ANALYSIS OF THE ANSI/RESNA WHEELCHAIR STANDARDS: A COMPARISON STUDY OF FIVE DIFFERENT ELECTRIC POWERED WHEELCHAIRS

by

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ABSTRACT

ANALYSIS OF THE ANSI/RESNA WHEELCHAIR STANDARDS: A COMPARISON STUDY OF FIVE DIFFERENT TYPES OF ELECTRIC POWERED WHEELCHAIRS

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The number of individuals using electric powered wheelchairs (EPWs) is increasing every year. Advances in technology have led to the design of EPWs that are more complex and can perform multiple functions. The ANSI/RESNA wheelchair standards consist of a battery of tests that are designed to evaluate the safety and performance of both manual and power wheelchairs. However, there is a deficit of information available to the general public on the performance of wheelchairs on these tests. The purpose of this study was to compare the results of standards testing on five different types of EPWs. The value and intentions of each section of the standard were also reviewed and suggestions were made for possible improvements.

A total of fifteen EPWs (three of each type) were tested using the following sections: static stability, dynamic stability, effectiveness of brakes, energy consumption, overall dimensions, speed and acceleration, seating dimensions, static, impact, and fatigue testing, climatic testing, obstacle climbing ability, and power and control systems. Statistical analysis was performed on the relevant sections. Significant differences were found between the different types of wheelchairs with respect to static stability, dynamic stability, braking distance, theoretical range, and obstacle climbing ability. The EPWs with the highest velocity and accelerations were found to be the most dynamically unstable and have the longest braking distances. Dynamic stability and braking distance were also found to be directly related to the slope of the test surface. It is apparent from the results that EPWs can differ in both performance characteristics and safety.

Evaluation of the wheelchair standards also illustrated the need to continually revise the standards to keep pace with new technology. Stability, fatigue strength, and control system testing are three of the sections that will need to be adapted to help evaluate the next generation of EPWs.

DESCRIPTORS

Electric Powered Wheelchairs | Wheelchair Standards

Wheelchair Performance | Wheelchair Safety

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1.0 INTRODUCTION

1.1 Electric Powered Wheelchairs

The number of people using wheelchairs in the United States is estimated to be near 2 million, with over 100,000 users in electric powered wheelchairs (EPWs) and 60,000 users in electric powered scooters [1]. Electric powered wheelchairs appear to be evolving faster than manual wheelchairs. Increased computing power, low cost microcontrollers, and a greater variety of sensors have produced a very complex interaction between electric powered wheelchairs and their users [2]. Electric powered wheelchairs no longer consist of simply a manual wheelchair fitted with two drive motors. There is a wide array of models available to consumers. There are rear-wheel, mid-wheel, and front-wheel drive wheelchairs. Certain types can climb stairs and even cluster over obstacles. With so many models and features available, consumers and clinicians should consider numerous safety and performance characteristics of an electric powered wheelchair when deciding what type of device to select. However, attempting to acquire performance information from wheelchair manufacturers can be difficult and challenging.

The ANSI/RESNA (American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America) wheelchair standards consist of a battery of tests developed to provide information about the performance and safety characteristics of wheelchairs. Information such as static tipping angles, braking distances, energy consumption, obstacle climbing ability, and many other performance characteristics can be determined from the standards. The results of these tests can be used to compare different EPWs and help users determine what device best suits their needs. The purpose of this study was to evaluate and compare the performance characteristics of five different types of EPWs. The intention was to not only provide specific information about these particular EPWs, but also to demonstrate how the wheelchair standards can be used to evaluate all types of wheelchairs. There are many factors that affect powered mobility. These include human abilities, technology features, environmental considerations, driving as an activity, and interaction effects [3]. Wheelchair performance is a key element of powered mobility. Speed, acceleration, braking performance, handling, and obstacle climbing ability are all elements that help match a user with a specific EPW.

This study was carried out over the course of three years with all of the testing being conducted at the Human Engineering Research Laboratories. In the past, we have tested over 100 manual and electric powered wheelchairs according to the ANSI/RESNA wheelchair standards. Similar studies have been performed involving depot, lightweight, and ultralight weight manual wheelchairs [4-6]. However, this is the largest electric powered wheelchair study to date in regards to the total number of wheelchairs tested and the scope and depth of the tests involved.

1.2 Specific Aims and Hypotheses

The purpose of this study was twofold. The first goal was to provide specific information about the safety and performance characteristics of five different models of electric powered wheelchairs that are routinely purchased by the Veterans Health Administration. The second goal was to evaluate the methods used by the ANSI/RESNA wheelchair standards to compare different wheelchairs so that users and clinicians can make informed decisions when deciding what type of wheelchair will be safest and most practical for their needs. In order to meet these goals, hypotheses were formed for each of the different sections of the ANSI/RESNA wheelchair standards. These hypotheses are listed below.

Hypothesis #1: Determination of static stability. There will be a significant difference between the uphill and downhill tipping angles of the five types of EPWs. Specifically, rear-wheel wheelchairs should be more stable in the downhill direction and front or mid-wheel wheelchairs should be more stable in the uphill direction. There should be little difference in lateral stability.

Hypothesis #2: Determination of dynamic stability. There will be significant differences in dynamic stability between the five types of EPWs. The front or mid-wheel wheelchairs should be more stable when traveling forwards uphill and backwards downhill and the rear-wheel wheelchairs should be more stable when traveling forwards downhill.

Hypothesis #3: Effectiveness of brakes. There will be significant differences in the braking distances of the five types of EPWs. The maximum speed and deceleration of a wheelchair will affect its ability to stop.

Hypothesis #4: Energy Consumption. There will be no significant differences in energy consumption. All of the wheelchairs use the same 12-volt gel batteries run in series to power a 24-volt system. Many of the wheelchairs also use the same or similar type motors to propel the wheelchair. Although speed has a direct effect on energy use, the overall distance covered by the wheelchairs should be similar.

Hypothesis #5: Speed, acceleration, and retardation. There will be significant differences between the speed, acceleration, and retardation of the five types of EPWs. Front-wheel drive wheelchairs often have lower maximum speeds than rear-wheel drive wheelchairs.

Hypothesis #6: Static, impact, and fatigue strength. There will be significant differences in the fatigue life of the five types of EPWs, but no differences in the static or impact strengths. Previous studies have shown significant differences in fatigue life between different models of wheelchairs that are similar in function and value. However, there have been very few failures from any type of wheelchair during the static and impact strength tests.

Hypothesis #7: Climatic tests. There will be no significant differences in the abilities of the EPWs to withstand harsh environmental conditions. Failures during climatic testing often involve the wheelchair controllers. Since four of the five types of EPWs use controllers from the same manufacturer, there should be no differences.

Hypothesis #8: Obstacle climbing ability. There will be significant differences in the obstacle climbing abilities of the five different types of EPWs. Obstacle climbing ability depends on speed, power, and wheel size.

1.3 Thesis Organization

The majority of this study is involved with the implementation and analysis of the ANSI/RESNA wheelchair standards. The Background section cites epidemiological studies concerning wheelchair use and injuries as well as previous experiments involving both manual and electric powered wheelchairs. Each section of the wheelchair standards is listed as a separate subheading. Methods, Results, and Discussion sections are included under each subheading. The Methods section describes the procedures used to test the wheelchairs as described in the standards. The Results section lists the raw data and statistical comparisons for each test. The Discussion section analyzes the statistical comparisons and explains the outcomes. The Summary section includes an overall analysis of the study as well as limitations and suggestions for future study.

2.0 BACKGROUND

2.1 Epidemiology

The number of people using wheelchairs and scooters is increasing every year. In addition to the estimated 2 million full-time wheelchair users in the United States alone, there are also several million part-time wheelchair users [7]. LaPlante et al found that the 1990 National Health Interview Survey on Assistive Devices determined that there are close to 13.1 million Americans using assistive devices to help overcome physical impairments and 7.1 million people had adapted their homes [8]. The selection of a wheelchair is critical to the well-being and quality of life of the user.

The number of wheelchair-related accidents has also risen steadily over the years. Kirby and MacLeod recently analyzed data from the National Electronic Injury Surveillance System of the United States Consumer Product Safety Commission to determine the incidence of wheelchair-related injuries that caused a person to seek attention at an emergency department [9]. The predicted number of annual visits to the emergency room rose from 25,829 in 1986 to 85,263 in 1999, with a significant upward trend over time (R^2 95%, $p<0.001$). A tip or fall was involved with 80% of the incidents. A study by Ummat and Kirby also found that 73.2% of the nonfatal accidents reported to the United States Consumer Product Safety Commission involved falls and tips [10]. Fatal accidents reported to the same commission showed that 68.5% of the incidents involved a tip or fall.

Gaal et al performed a study looking at the causes of wheelchair injuries. They interviewed 109 wheelchair users who had experienced some type of incident [11]. In the previous five years, 253 incidents occurred. A total of 53% of these incidents involved electric-powered wheelchairs. Tips and falls were the most common cause accounting for 42% of the accidents. Component failures were cited for an additional 33% of the reports. Rolling surface, wheelchair design, and wheelchair configuration were determined to be the major factors that contributed to the incidents.

Kirby et al conducted a study that examined reports in the Medical Device Reporting System database of the FDA [12]. They reviewed a total of 651 reports from 1975 to 1993. Twenty-one of the 368 documented wheelchair-related injuries were fatal. Overall, 45.5% of the injuries involved fractures, 22.3% involved lacerations, and 20.1% involved contusions or abrasions. A majority of the accidents occurred when driving a scooter (52.8%) followed by electric-powered wheelchairs (24.6%) and manual wheelchairs (22.6%). Design issues, environmental conditions, and operator error were all considered to be important factors in the accidents.

Calder and Kirby searched the database for the National Information Clearinghouse of the Consumer Product Safety Commission [13]. The records listed 770 deaths that were related to wheelchair use. Tips and falls accounted for 77.4% of these deaths. There were also 51 deaths that involved stairs, and burns were responsible for 48 deaths.

Two main conclusions can be drawn from these studies concerning wheelchair use. First, the number of people using wheelchairs is increasing every year. As the market for wheelchairs

People will be confronted with having to attempt to discern what wheelchair bests meets their needs. The number of wheelchair related accidents and injuries will also keep pace with the increase in wheelchair use. More wheelchair users means more tips and falls. One of the main purposes of this study is to help address these specific issues. Information about safety and performance characteristics will help individuals select wheelchairs that are both practical and safe. It should also help influence the design of better wheelchairs by manufacturers.

2.2 ANSI/RESNA Wheelchair Standards

2.2.1 General Background

The ANSI/RESNA wheelchair standards were originally conceived in March of 1982 [14]. A diverse committee consisting of rehabilitation engineers, wheelchair manufacturers, governmental representatives, university researchers, and many others established eighteen standards. Since that time, three new sections have been added and many of the original standards have been revised to accommodate advances in wheelchair design and technology. The standards used for this study were approved in 1998. Volume 1 of the standards applies to manual wheelchairs. Volumes 1 and 2 are both needed in order to perform testing on electric-powered wheelchairs and scooters.

The results of this study are based on the testing of a sample of three wheelchairs for five different models. The ANSI/RESNA wheelchair standards are intended to provide objective information about wheelchairs. It should be noted that the performance a specific wheelchair user may get from his or her own wheelchair could vary depending on set-up, driving ability, and environmental conditions.

