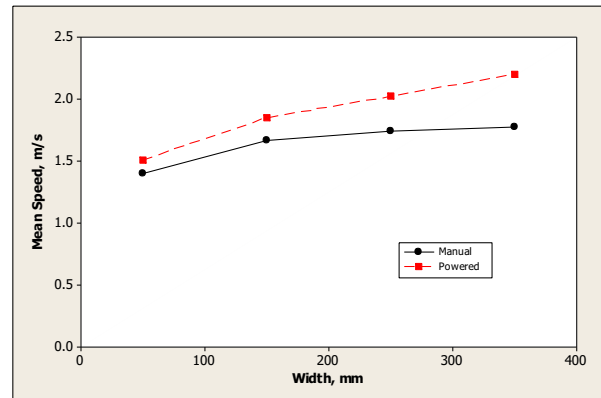
An exploratory analysis was performed to identify relationships between selected demographic and human function variables and controllability performance. A factor analysis was performed on demographic variables for the grip strength and turning task data. The results were used to correlate identified factors with maneuvering performance.

**Results**

*Research Participants:* Participants were recruited from the Pittsburgh, PA area for a large-scale anthropometric research study. Thirty-one research participants reporting a spinal cord injury at any level and any extent of lesion, average age (standard deviation) was 46.1 (12.3) years, are represented in this analysis. The average (s.d.) for years with disability was 18.0 (11.6). There were 10 power wheelchair users and 21 manual wheelchair users. These participants were considered experienced, the majority reporting the use of a wheelchair for more than ten years (70.9%; n=22), and using their wheelchairs more than ten hours a day (80.6%; n=25). The majority of the sample was male (90.3%; n=28), and able to transfer without assistance (83.8%; n=26).

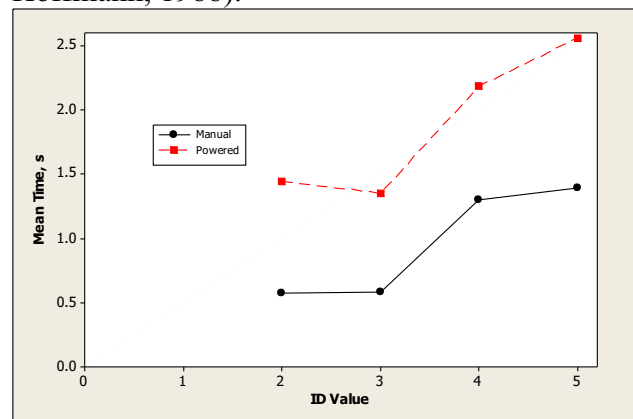
*Path Control Task:* Width and Width X Type of Wheelchair were both significant

( $F(3, 87) = 42.2, p < 0.001$ ;  $F(3, 365) = 3.28, p = 0.025$  respectively) but Type of Wheelchair had no main effect ( $F(1, 29) = 3.35, p = 0.077$ ). Figure 1 shows the significant interaction, where speed increases more rapidly with Width for Powered wheelchairs than for Manual wheelchairs.



**Figure 1: Speed vs. path width for the lateral control task (c.f. Drury, 1971)**

*Terminal Aiming Task:* Wheelchair Type, ID value and their interaction were all significant ( $F(1, 29) = 47.7, p < 0.001$ ;  $F(3, 87) = 72.6, p < 0.001$ ;  $F(3, 124) = 3.43, p = 0.021$  respectively). The interaction is shown in Figure 2, using mean times rather than mean  $\ln(\text{times})$  for clarity. For this task, the Manual wheelchair outperformed the Powered one. Also note that Fitts' Law appears to hold for ID values above about 3 (c.f. Gann and Hoffmann, 1988).