2.2.2 Electric Powered Wheelchair Standards

There are twenty different sections of the ANSI/RESNA wheelchair standards. While only certain sections apply to manual wheelchairs, all of the sections are relevant for electric-powered wheelchairs. However, only ten of the sections were selected for this study. These sections are listed below:

Section 1: Determination of static stability

Section 2: Determination of dynamic stability for electric wheelchairs

Section 3: Test methods and requirements for the effectiveness of brakes

Section 4: Determination of energy consumption of electric wheelchairs- Theoretical range

Section 5: Determination of overall dimensions, mass, and turning space

Section 6: Determination of maximum speed, acceleration, and retardation of electric wheelchairs

Section 7: Method of measurement of seating and wheel dimensions

Section 8: Requirements and test methods for static, impact, and fatigue strengths

Section 9: Climatic tests for electric wheelchairs

Section 10: Determination of obstacle-climbing ability of electric wheelchairs

Section 14: Power and control systems for electric wheelchairs

These ten standards provide detailed information about the safety, performance, and seating characteristics of an electric-powered wheelchair. Sections 1,2,3,4,6,10, and 14 provide important data about how an EPW performs. Sections 8 and 9 determine the durability of an EPW. Sections 5 and 7 provide information about seating and overall dimensions. The results of these ten tests can be used to compare different models of EPWs as well as to determine whether a specific wheelchair is best suited for a given user.

2.3 Previous Studies

2.3.1 Wheelchair Standards Testing

There have been several studies conducted using the ANSI/RESNA wheelchair standards. The most relevant study was conducted in 1993 when ten different EPWs were tested by the National Rehabilitation Hospital.

The National Rehabilitation Hospital tested ten EPWs from seven manufacturers according to the ANSI/RESNA wheelchair standards that were sanctioned in 1990 [15]. The results showed that none of the wheelchairs were ideal for every environment and that the advantages of each unit should be carefully considered when choosing an EPW. This holds true today, since there are even more wheelchairs and more options available to the consumer.

The report showed that there were differences between the wheelchairs for all of the tests. However, no statistical analyses could be performed because of the small sample sizes. Many of the wheelchair standards have also been revised since 1990. The sections for dynamic stability and effectiveness of brakes now involve testing on 0°,3°,6°, and 10° slopes as opposed to only 0° and 5° slopes.

Cooper et al. have performed studies using the ANSI/RESNA wheelchair standards on several different types of manual wheelchairs. An evaluation of selected ultralight manual wheelchairs found significant differences in fatigue life, value, and rearward stability tilt angle among the wheelchairs tested [6]. It was also discovered that the ultralight wheelchairs had significantly higher fatigue lives than lightweight manual wheelchairs. A cost analysis showed that although ultralight wheelchairs are initially more expensive than lightweight wheelchairs, they will last much longer and ultimately provide more value to the user.

The lack of safety and performance information available to users demonstrates the need for more test studies involving wheelchairs. Previous studies have shown that many differences exist between both manual and electric-powered wheelchairs that are considered to be similar in size and function.

2.3.2 Crash/Injury Studies

Cooper et al. also performed a study investigating the effect of braking method and restraints on electric-powered wheelchairs [16]. A 50th percentile Hybrid II test dummy (HTD) was used with eight different EPWs. The wheelchairs were driven at maximum speed and braking was initiated by releasing the joystick, reversing the joystick, and turning off the power. Trials were also conducted with a combination of the seatbelt and legrests on and off. Significant differences in braking distance, braking time, and braking acceleration were found for the three different methods. There were also significant differences in the head and trunk displacement. The HTD fell out of the test wheelchair 25.3% of the time when the legrests and seatbelt were removed. Falls were also found to be more likely when testing faster wheelchairs.

A study by Sosner et al. examined the forces, moments and accelerations experienced by a 50th percentile HTD in a manual wheelchair negotiating a curb [17]. They found that when the wheelchair was pushed off of a curb and the HTD hit the floor, the forces it experienced exceeded published Injury Assessment Values and Head Injury Criteria values. Fast et al also studied moments and accelerations on a restrained HTD III [18]. He found that restraints were effective in lowering forces experienced by the HTD when rolled into and off of a curb at a speed of 1m/s. Corfman et al found that when driving a wheelchair into a curb, 73% of the falls that occurred happened at a speed of 2m/s [19]. It was also discovered that 100% of the falls occurred when the seatbelt and legrests were off.

These studies demonstrate that there are significant safety and performance differences associated with both manual and electric powered wheelchairs. Differences in cost, stability, and fatigue life among similar types of wheelchairs are very common. Information concerning these factors can often help predict possible safety issues.

2.4 Test Wheelchair Information

The following section lists information about the five different models of electric powered wheelchairs selected for this study. In order to perform the testing without the knowledge of the wheelchair manufacturers, the wheelchairs were purchased through three different dealers by the Center for Assistive Technology at the University of Pittsburgh. Wheelchairs of different models were ordered with the same dimensions and components whenever possible. All of the wheelchairs have programmable speeds, accelerations, and retardations. The wheelchairs were tested according to the factory settings for these variables.

2.4.1 Everest & Jennings Lancer 2000

The Everest & Jennings Lancer 2000 is a rear-wheel drive electric-powered wheelchair. It comes equipped with removable armrests and legrests. It has a sling style backrest and is powered by two 12-volt, 60 amp-hour gel batteries that are connected in series. The controller is a programmable Penny & Giles PG8-55 (type# D49362) that was configured to the factory settings. Figure 1 shows a picture of the E&J Lancer 2000 ready for testing.

Figure 1 E&J Lancer 2000

Table 1 lists the serial numbers and price for each wheelchair.

Table 1 E&J Lancer 2000 Information

Power Study ID#	Serial Number	Unit Price
EJ#1	503001	$5,672
EJ#2	495012	$5,400
EJ#3	489069	$5,240

Manufacturer information:

Everest and Jennings Inc.

3601 Rider Trail South

Earth City, Missouri 63045

(800) 235-4661

(314) 512-7000

Fax (314) 512-7123

2.4.2 Sunrise Medical Quickie P200

The Sunrise Medical Quickie P200 is a rear-wheel drive electric-powered wheelchair. However, it is equipped with anti-tipping wheels that engage at slopes of 5° or greater and allows the wheelchair to function as a mid-wheel drive device. It comes equipped with removable armrests and legrests. It has a sling style backrest and is powered by two 12-volt, 60 amp-hour gel batteries that are connected in series. The controller is a programmable Penny & Giles (type # D49307) that was configured to the factory settings. Figure 2 shows a picture of the Quickie P200 ready for testing.

Figure 2 Quickie P200

Table 2 lists the serial numbers and price for each wheelchair.

Table 2 Quickie P200 Information

Power Study ID#	Serial Number	Unit Price
Q#1	P2-0011831	$5,172
Q#2	P2-0011712	$5,288
Q#3	P2-0011743	$5,576

Manufacturer information:

Mobility Products Division

7477 East Dry Creek Parkway

Longmont, CO 80503

(800) 456-8165

Fax (800) 300-7502

2.4.3 Invacare Action Arrow Storm

The Invacare Action Arrow Storm is a rear-wheel drive electric-powered wheelchair. It comes equipped with removable armrests and legrests. It has a sling style backrest and is powered by two 12-volt gel batteries that are connected in series. The controller is a programmable Invacare MKIVA (1065944) that was configured to the factory settings. Figure 3 shows a picture of the Action Storm ready for testing.

Figure 3 Invacare Action Arrow Storm

Table 3 lists the serial numbers and price for each wheelchair.

Table 3 Invacare Action Information

Power Study ID#	Serial Number	Unit Price
A#1	98B15408	$7,200
A#2	98B71193	$6,720
A#3	98B25631	$7,408

Manufacturer information:

Invacare Corporation

899 Cleveland Street

Elyria, Ohio 44036-4028

(800) 333-6900

Fax (800) 678-4682

2.4.4 Pride Health Care Jazzy 1100

The Pride Health Care Jazzy 1100 is a mid-wheel drive electric-powered wheelchair. It comes equipped with nonremovable armrests and legrests. It has a cushioned seat and backrest and is powered by two 12-volt, 60 amp-hour gel batteries that are connected in series. The controller is a programmable Penny & Giles Pilot series (type# D49637) that was set to the factory settings. Figure 4 shows a picture of the Pride Jazzy ready for testing.

Figure 4 Pride Health Care Jazzy 1100

Table 4 lists the serial numbers and price for each wheelchair.

Table 4 Pride Jazzy Information

Power Study ID#	Serial Number	Unit Price
J#1	J-920543	$4,063
J#2	J-919812	$4,633
J#3	J-920061	$4,280

Manufacturer information:

Pride Health Care, Inc.

182 Susquehanna Avenue

Exeter, PA 18643

(800) 800-8586

Fax (800) 800-1636

2.4.5 Permobil Chairman Corpus Power

The Permobil Chairman Corpus Power is a front-wheel drive electric-powered wheelchair. It comes equipped with nonremovable armrests and legrests. It has a cushioned seat and backrest and is powered by two 12-volt, 60 amp-hour gel batteries that are connected in series. The controller is a programmable Penny & Giles (type# D49323) that was configured to the factory settings. The Permobil Chairman differs from the other EPWs in this study because it has a motorized reclining back. This option comes standard on all Permobil wheelchairs. Figure 5 shows a picture of the Permobil Chairman ready for testing.

Figure 5 Permobil Chairman Corpus Power

Table 5 lists the serial numbers and price for each wheelchair.

Table 5 Permobil Chairman Information

Power Study ID#	Serial Number	Unit Price
P#1	46024WC	$13,550
P#2	45945WC	$13,508
P#3	45910WC	$13,264

Manufacturer information:

Permobil Inc.

6 B Gill St.

Woburn, MA 01801

888-737-6624

Fax 781-932-0428

Table 6 Wheelchair Components

	E&J Lancer	Quickie P200	Invacare Storm	Pride Jazzy	Permobil
Armrests	Detachable	Detachable	Detachable	Nonremovable	Nonremovable
Footrests	Swing-Away	Swing-Away	Swing-Away	Fold-Up	Fold-Up
Backrest	Sling	Sling	Sling	Cushion	Cushion
Controller	Penny & Giles	Penny & Giles	Invacare	Penny & Giles	Penny & Giles
Front Wheel Type Size (mm) Pressure (psi)	 Pneumatic 200x44 70	 Pneumatic 200x50 36	 Solid 190x50 n/a	 Pneumatic 300x80 50	 Pneumatic 300x80 30
Rear Wheel Type Size (mm) Pressure (psi)	 Pneumatic 355X54 45	 Pneumatic 260x85 50	 Pneumatic 200x76 50	 Solid 200x50 n/a	 Pneumatic 200x50 36

2.5 Power Analysis

In order to perform analysis of variance studies, it is vital to determine whether the proposed sample sizes provide enough power to prevent both Type I and Type II errors. A Type I error is the probability of rejecting a true hypothesis (α). A Type II error is the probability of retaining a false hypothesis (β). Statistical power is defined as $1-\beta$. It determines the probability of rejecting a false hypothesis. Statistical power is affected by the value of α, the sample size, and the effect size. In this study, statistical power was enhanced due to the fact that all of the groups had equal sample sizes. For pairwise comparisons of all treatment means, equal sample sizes maximize the precision of comparisons, as well as reduce problems associated with non-normality and other departures from the ANOVA model.

The equations below represent the method used to determine the statistical power of the analyses performed in this study [20].

$$\text{Power} = P\{F^* > F(1-\alpha; r-1, n_T - r) \mid \phi\}$$

Where ϕ is the noncentrality parameter:

$$\phi = \frac{1}{\sigma}\sqrt{\frac{n_i}{r}\sum(\mu_i - \mu_.)^2}$$

Where μ_i = treatment means, $\mu.$ = weighted mean, σ = standard deviation of the error terms, n_i = group i sample size, r = number of groups.

The statistical power was then obtained by using the number of degrees of freedom for the numerator, $\nu_1 = r - 1$ (5-1 = 4), the number of degrees of freedom for the denominator, $\nu_2 = n_T - r$ (15-5 = 10), the level of significance, $\alpha = 0.05$, and the noncentrality parameter, ϕ. These values were then used in accordance with a table listing power values for analysis of variance. The power values for the ANOVA and ANCOVA models used in this study are listed below in Tables 7-9.

The effect size of each model was also determined by computing the value of η^2. Eta squared is a measure of the explained variation and is defined in the equation below [21].

$$\eta^2 = \frac{SS_B}{SS_T}$$

where $SS_B = \sum n_i(\overline{Y_i} - \overline{Y})^2$ and $SS_T = SS_B + \sum(n_i - 1)S^2_{Y_i}$ with $\overline{Y_i}$ = the mean of group i, $\overline{Y}$ = the overall mean, and $S^2_{Y_i}$ = the variance of group i.

The effect size of each model is also listed in Tables 7-9.

Table 7 Static Stability Power Parameters

Parameter	Uphill Most Stable	Uphill Least Stable	Downhill Most Stable	Downhill Least Stable	Lateral Most Stable	Lateral Least Stable
Power	.64	.64	.62	.60	.27	.29
η^2	.95	.96	.79	.89	.36	.41

Table 8 Braking Power Parameters

Slope	Parameter	Forward Release	Forward Reverse	Forward Off	Backward Release	Backward Reverse	Backward Off
0º	Power	.54	.5	.56	.6	.6	.63
	η^2	.88	.83	.91	.95	.94	.99
3º	Power	.57	.5	.57	.53	.49	.49
	η^2	.79	.65	.78	.82	.69	.68
6º	Power	.54	.43	.62	.69	.58	.58
	η^2	.71	.79	.94	.89	.81	.80
10º	Power	.61	.63	.64	.63	.64	.62
	η^2	.90	.90	.97	.95	.97	.93

Table 9 Range and Obstacle Climbing Power Parameters

Parameter	Theoretical Range	Obstacle Climbing Ability			
		Forward		Backward	
		No Run-Up	0.5m Run-Up	No Run-Up	0.5m Run-Up
Power	.52	.53	.22	.40	.47
η^2	.74	.76	.31	.54	.65

It is evident from Tables 7-9 that some of the models are low on calculated statistical power. The normal procedure to increase power would be to increase the sample sizes. However, this method is impractical for this study due to the costs of the EPWs. The average cost of an EPW in this study was $7,132. In order to increase the sample size of each group by one, it would cost approximately $35,660. However, the effect size of most of the models helps to increase the power. For instance, $\eta^2 = .87$ for static stability testing in the uphill direction in the most stable configuration. This means that 87% of the variation is explained by the type of EPW. The large effect sizes help make up for the power lost due to the limited sample sizes.

3.0 STATIC STABILITY

3.1 Background

Section 1 of the ANSI/RESNA Wheelchair Standards is the Determination of Static Stability. The intention of this test is to provide basic information about the static tipping angle of wheelchairs in both the most and least stable configurations. Each wheelchair is tested facing uphill, downhill, and sideways.

The stability of a wheelchair depends largely on its footprint [22]. When a wheelchair is positioned on a level surface, each wheel has a contact point with the surface. If these points are connected with a continuous line, the footprint of the wheelchair is determined (see Figure 6). A wheelchair is considered to be statically stable if the center of gravity (cog) of the rider/wheelchair system remains within the footprint. The wheelbase of a wheelchair can be determined by measuring the length from the front wheel point of contact to the rear wheel point of contact. The width of the front wheels, from the outside edge to the outside edge was measured. The width of the rear wheels was measured in the same manner. The seat height was also measured. The cog of the rider/wheelchair system is affected by the height of the seat.

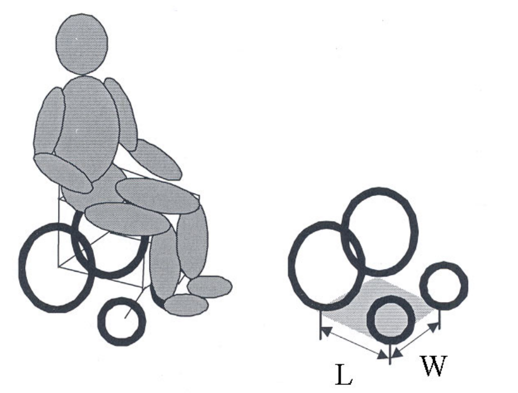

Figure 6 The Stability Footprint Created by a Wheelchair, W Represents the Track Width and L is the Wheelbase Length.

Adjusting certain components can alter the static stability of a wheelchair. For instance, increasing the angle of the backrest will shift the center of gravity of the user/wheelchair system towards the rear wheel contact points. This will increase stability in the downhill direction, but decrease stability in the uphill direction. Figure 7 shows the adjustable components on an EPW that may affect static stability.

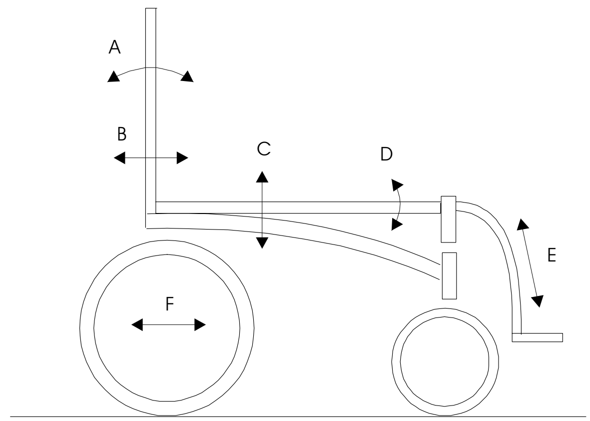

Figure 7 The Various Adjustable Components on an EPW That May Affect Static Stability. A is the Backrest Angle, B is the Horizontal Seat Position, C is the Vertical Seat Position, D is the Seat Angle, E is the Footrest Length, and F is the Horizontal Rear Wheel Position

It is possible to estimate the static stability of a wheelchair by creating a simple geometric model. A wheelchair becomes statically unstable when its cog passes beyond the boundary of its footprint. A right triangle can be created with the hypotenuse defined by the rear wheel point of contact (poc) and the cog (Figure 8). The corresponding angle, θ, represents the rearward tipping angle of the wheelchair. Since $\tan\theta = X/Y$, θ can be solved for if the values of X and Y are known. X is simply the horizontal distance from the poc of the rear wheel to the cog. This value can be measured by determining the distance of the backrest from the poc of the rear wheel and then adding the distance from the backrest to the cog. Y can be determined by adding the seat height to the vertical distance of the cog from the seat. For instance, the Quickie P200 has a seat height of 470mm and the backrest is 160mm in front of the rear wheel. The cog of the dummy/wheelchair was estimated to be at the stomach area of the dummy (120mm above the seat and 100mm in front of the backrest) [17]. Therefore, X= 260 and Y= 590. Since θ =

inv(tan)[260/590], θ = 23.8°. The forward and lateral tipping angles can be determined in a similar fashion. Uphill tipping angles for all of the wheelchairs using this model are listed in the results. Clinicians may utilize this simple method to estimate the static stability of different wheelchairs and set-ups before deciding what wheelchair is best for a given consumer. Wheelchair users may also use this method to determine how changing their own wheelchair will affect static stability.

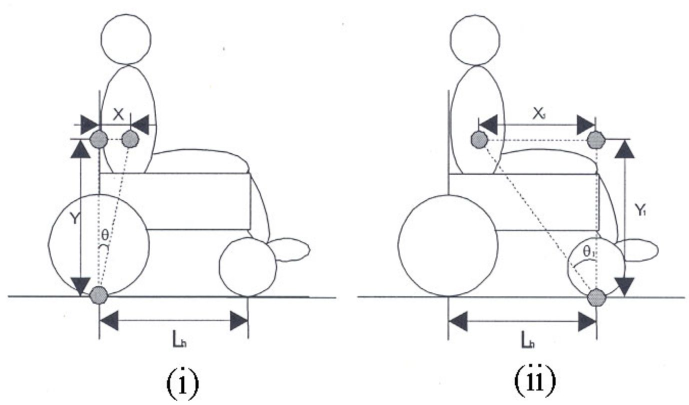

Figure 8 Geometric Tipping Angle for Backward (i) and Forward (ii) Directions

3.2 Methodology

3.2.1 Testing in the Downhill Direction

1.) All of the adjustable parts of the test wheelchair were set to the least stable configuration for downhill stability. Table 10 lists the components and positioning for this test.

Table 10- Component Configurations for Downhill Stability

Adjustable Wheelchair Component	Least Stable Configuration	Most Stable Configuration
Rear-wheel position	Forward	Back
Caster attachment to frame	Back	Forward
Seat position	Forward	Back
Seat position	High	Low
Seat-back position	Forward	Back
Seat-back position	Upright	Back
Seat position	Upright	Down

2.) A 100 kg ANSI/RESNA test dummy was then placed in the wheelchair seat.

3.) The wheelchair was positioned facing downhill with either straps or a block of wood used to prevent it from rolling or sliding. A piece of printer paper (0.08 mm thick) was also placed under the uphill wheel.

4.) The test plane was then inclined until the tipping angle was reached. This value was then recorded. The tipping angle was reached when the piece of paper could be slid out from under the uphill wheel.

5.) The test dummy was then removed from the wheelchair and the adjustable components were set to the most stable configuration for downhill stability.

6.) Steps 2-4 were then repeated and the tipping angle was recorded.

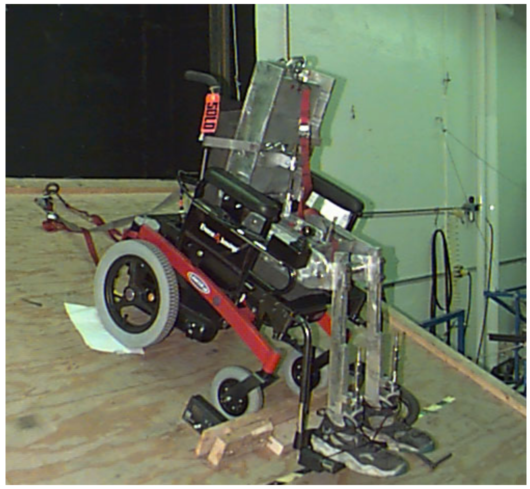

Figure 9 An E&J Lancer 2000 being tested for downhill static stability

3.2.2 Testing in the Uphill Direction

1.) All of the adjustable parts of the test wheelchair were set to the least stable configuration for uphill stability.

Table 11 Component Configurations for Uphill Stability

Adjustable Wheelchair Component	Least Stable Configuration	Most Stable Configuration
Rear-wheel position	Forward	Back
Caster attachment to frame	Back	Forward
Seat position	Back	Forward
Seat position	High	Low
Seat-back position	Back	Upright
Seat-back position	Back	Forward
Seat position	Back	Upright

2.) A 100 kg ANSI/RESNA test dummy was then placed in the wheelchair seat.