**Figure 2: Time vs. ID Value for the terminal aiming task (c. f. Fitts' Law)**

*Demographics and Inter-correlations:* For both data sets, the factor analysis demonstrated that a single factor accounted for most of the variance, 93.1% for Grip Strength and 67.3% for Turns. Thus the factor scores for Grip Strength and Turns were used as two possible individual difference measures along with Age. Inter-correlations between these and the performance variables (Speed for lateral control and Time for terminal aiming) showed only one significant effect, the correlation between Time and Turn was 0.660 ( $p < 0.001$ ). One-way ANOVAs of the three individual difference measures between Manual and Powered wheelchairs showed the only Turn score significant ( $F(1, 29) = 69.0, p < 0.001$ ). Converting back to the mean clearance required for turning across all four turning tasks, the Manual wheelchair required 132 mm while the Powered one required 155 mm.

## Discussion

This analysis of a restricted but homogenous sub-set of the data showed that the measures we have used gave consistent and interpretable results. For the lateral control task, the expected relationship between speed and width is linear but leveling out when sufficient lateral tolerance allows the maximum desired speed to be reached (e.g. Daniels, Kobas and Drury, 1976). Figure 2 shows just such an effect, with a more pronounced leveling of speed for the Manual wheelchair as indicated by the significant Width X Wheelchair Type interaction. The terminal aiming task also produced the expected relationships, with a roughly linear portion above  $ID = 3$  showing that Fitts' Law holds, while the leveling out at  $ID < 3$  confirms Gan and Hoffmann's (1988) prediction of essentially ballistic movements at low ID values. Thus the protocols do produce interpretable model-based results, providing a step up from the strictly empirical-

based data used historically to evaluate wheelchair performance.

Testing of the two types of wheelchairs showed quite different results on the two tasks. In lateral control, Powered wheelchairs were able to move faster at large width tolerances. Conversely, in terminal aiming the Manual wheelchairs performed better. There is clearly a need for powered wheelchairs to have a better longitudinal control system to at least match the naturalness of starting and stopping with a Manual wheelchair. In fact, since SCI users are likely to have programmable controllers, it may be possible for clinicians to apply a modified version of the protocol used in this study to identify the control setting that provides optimal maneuvering performance.

As an example of how we can use the model-based data for design, we now begin to define the minimum lateral tolerances required for each type of wheelchair using Figure 1. The Manual wheelchair has no performance improvement beyond about 150 mm lateral tolerance, while the Powered wheelchair continues improving out to the maximum width tested (350 mm). This suggests that wider corridors (for example) might benefit Powered wheelchair users but not Manual wheelchair users. Similar arguments have been made for other vehicles such as fork-lift trucks or hand-pushed materials handling devices (Drury, 1971). Interestingly, the Turn data showed a large maneuverability advantage for the Manual wheelchair. The correlation between the results of the terminal aiming task and the Turn task implies that turning corners relies heavily on longitudinal control (starting and stopping), an example of using between-participant correlations to help understand human performance in novel tasks, a technique dating back at least to Fleishman and Rich (1963).

The spinal cord injury group studied here was experienced and high functioning. More

disability group specific study on wheelchair controllability needs to be performed. Current data collection efforts will provide additional participants and a wider range of disability groups to increase the generalizability of the results.

### Conclusions

This study utilized model-based data for assessing wheelchair controllability for an experienced group of wheelchair users. For both power and manual wheelchair users, experience can influence skill in straight path control, negotiating turns through tight clearances, and stopping one's wheelchair appropriately. The population studied here was experienced and further research should explore the impact of experience with respect to wheelchair controllability within a controlled experimental condition. Additionally, other wheeled mobility device groups should be studied using this protocol, allowing for a deep understanding of controllability across disability groups.

For this study, all of the spinal cord injury users likely had programmable controllers and the results were likely related to individual control settings which has been set according to the environments, terrain, etc. that they generally encounter. One potential clinical application of this approach is the identification of individual control settings for optimal maneuvering performance through improvements in training for 'tuning' the control system or perhaps in the design of smarter, adaptive tuning in accordance to individual control input and navigating the environment.

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