3.) The wheelchair was positioned facing uphill with either straps or a block of wood used to prevent it from rolling or sliding. A piece of paper was also placed under the uphill wheel.

4.) The test plane was then inclined until the tipping angle was reached. This value was then recorded. The tipping angle was reached when the piece of paper could be slid out from under the uphill wheel.

5.) The test dummy was then removed from the wheelchair and the adjustable components were set to the most stable configuration for uphill stability.

6.) Steps 2-4 were then repeated and the tipping angle was recorded.

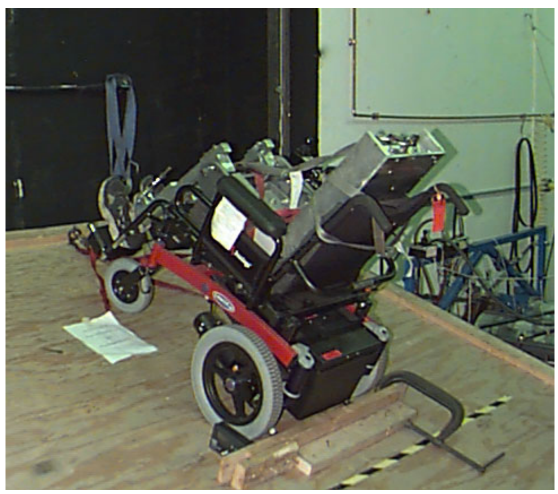

Figure 10 An E&J Lancer 2000 being tested for uphill stability

3.2.3 Testing in the Lateral Direction

1.) All of the adjustable parts of the test wheelchair were set to the least stable configuration for lateral stability.

Table 12 Component Configurations for Lateral Stability

Adjustable Wheelchair Component	Least Stable Configuration	Most Stable Configuration
Rear-wheel position	Narrowest Track	Widest Track
Caster attachment to frame, fore-aft	Back	Forward
Caster attachment to frame, inside-outside	Inside	Outside
Seat position, fore-aft	Forward	Back
Seat-back position, vertical	High	Low
Seat position, tilt	Upright	Back
Seat-back position, recline	Upright	Back

2.) A 100 kg ANSI/RESNA test dummy was then placed in the wheelchair seat.

3.) The wheelchair was positioned facing sideways with either straps or a block of wood used to prevent it from rolling or sliding. A piece of paper was also placed under the uphill wheel.

4.) The test plane was then inclined until the tipping angle was reached. This value was then recorded. The tipping angle was reached when the piece of paper could be slid out from under the uphill wheel.

5.) The test dummy was then removed from the wheelchair and the adjustable components were set to the most stable configuration for lateral stability.

6.) Steps 2-4 were then repeated and the tipping angle was recorded.

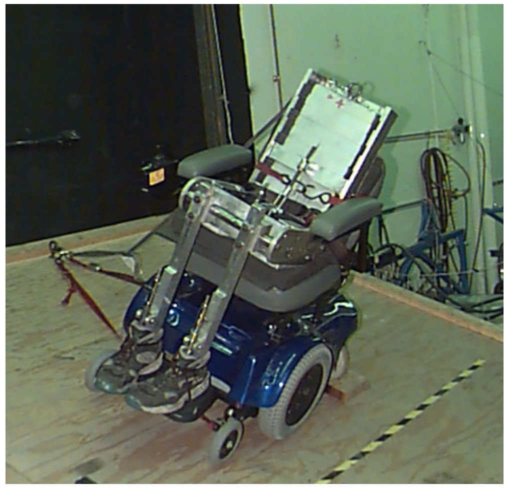

Figure 11 A Pride Jazzy being tested for lateral stability

3.2.4 Wheelbase Measurements

1.) The length of each wheelchair was measured from the center of the front wheels to the center of the rear wheels.
2.) The width of each wheelchair was measured from the outer edge of the front wheels as well as from the outer edge of the rear wheels.

3.2.5 Statistical Analysis

Analysis of covariance (ANCOVA) with a significance level of $p < .05$ was used to test the hypotheses. Although the data were not normally distributed, ANCOVA was used because the sample sizes were equal, the error terms were independent, and the nonnormality was not extreme. Several different ANCOVA models were developed to test the hypotheses. The static stability of a wheelchair depends on its wheelbase and seat height dimensions. A wheelchair with a low seat height and long wheelbase will be more stable than a wheelchair with a higher seat height and shorter wheelbase. Therefore, wheelbase and seat height were used as covariates when performing the analysis of covariance for static stability. Wheelbase length was used as a covariate for all of the uphill and downhill tests. Wheelbase width was used for the lateral tests. The Bonferoni method was used to perform post hoc analysis with $\alpha = .05$ and p distributed evenly among all tests. All statistical analyses were performed with SPSS.

3.3 Results

The results for static stability testing are listed in Table 13. The table shows the average angle when each type of wheelchair tips completely over as well as the standard deviation.

Table 13 Static Stability Tip Angles

	UPHILL				DOWNHILL				LATERAL	
WC	Most Stable	Least Stable	Antitip		Most Stable	Least Stable	Antitip		Most Stable	Least Stable
			Most Stable	Least Stable			Most Stable	Least Stable		
EJ #1	19.7°	15.7°	21.8°	19.1°	28.9°	26.4°	N/A	N/A	17.4°	17.4°
EJ #2	19.5°	17.8°	22.4°	19.8°	33.8°	29.1°	N/A	N/A	19.3°	17.8°
EJ #3	19.3°	16.8°	21.7°	20.1°	34.7°	28.2°	N/A	N/A	18.6°	17.7°
Q #1	5.1°	5.0°	25.5°	22.4°	27.9°	23.2°	N/A	N/A	24.8°	24.5°
Q #2	9.1°	4.8°	24.1°	23.0°	26.2°	22.5°	N/A	N/A	17.3°	16.9°
Q #3	5.7°	5.0°	25.7°	22.1°	27.1°	20.9°	N/A	N/A	17.8°	16.7°
A #1	22.5°	19.6°	26.4°	23.2°	19.7°	16.5°	N/A	N/A	16.2°	14.8°
A #2	19.8°	18.8°	25.1°	24.3°	25.9°	22.7°	N/A	N/A	17.6°	16.8°
A #3	20.3°	19.2°	26.6°	23.9°	29.7°	19.6°	N/A	N/A	18.7°	15.6°
J #1	18.2°	15.1°	N/A	N/A	25.6°	23.7°	27.5°	21.6°	18.7°	19.6°
J #2	17.5°	14.9°	N/A	N/A	20.8°	20.5°	23.0°	22.0°	16.1°	14.7°
J #3	17.1°	14.7°	N/A	N/A	19.5°	18.9°	24.0°	22.8°	14.7°	14.7°
P#1	32.1°	17.5°	N/A	N/A	37.3°	30.5°	N/A	N/A	18.6°	20.3°
P#2	31.5°	19.3°	N/A	N/A	37.3°	30.5°	N/A	N/A	21.2°	20.8°
P#3	33.6°	18.5°	N/A	N/A	37.8°	29.3°	N/A	N/A	20.6°	19.3°

N/A- Not Applicable

Table 14 shows the differences between the experimental and the theoretical model approach for the EPW's in the most stable configuration for the uphill direction.

Table 14 Experimental Vs. Theoretical Tipping Angles

Wheelchair	Experimental	Geometric Model	Difference
E&J Lancer	21.8°	20.1°	+1.7°
Quickie P200	25.1°	23.8°	+1.3°
Invacare Storm	25.9°	24.3°	+1.6°
Pride Jazzy	17.6°	23.3°	-5.4°
Permobil Chairman	32.4°	29.9°	+2.5°

Table 15 Wheelbase, Height, and Mass Measurements

WC	Length (mm)	Width (mm)	Seat Height (mm)	Mass (kg)
E&J Lancer	486;494	580	455	111
Quickie P200	635	590	470	92
Invacare Storm	450;500	610	510	117
Pride Jazzy	790	470	530;570	110
Permobil Chairman	640	460	540;690	123

Cells with two values for length and height represent the minimum and maximum adjustable dimensions.

There were significant differences between the five different types of EPWs for all of the static stability tests except for downhill stability in the least stable configuration and lateral stability in the most and least stable configurations. The Permobil Chairman tipped at a significantly larger angle than the Pride Jazzy when facing uphill in the most stable configuration ($p= .032$). The Permobil Chairman also tipped at a significantly larger angle than the Quickie P200, the Invacare Storm, and the Pride Jazzy when facing downhill in both the most ($p= .001$) and least ($p=.000$) stable configurations. The E&J Lancer tipped at a significantly larger angle than the Quickie P200, the Invacare Storm, and the Pride Jazzy when facing downhill in the least stable configuration ($p= .000$).

3.4 Discussion

Static stability is one of the most important factors when determining wheelchair safety. The Permobil Chairman is the most statically stable of the five types of wheelchairs. It recorded the largest tipping angles on all of the tests in the most stable configuration. The Permobil Chairman was the only front-wheel drive wheelchair tested. This would appear to give the Permobil Chairman more stability when facing uphill, but less stability when facing downhill. However, the placement of the seat over the center of the drive train and the low center of gravity of the body contribute to making this wheelchair most stable under nearly all of the conditions. The E&J Lancer and the Invacare Storm are both rear wheel drive wheelchairs. These wheelchairs are equipped with antitip devices that increase the stability of the wheelchair. Without these devices, the wheelchairs would tip over at a smaller angle. The Quickie P200 and the Pride Jazzy are essentially mid-wheel drive wheelchairs. The Quickie P200 has casters in the front and an additional set of wheels in the rear that are spring-loaded and contact the ground on slopes above 6°. The Pride Jazzy has caster wheels in the back and spring-loaded wheels in the front, similar to those of the Quickie.

The set-up of a wheelchair can also significantly affect the tipping angle. The results show that the difference in the tipping angle between the most and least stable configurations of a wheelchair can range anywhere from 2° to 14°. Kirby et al reported that adding loads to different positions on a wheelchair will affect the rear and forward stability [23]. The best location to place loads without significantly reducing stability is in the lap or the lower anterior portion of the wheelchair. Another study by Majaess et al suggests that the position of the seat also has a significant effect on static and dynamic forward and rear stability [24]. Moving the seat will alter the location of the center of gravity. For instance, moving the seat back will push the cog closer to the edge of the wheelchair's footprint created by the rear wheel. The wheelchair will then tend to tip when facing uphill at a smaller angle than before. The tipping range of a wheelchair in different configurations can provide important information to clinicians and consumers. Some people may want the ability to adjust the stability of their wheelchair for different conditions. The Pride Jazzy has very few adjustments and there is little difference between the most and least stable configurations. Most of the other wheelchairs, however, provide ample adjustment to produce a change of at least 5°.

A simple geometric model can be used to estimate static stability. The track width, wheelbase, seat height, and user dimensions are the only measurements necessary to estimate static stability. This information can be helpful when selecting the right wheelchair and to determine how stable certain set-ups will be. The geometric tipping results compared very favorably to the experimental results. Most of the tipping angles were within 2º of each other. The sole exception was the Jazzy wheelchair. The theoretical tipping angle differed from the experimental angle by 5.4°. The reason for this difference is that the Jazzy has a simple suspension system. When the wheelchair is tested in the uphill direction, it rocks backwards on springs and therefore reduces the tipping angle. The suspension system was not accounted for in the geometric model.

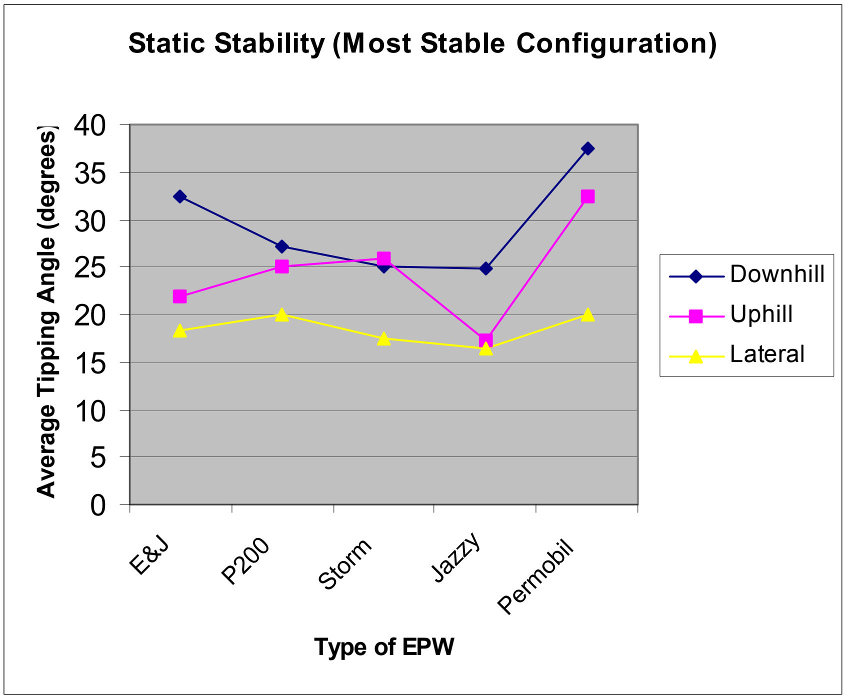

Figure 12 Average Tipping Angles of EPWs in the Most Stable Configuration

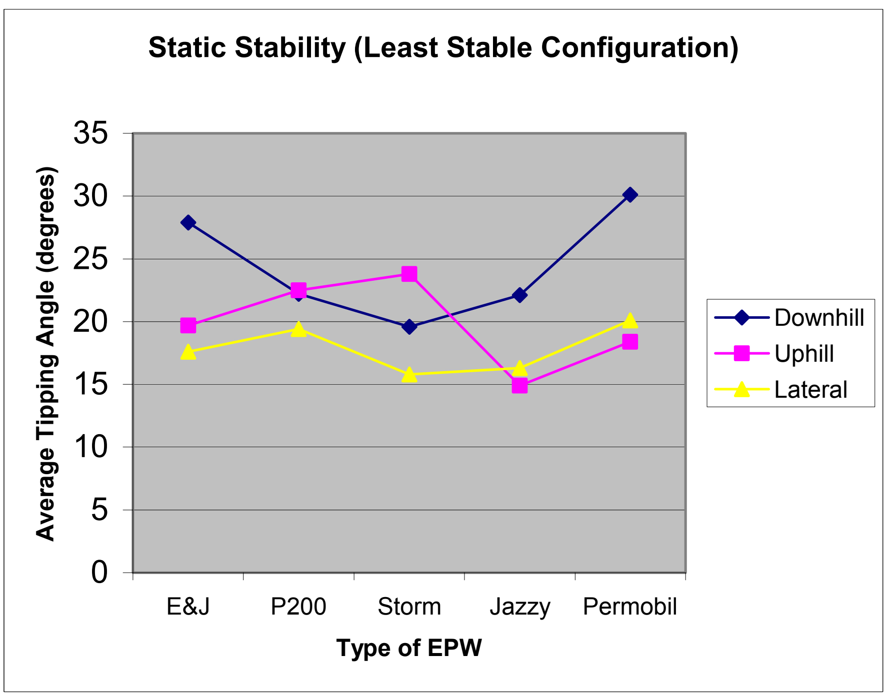

Figure 13 Average Tipping Angles of EPWs in the Least Stable Configuration

Figures 12 and 13 show that for all of the EPWs, the lateral direction had the smallest tipping angles, except for the Jazzy in the uphill direction in the least stable configuration. Lateral stability is just as important as uphill and downhill stability. Many EPW users do not traverse hills or slopes in a straight up and down direction. Antitip devices are also not as readily available to help prevent lateral tipping as they are for the front and back of wheelchairs. It also evident from the graphs that both the mid-wheel drive and front-wheel drive wheelchairs were more stable in the uphill than the downhill direction. This makes sense since the center of gravity of the wheelchair and the rider is positioned towards the front of the wheelchair. Interestingly, while the E&J was considerably more stable in the downhill direction, the other two rear-wheel wheelchairs did not have a large difference between the uphill and downhill directions. This similarity in stability can be attributed to the antitip devices. The results from this section demonstrate that the static tipping angles of the EPWs studied should provide enough of a safety factor for most users. None of the wheelchairs tipped below a value of 15º for any of the tests.

The ANSI/RESNA standard for determining static stability is an effective tool for comparing the stability of different EPWs, as well as calculating the change in stability of a specific wheelchair by altering the configuration. EPW users can compare the stability of different wheelchairs to help to determine which device will benefit them best. Having data available on the range of tipping when altering the original set-up will also provide valuable information on how the positioning of different components will affect overall stability.

4.0 DYNAMIC STABILITY

4.1 Background

Section 2 of the ANSI/RESNA Wheelchair Standards is the Determination of Dynamic Stability of Electric Wheelchairs. This test is intended to determine the stability of a power wheelchair when it is driven up and down inclined planes of varying degrees. The wheelchair is driven at maximum speed on slopes of 0º, 3º, 6º, and 10º. Forward downhill braking, backward downhill braking, and forward uphill braking are performed on the slopes. The stability of the wheelchair during these maneuvers is then rated.

Dynamic and static stability are the most important factors to consider when determining the safety of a wheelchair. The majority of wheelchair accidents are classified as tips or falls. Calculating the dynamic stability of an EPW can help determine the maximum slope that a user should attempt to negotiate and the maneuvers that can be performed on a given slope.

Past studies have demonstrated that the dynamic stability of an EPW depends extensively on the slope of the riding surface [15]. The information obtained from performing dynamic stability tests is also very different from the static stability testing. Speed, acceleration, and deceleration all influence the dynamic stability of an EPW. Similar to static stability, the location of the overall cog is very important. Front and mid-wheel drive wheelchairs are usually more stable in the uphill direction than in the downhill direction. The opposite holds true for most rear-wheel drive wheelchairs. Many different factors can combine to affect the dynamic stability of a wheelchair and performing the standard testing is the best way to compare these factors and their effects on different wheelchairs.

4.2 Methodology

4.2.1 Rearward Dynamic Stability

1.) The wheelchair seat was set to its maximum allowable height.
2.) The speed control was set to its maximum value.
3.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.
4.) The antitip devices were set in their shortest and highest positions.
5.) The performance of each wheelchair was rated according to the scale shown in Table 16.

Table 16 Scoring Criteria for Dynamic Stability

Observed Dynamic Response		Score
No tip:	At least one uphill wheel remains on the test plane.	4
Transient tip:	All uphill wheels lift, then drop back onto the test plane, and the antitip devices do not contact the test plane.	3
Transient antitipper:	All uphill wheels lift, then drop back onto the test plane, and one or more antitip devices contact the test plane.	2
Stuck on antitipper:	All uphill wheels lift off, the wheelchair antitip device contacts the test plane, and the wheelchair remains on the antitip device.	1
Full tip:	The wheelchair tips completely over with the wheelchair coming to rest at least 90° from its original orientation.	0

6.) The wheelchair, with the test driver in it, was then placed on a level test plane.

7.) From a stationary start, the controls were operated to give maximum acceleration in the forward direction. The dynamic response was scored according to table 1.

8.) Step #7 was then repeated on slopes of 3°, 6°, and 10° with the wheelchair facing uphill.

9.) The wheelchair was then run at maximum speed on the level test plane.

10.) Braking was initiated by releasing the joystick and the dynamic response of the wheelchair was scored according to table 17.

11.) Steps #9-10 were repeated, but braking was initiated by putting the joystick in reverse.

12.) Steps #9-10 were repeated again, but braking was initiated by turning the wheelchair power off.

13.) Steps #9-12 were repeated on slopes of 3°, 6°, and 10° with the wheelchair traveling forward on the uphill slope.

14.) Steps #9-13 were then repeated with the wheelchair traveling at maximum speed backwards down the slope.

4.2.2 Forward Dynamic Stability

1.) The backrest angle of the wheelchair was set to the most upright position.

2.) The leg rest angle of the wheelchair was set to the maximum elevation.

3.) The seat was set to the most forward position.

4.) The speed control was set to its maximum value.

5.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.

6.) The wheelchair was run at maximum speed down a 3° slope.

7.) Braking was initiated by releasing the joystick and the dynamic response of the wheelchair was scored according to table 1.

8.) Steps #6-7 were repeated, but braking was initiated by putting the joystick in reverse.

9.) Steps #6-7 were repeated again, but braking was initiated by turning the wheelchair power off.

10.) The wheelchair is run at maximum speed down a 3° slope onto a horizontal test plane.

11.) The dynamic response of the wheelchair was scored according to table 17.

4.2.3 Lateral Dynamic Stability

1.) The backrest angle of the wheelchair was set to the most upright position.

2.) The leg rest angle of the wheelchair was set as close as possible to 120°.

3.) The seat was set to the rearmost position.

4.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.

5.) The wheelchair was positioned facing downhill on a 3° test plane.

6.) The wheelchair was turned to the left with maximum acceleration until it was facing uphill.

7.) The dynamic response of the wheelchair was scored according to table 17.

8.) Steps #5-7 were repeated on 6° and 10° slopes.

4.2.4 Statistical Analysis

The Kruskal-Wallis one-way analysis of variance by ranks test was used to determine dynamic stability differences between the five groups. A non-parametric test was used because the data in this section were non-metric. The Mann-Whitney U test was then employed to perform pairwise comparisons of the different groups when a significant difference was found. For each test, $\alpha = 0.05$. All statistical testing was performed using SPSS.

4.3 Results

Table 17 Dynamic Stability Scores on Level Test Surface

WC	Forward				Backward			Turning	
	Start	Rel.	Rev.	Off	Rel.	Rev.	Off	Turn	Circle
EJ #1	4	4	4	4	4	4	3	4	4
EJ #2	4	4	4	4	4	4	2	4	4
EJ #3	4	4	4	4	4	4	4	4	4
Q #1	2	4	4	4	2	2	2	4	4
Q #2	2	4	4	4	2	2	2	4	4
Q #3	2	4	4	4	4	2	2	4	4
A #1	4	4	4	4	4	4	3	4	4
A #2	3	4	4	4	4	4	3	4	4
A #3	1	4	4	4	2	2	2	4	4
J #1	4	4	4	4	4	4	4	4	4
J #2	4	4	4	3	4	4	4	4	4
J #3	4	4	4	4	4	4	4	4	4
P#1	4	4	4	3	4	4	4	4	4
P#2	4	4	4	3	4	4	4	4	4
P#3	4	4	4	4	4	4	4	4	4

Table 18 Dynamic Stability Scores on 3° Test Slope

WC	Forward Uphill				Forward Downhill			Backward Downhill			Turning	
	Start	Rel.	Rev.	Off	Rel.	Rev.	Off	Rel.	Rev.	Off	Turn	Slope
EJ #1	4	4	4	4	4	4	4	4	4	3	4	4
EJ #2	4	4	4	4	4	4	4	4	4	2	4	4
EJ #3	4	4	4	4	4	4	4	4	4	3	4	4
Q #1	2	4	4	4	4	4	4	2	2	2	4	4
Q #2	2	4	4	4	4	4	4	2	2	2	4	4
Q #3	2	4	4	4	4	4	4	2	2	2	4	4
A #1	2	4	4	4	4	4	4	2	2	2	4	4
A #2	2	4	4	4	4	4	4	2	2	2	4	4
A #3	1	4	4	4	4	4	4	1	1	1	4	4
J #1	4	4	4	4	4	4	3	4	4	4	4	4
J #2	4	4	4	3	4	4	3	4	4	4	4	4
J #3	4	4	4	3	4	4	3	4	4	4	4	4
P#1	4	4	4	3	3	3	4	4	4	4	4	4
P#2	4	4	4	3	4	4	3	4	4	4	4	4
P#3	4	4	4	4	4	3	3	4	4	4	4	4

Table 19 Dynamic Stability Scores on 6° Test Slope

WC	Forward Uphill				Forward Downhill			Backward Downhill			Turning	
	Start	Rel.	Rev.	Off	Rel.	Rev.	Off	Rel.	Rev.	Off	Turn	Slope
EJ #1	4	4	4	4	4	4	4	4	4	3	4	4
EJ #2	4	4	4	4	4	4	4	4	4	2	4	4
EJ #3	4	4	4	4	4	4	4	4	4	2	4	4
Q #1	2	4	4	4	4	4	4	2	2	2	4	4
Q #2	1	4	4	4	4	4	4	2	2	2	4	4
Q #3	2	4	4	4	4	4	4	2	2	2	4	4
A #1	2	4	4	4	4	4	4	2	2	2	4	4
A #2	1	4	4	4	4	4	4	2	2	2	4	4
A #3	1	4	4	4	4	4	4	1	1	1	4	4
J #1	4	4	4	4	3	3	3	4	4	4	4	4
J #2	4	4	4	3	3	3	3	4	4	4	4	4
J #3	4	4	4	3	3	3	3	4	4	4	4	4
P#1	4	4	4	3	3	3	4	4	4	4	4	4
P#2	4	4	3	3	4	3	3	4	4	4	4	4
P#3	4	4	4	4	4	3	3	4	4	4	4	4

Table 20 Dynamic Stability Scores on 10° Test Slope

WC	Forward Uphill				Forward Downhill			Backward Downhill			Turning	
	Start	Rel.	Rev.	Off	Rel.	Rev.	Off	Rel.	Rev.	Off	Turn	Slope
EJ #1	4	4	4	4	4	4	4	4	3	3	4	4
EJ #2	4	4	4	4	4	4	4	4	3	2	4	4
EJ #3	4	4	4	4	4	4	4	4	2	2	4	4
Q #1	1	1	1	1	4	4	4	1	1	1	4	4
Q #2	1	1	1	1	4	4	4	1	1	1	4	4
Q #3	1	1	1	1	4	4	4	1	1	1	4	4
A #1	1	1	1	1	4	4	4	1	1	1	4	4
A #2	1	1	1	1	4	4	4	1	1	1	4	4
A #3	1	1	1	1	4	4	4	1	1	1	4	4
J #1	4	4	4	4	2	2	2	4	4	4	4	4
J #2	4	4	4	3	2	2	2	4	4	4	4	4
J #3	4	4	4	3	2	2	2	4	4	4	4	4
P#1	4	4	4	3	3	3	3	4	4	4	4	4
P#2	4	4	3	3	3	3	3	4	4	4	4	4
P#3	4	4	4	4	3	3	3	4	4	4	4	4

There were significant differences found between the wheelchairs when starting forward on a level surface. Differences were also found when braking while traveling backwards on a level slope by reversing the direction of the joystick and turning off power to the joystick. Significant differences were also found when braking while traveling backwards on a 3° slope using all three methods, as well as when starting forward when facing uphill. There were also significant differences when braking while traveling downhill using all three methods. Results from the testing on a 6° slope showed significant differences when braking while traveling backwards using all three methods. There were also significant differences when starting forward while facing uphill as well as braking while traveling forward downhill using all three methods. There were significant differences between the wheelchairs for all of the tests conducted on a 10° slope.

The Quickie P200 and the Invacare Storm were significantly less stable than the other three wheelchairs under the following conditions: starting forwards uphill on a 3°, 6°, and 10° slope, reversing the joystick while traveling backwards on level surface, releasing and reversing the joystick while traveling backwards down a 3°, 6°, and 10° slope, releasing and reversing the joystick and turning off power while traveling forwards up a 10° slope, and turning off the power when traveling backwards down a 10° slope. The Quickie P200 was significantly less stable than the E&J Lancer, the Pride Jazzy, and the Permobil Chairman when starting forward on a level surface. The Pride Jazzy and Permobil Chairman were significantly less stable than the three other wheelchairs when braking while traveling forwards down a 10° slope by releasing and reversing the joystick, and turning off the power. They were significantly more stable than the Quickie P200 and Invacare Storm when turning off the power while traveling backwards on a level surface as well as a 3° and 6° slope. The Pride Jazzy was significantly less stable than the E&J Lancer 2000, the Quickie P200, and the Invacare Storm when releasing the joystick, reversing the joystick, and turning off the power while traveling forwards down a 6° slope. The Pride Jazzy was also less stable than the Quickie P200 when braking while traveling forward down a 3° slope by using all three braking methods. The Pride Jazzy was also less stable than the E&J Lancer when braking while traveling forward downhill by turning off the power on a 3° slope. The E&J Lancer 2000 was significantly less stable than the Permobil Chairman and the Pride Jazzy when reversing the joystick and turning off the power while traveling backwards down a 10° slope, as well as braking while traveling backwards down a 3° and 6° slope by turning off the power. The Permobil Chairman was significantly less stable than the E&J Lancer, Quickie P200, and the Invacare Storm when braking while traveling forward downhill by reversing the joystick on a 6° slope.

4.4 Discussion

Dynamic stability testing is necessary to insure the safety of wheelchair users on inclined surfaces. Different braking conditions can affect the rate of deceleration of a wheelchair and influence stability. For instance, when the joystick is released, a wheelchair will come to a gradual stop because the motors have disengaged. However, if power to the joystick is cut off, then the electromechanical brakes will engage and the wheelchair will come to an abrupt stop.

The Quickie P200 and the Invacare Storm had the lowest stability scores when braking while traveling backwards downhill on all of the test slopes. They were also less stable than the other wheelchairs when starting forwards on an uphill slope. However, the Permobil Chairman and the Pride Jazzy both showed instability when braking while traveling forwards on a downhill slope. The tendency from these results suggests that the front and mid-wheel drive wheelchairs are less stable during dynamic braking on a downhill slope. This is an important issue for users to consider. Areas with numerous hills and slopes present stability problems for wheelchair users. With many wheelchair accidents being attributed to tips and falls, it is critical for clinicians and consumers to consider dynamic stability when selecting a wheelchair.

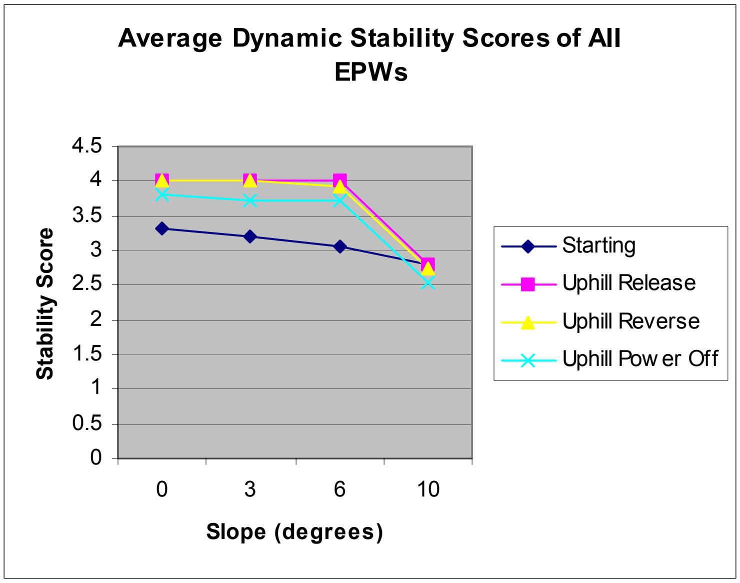

Figure 14 Stability Scores- Each Data Point Equals Average of all EPWs for Given Stability Condition

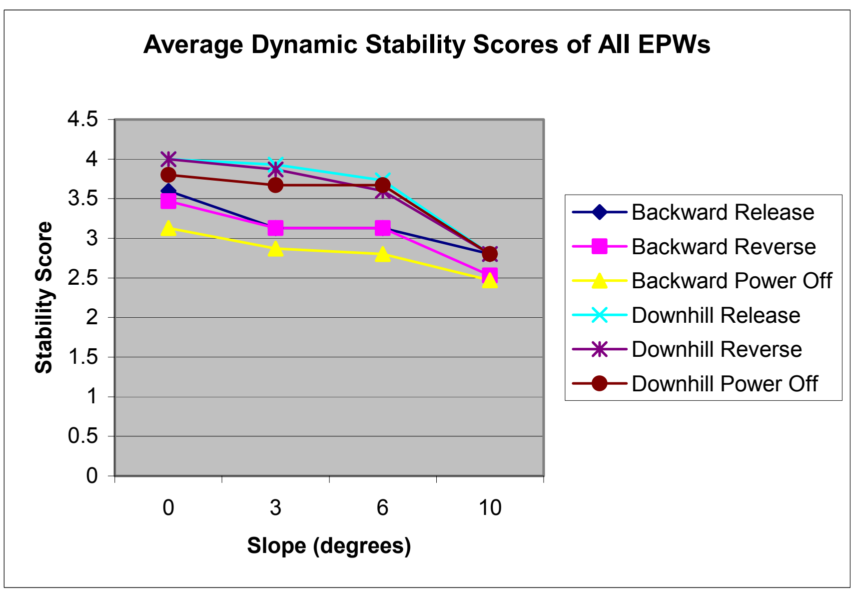

Figure 15 Stability Scores Contd.- Each Data Point Equals Average of all EPWs for Given Stability Condition

Figures 14 and 15 illustrate that the average dynamic stability scores for the EPWs in this study decrease as the angle of the test slope increases. The average score for all conditions drops below three on a 10º slope. This means that there is some degree of tipping for every test on the 10º slope. The change in stability between 3º and 6º is much less than the change in stability between 6º and 10º. However, none of the EPWs tipped completely on either the 6º or 10 º slopes. The backward stopping conditions produced the most unstable results on all slopes. These results highlight the effectiveness of antitip devices. The Permobil was the only EPW without any antitip devices. The limited maximum speed and considerable mass of the powerbase help prevent the Permobil from tipping. The results from this section demonstrate that the maximum forward and backward speeds and the use of antitip devices are significant factors in the evaluation of dynamic stability.

Since most EPW accidents and injuries result from some type of tip or fall, dynamic stability is an important factor that should be assessed when evaluating EPWs. Section 2 of the ANSI/RESNA standards provides useful information on the stability of wheelchairs under different braking conditions on different slopes [14]. The results show that dynamic stability is not only a function of the type of wheelchair (front, mid, or rear-wheel drive) but also the angle of the driving surface. One area that the standard appears to be lacking in is the ability to measure lateral dynamic stability. EPWs become very unstable when driven downhill and then turned sharply. Additional tests could be incorporated into the standard that account for dynamic turning, as well as performing the current tests while driving downhill at a skewed angle. The maximum speed and turning radius are also crucial factors that affect lateral dynamic stability. The faster a wheelchair drives and the tighter the turning radius, the greater the chance that it may tip when attempting to turn on a slope. The more data there is available on different dynamic stability conditions, the more educated people will be on the limitations of specific wheelchairs.

5.0 EFFECTIVENESS OF BRAKES

5.1 Background

Section 3 of the ANSI/RESNA Wheelchair Standards is the Test Methods and Requirements for the Effectiveness of Brakes. This test is intended to determine the braking distance of a power wheelchair. Three different braking conditions are used on four different slopes in order to determine the effectiveness of brakes under various conditions.

It is important for an EPW user to know the braking distance of his or her wheelchair under different conditions. The speed of the wheelchair and the slope of the surface are both integral factors in the braking ability of an EPW. The braking method also has an effect on the stopping distance. Releasing the joystick allows the motors to ramp down and usually creates the longest stopping distance. When power to the joystick is cut and the electromechanical brakes engage, the stopping distance can be significantly shorter.

5.2 Methodology

5.2.1 Forward/Backward Braking

1.) The user accessible speed control was set to its maximum value.
2.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.

3.) The wheelchair was driven forward at maximum speed on a level test plane and braking was then initiated by releasing the joystick.

4.) The braking distance of the wheelchair was measured and recorded. The braking distance is defined as the distance traveled by the wheelchair between initiating the command to halt and the wheelchair finally coming to rest.

5.) Repeat step #3-4 two more times.

6.) Steps #3-5 were repeated with the wheelchair traveling backwards on the level test plane.

7.) Steps #3-6 were repeated on 3°, 6°, and 10° slopes.

8.) Steps #3-6 were repeated with braking initiated by reversing the direction of the joystick.

9.) Steps #3-6 were repeated with braking initiated by turning the wheelchair power off.

5.2.2 Statistical Analysis

Analysis of covariance (ANCOVA) with a significance level of $p < .05$ was used to test the hypotheses. Although the data were not normally distributed, ANCOVA was used because the sample sizes were equal, the error terms were independent, and the nonnormality was not extreme. Two different ANCOVA models were developed to test the hypotheses. Speed is a significant factor that will affect the braking distance of a wheelchair. The faster a wheelchair can be driven, the longer the braking distance will be. Wheelchair speed was therefore used as a covariate when analyzing the braking distances of the wheelchairs. The Bonferoni method was used to perform post hoc analysis with $\alpha = .05$ and p distributed evenly among the tests. All statistical analyses were performed with SPSS.

5.3 Results

Table 21 Braking Distances on Level Test Surface

WC	Forward Braking (mm)			Backward Braking (mm)		
	Rel.	Rev.	Off	Rel.	Rev.	Off
EJ #1	1866.7	1370.0	856.7	843.3	446.7	136.7
EJ #2	2163.2	1583.3	1071.0	905.9	588.4	194.7
EJ #3	1092.2	791.6	753.5	402.2	283.6	215.9
Q #1	2543.3	2015.0	1950.0	1453.3	853.3	526.7
Q #2	1960.0	1511.3	1380.1	1308.1	719.7	580.0
Q #3	2273.3	1685.0	1635.0	1251.7	843.3	508.3
A #1	1989.7	1231.9	922.9	313.3	173.6	55.0
A #2	2246.2	1345.5	1173.9	343.2	254.0	101.6
A #3	2827.9	1570.6	1337.7	478.4	321.7	131.2
J #1	1236.1	956.7	884.8	571.5	402.2	342.9
J #2	1248.8	948.3	927.1	664.6	436.0	330.2
J #3	1096.4	901.7	838.2	516.5	410.6	325.8
P#1	1151.5	1011.8	824.0	482.6	342.9	249.8
P#2	984.3	961.0	639.2	317.5	275.2	207.4
P#3	1092.2	791.6	753.5	402.2	283.6	215.9

Table 22 Braking Distances on 3° Test Slope

WC	Forward Braking (mm)			Backward Braking (mm)		
	Rel.	Rev.	Off	Rel.	Rev.	Off
EJ #1	2326.7	1970.0	1276.7	1050.0	673.3	423.3
EJ #2	2730.5	2159.0	1638.3	1134.5	791.6	393.7
EJ #3	2561.2	1905.0	1511.3	1312.3	850.9	465.7
Q #1	3056.7	2940.0	2646.7	1640.0	1300.0	1026.7
Q #2	2116.7	1591.7	1854.2	1223.4	723.9	656.2
Q #3	1993.3	1498.3	1956.7	1231.7	918.3	763.3
A #1	2319.9	1723.0	1469.0	359.8	169.3	63.5
A #2	2394.7	2019.2	1544.7	567.0	382.2	386.2
A #3	3090.3	2167.5	1833.0	668.9	550.3	410.6
J #1	1316.6	1045.6	1049.9	740.8	436.0	393.7
J #2	1130.3	1011.8	1011.8	740.8	406.4	342.9
J #3	1189.6	1045.6	956.7	580.0	406.4	326.0
P#1	1117.6	901.7	1011.8	563.0	393.7	304.8
P#2	1010.0	716.7	623.3	370.0	220.0	143.3
P#3	1240.4	961.0	961.0	465.7	258.2	338.7

Table 23 Braking Distances on 6° Test Slope

WC	Forward Braking (mm)			Backward Braking (mm)		
	Rel.	Rev.	Off	Rel.	Rev.	Off
EJ #1	2630.0	2330.0	2213.3	1250.0	726.7	493.3
EJ #2	2794.0	2298.7	2167.5	1316.6	778.9	503.8
EJ #3	2662.8	2641.6	2497.7	1384.3	876.3	656.2
Q #1	4144.0	3813.3	4250.0	2345.3	1964.3	2108.2
Q #2	2696.6	2366.4	3509.4	1816.1	1502.8	1473.2
Q #3	1842.0	2582.3	3390.9	1621.4	1282.7	1384.3
A #1	2904.1	2802.5	2705.1	499.5	186.3	93.1
A #2	3136.3	2805.2	2660.5	793.9	681.8	616.8
A #3	3505.2	2777.1	2612.0	825.5	732.4	647.7
J #1	1291.2	1100.7	1100.7	800.1	512.2	482.6
J #2	1265.8	1104.9	1109.1	783.2	588.4	533.4
J #3	1282.7	1024.5	1003.3	766.2	563.0	461.4
P#1	1172.6	880.5	1248.8	651.9	427.6	571.5
P#2	1006.7	943.3	1080.0	490.0	293.3	380.0
P#3	1270.0	1016.0	1536.7	609.6	368.3	461.4

Table 24 Braking Distances on 10° Test Slope

WC	Forward Braking (mm)			Backward Braking (mm)		
	Rel.	Rev.	Off	Rel.	Rev.	Off
EJ #1	5130.8	5334.0	5689.6	1430.9	804.3	1278.5
EJ #2	5520.3	5554.1	6214.5	1367.4	859.4	1193.8
EJ #3	5063.1	4919.1	5799.7	1854.2	1024.5	1422.4
Q #1	6764.9	6798.7	7552.3	2667.0	2370.7	3496.7
Q #2	5249.3	5046.1	6663.3	2277.5	2006.6	2726.3
Q #3	4487.3	4470.4	6629.4	2370.7	2235.2	2671.2
A #1	3039.5	2696.6	2810.9	838.2	639.2	694.3
A #2	3878.8	3692.5	3353.4	829.0	558.5	879.5
A #3	4229.1	4119.0	3784.6	770.5	499.5	1049.9
J #1	1515.5	969.4	1054.1	821.3	622.3	651.9
J #2	1485.9	1308.1	1193.8	829.7	605.4	550.3
J #3	1718.7	1405.5	1557.9	935.6	740.8	622.3
P#1	1303.9	1058.3	1727.2	677.3	474.1	770.5
P#2	1299.2	1056.6	1878.4	650.0	483.0	757.0
P#3	1363.1	999.1	2159.0	643.5	478.4	690.0

There were significant differences between the five different types of EPWs for all of the effectiveness of brakes conditions. The E&J Lancer 2000, the Quickie P200, and the Invacare Storm had significantly longer braking distances than the other two chairs under the following conditions: releasing ($p= .002$), reversing the joystick ($p= .000$) while traveling forwards down a

6° slope, and releasing the joystick ($p= .000$) while traveling forwards down a 3° slope. The Quickie P200 had a significantly longer braking distance than the other four wheelchairs under the following conditions: releasing ($p= .000$) and reversing ($p= .000$) the joystick and turning off the power ($p= .000$) while traveling backwards on a level surface and down a 3°, 6°, and 10° slope, and turning off the power ($p= .000$) while traveling forwards down a 6° slope. The Quickie P200 also had a significantly longer braking distance than the Pride Jazzy and Permobil Chairman when releasing ($p= .003$) and reversing ($p= .009$) the joystick and turning off the power ($p= .001$) while traveling forwards on a level surface, and turning off the power ($p= .001$) while traveling forwards down a 3° slope, as well as turning off the power ($p= .000$) while traveling forwards down a 6° slope. The Pride Jazzy and Permobil Chairman had significantly shorter braking distances than the Invacare Storm when releasing the joystick ($p= .000$,.002) while traveling forwards on a level surface and down a 3° and 6° slope, and turning off the power ($p= .000$,.000) when traveling forwards down a 6° and 10° slope. The Permobil Chairman had a significantly shorter braking distance than the E&J Lancer and the Quickie P200 when reversing the joystick ($p= .006$) while traveling forwards down a 3° slope.

The Quickie P200 had the longest braking distances for most of the tests. Conversely, the Permobil Chairman and Pride Jazzy regularly had the shortest stopping distances. These results correspond with the top speeds of each wheelchair. The Quickie P200 and Invacare Storm were the fastest wheelchairs with average top speeds of 3.19m/s and 2.67m/s on a level surface. The Pride Jazzy and Permobil Chairman had average top speeds of 1.84m/s and 1.87m/s, respectively, and the E&J Lancer had an average top speed of 2.32m/s on a level surface

5.4 Discussion

The braking distance of a wheelchair can vary depending on its speed, the slope of the stopping surface and the method of braking. A wheelchair with a long braking distance may be harder to control when braking. Consumers must also be conscious of the fact that braking distances can be greatly increased by a downhill slope. The average braking distance of the E&J Lancer 2000 when turning off power to the joystick while traveling forwards downhill on a 10° slope is over six times the distance by braking the same way on a level surface. Wheelchair users should know how their wheelchair will perform under extreme conditions in order to prevent serious accidents. The maximum speed of a wheelchair also affects the stopping distance. This is an important factor for clinicians to consider when recommending what limitations should be placed on speed. All of the wheelchairs in this study have adjustable maximum speeds. The factory settings were used for this study.

The results from this study can also be compared to the results of the National Rehabilitation Hospital study conducted in 1993 [15]. The E&J Lancer, the Invacare Action XT, and the Permobil Max 90 were tested along with seven other EPW's. The braking distances have decreased for most of the wheelchairs since 1993. Table 25 compares the braking distances for three of the EPWs in each study.

Table 25 Braking Distances of EPWs Compared to NRH Study

WC	Speed (m/s)			Forward (mm)		Backward (mm)		Downhill* (mm)	
	For.	Rev.	Downhill*	Rel.	Rev.	Rel.	Rev.	Rel.	Rev.
E&J Lancer 2000	2.32	1.00	2.99	1707	1248	717	440	2696	2423
E&J Lancer[1]	2.4	1.6	3.1	2000	1700	1200	900	3500	2800
Invacare Action Storm	2.67	1.29	3.40	2355	1383	378	250	3182	2795
Invacare Action Arrow[1]	2.4	1.5	3.2	2300	1700	1000	500	4100	2800
Permobil Chairman	1.87	0.85	2.06	1076	922	401	301	1150	947
Permobil Max 90[1]	1.7	0.8	2.2	1100	900	500	400	1000	800

* Denotes that NRH study used 5º slope and this study used 6º slope
[1]Denotes EPW from National Rehabilitation Hospital Study

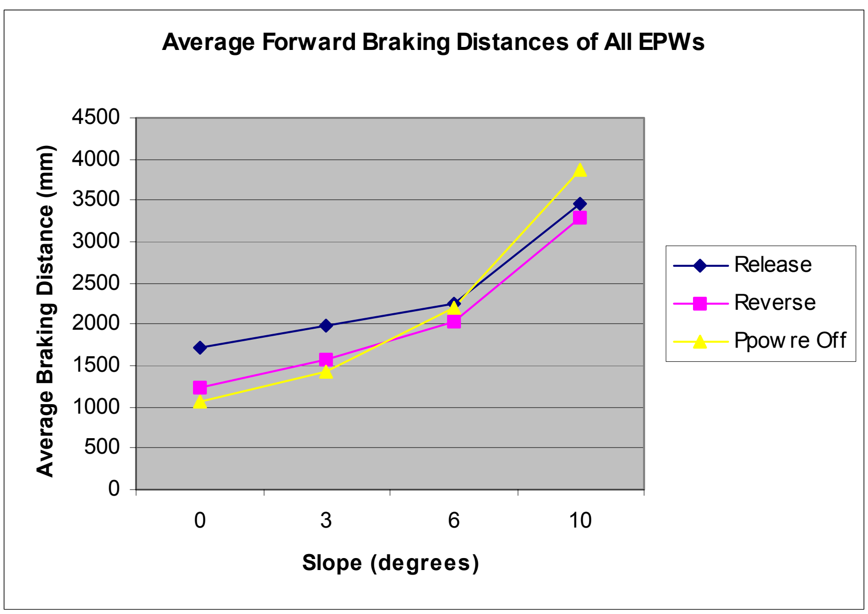

Figure 16 Braking Distance- Each Data Point Equals Average Forward Stopping Distance of All EPWs for Given Braking Method

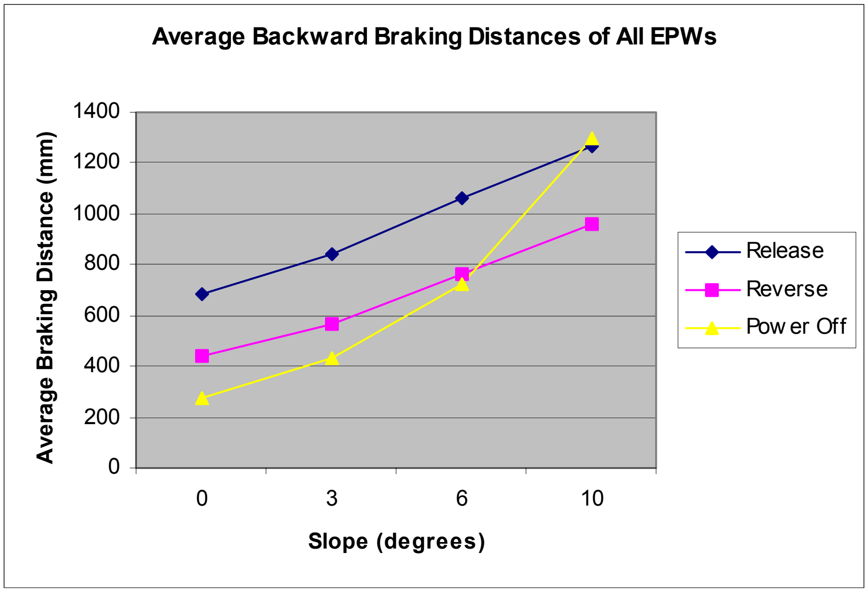

Figure 17 Braking Distance- Each Data Point Equals Average Backward Stopping Distance of All EPWs for Given Braking Method

Figures 16 and 17 demonstrate that the average braking distance of the EPWs increase as the degree of the test slope increases. Linear regression analysis performed on each braking condition for each slope shows that there is a positive upward trend for braking distance and slope (α = .05). Table 26 lists the R^2 values and significance levels for these tests.

Table 26 Linear Regression of Braking Distance and Slope

	Forward Release	Forward Reverse	Forward Off	Backward Release	Backward Reverse	Backward Off
R^2	.89	.94	.94	.99	.99	.95
Sig.	.055	.03	.029	.003	.003	.021

It should also be noted that while braking by turning off the power produced the shortest stopping distances on both the 3° and 6° slopes, this method of braking produced the longest stopping distances on the 10° slope. This is because of excessive sliding on the steeper slopes. When the power was killed and the elcetromechanical brakes engaged on a steep slope, the sudden deceleration caused most of the EPWs to continue sliding. The results of this testing shows that speed, braking method, slope, and surface conditions are all significant factors in the determination of effective braking distance.

6.0 ENERGY CONSUMPTION/THEORETICAL RANGE

6.1 Background

Section 4 of the ANSI/RESNA Wheelchair Standards is the Determination of Energy Consumption of Electric Wheelchairs and Scooters- Theoretical Range. The intention of this test is to determine the theoretical range of a power wheelchair on a full battery charge. All of the wheelchairs in this study run on a 24-volt system. Two 12-volt batteries are connected in series to provide the necessary 24 volts.

Wheelchairs use deep cycle batteries to power the motors that run them. A deep cycle battery is one that is designed to supply large amounts of energy over a lengthy period of time. The battery can then be recharged and drained over and over again. Most automobiles, on the other hand, utilize starting batteries. These batteries are designed to deliver high but short bursts of energy. They are not capable of being fully discharged and then continuously recharged.

Most EPW's run on one of three different types of batteries, group 22, 24, or 27. The larger the group, the more energy the battery can store. All of the EPW's in this study used group 24 batteries. The two main factors to consider when choosing a battery are amp-hours and cycle life. Amp-hours refer to the total energy that a battery can supply at a constant rate of discharge over a given period of time, usually twenty hours, before the charge drops to 10.5 volts. For instance, a 100Ah battery can supply a current of 5 amps for 20 hours before it is considered dead. Life cycle refers to how many times a battery can be fully discharged and then recharged before needing replaced. This is extremely important because wheelchair batteries function best on a full charge. Many users charge their batteries every night. Most EPW users find that typical battery life is about 9-14 months or around 365 cycles [25].

The range of an EPW is dependent upon many different variables. The total wheelchair and user weight, average speed, slope of the terrain, amount of starting, stopping, and turning, driving surface, weather, and driving style are a few of these variables. It is vital for EPW users to have an idea of how far their wheelchair can travel on a single charge, otherwise, they risk getting stranded, possibly in harmful or detrimental situations. Section 4 estimates the theoretical range of a wheelchair by measuring the current drain on the battery over a given distance. This value is then added to an equation that accounts for the energy capacity of the battery and determines what the maximum range of the wheelchair should be under the stated test conditions.

6.2 Methodology

6.2.1 Energy Consumption

1.) The wheelchair was conditioned at a temperature between 18°C and 25°C for not less then 8 hours.
2.) The batteries were fully charged.
3.) A watt-hour meter was attached to the wheelchair in order to measure the electric charge ampere-hours consumed from the wheelchair batteries.

4.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.

5.) The wheelchair was driven around the test track ten times to warm up the drive system.

6.) The wheelchair was driven around the test track at the maximum speed possible while staying within the confines of the track. The wheelchair was driven ten times in a clockwise direction and ten times in a counter-clockwise direction, starting and stopping the test in the same place.

7.) The electric charge ampere-hours used by the wheelchair was recorded.

8.) The theoretical range of the wheelchair was then determined by using the following formula:

$$R = \frac{C * D}{E * 1000} \quad (1)$$

Where

R = Theoretical range in km.

C = Capacity of the battery in ampere hours at five hours rate of discharge as declared by the battery manufacturer.

D = Total length of the test track in meters.

E = Electric charge ampere hours used during the test.

All of the batteries used for the energy consumption test had a 60 amp-hour rating. The total length of the test rack was 1090m.

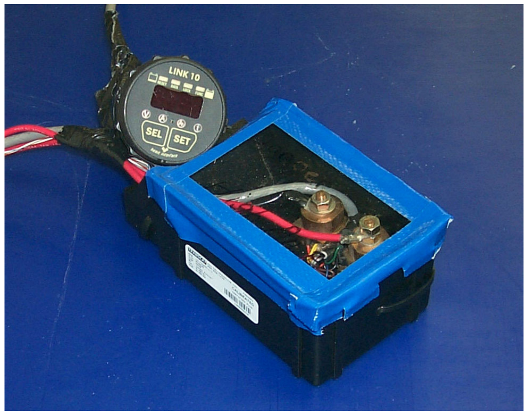

Figure 18 The Watt-Hour Device Used to Measure the Amp-Hour Drain on the Wheelchair Battery

6.2.2 Statistical Analysis

Analysis of variance (ANOVA) with a significance level of $p < .05$ was used to test the hypotheses. The data were fairly normally distributed and independent. The Bonferoni method was used to perform post hoc analysis with $\alpha = .05$. All statistical analyses were performed with SPSS.

6.3 Results

The results for energy consumption testing are listed below in Table 27.

Table 27 Theoretical Range of EPWs

Wheelchair	Amp-Hours	Theoretical Range (km)
EJ #1	2.2	29.7
EJ #2	2.2	29.7
EJ #3	2.2	29.7
Q #1	2.2	29.7
Q #2	1.9	34.4
Q #3	2.0	32.7
A #1	2.2	29.7
A #2	2.3	28.4
A #3	2.5	26.2
J #1	2.2	29.7
J #2	2.2	29.7
J #3	2.4	27.3
P#1	2.5	26.2
P#2	2.6	25.2
P#3	2.5	26.2

Equation (1) is shown again below, with the values obtained for EJ #1 inserted for the test variables. All of the theoretical ranges were determined with this method.

$$R = \frac{60Ah * 1090m}{2.2Ah * 1000} = 29.7km$$

There was a significant difference between the theoretical range of the Quickie P200 and the Permobil Chairman. There were no other significant differences between any of the EPW's.

6.4 Discussion

This testing was performed under ideal conditions. The temperature was approximately 22ºC, the test track was smooth and level, and all of the tires were inflated to their maximum values. Since the only variables involved in this testing were total mass of the rider/wheelchair system and speed, it is reasonable that the theoretical ranges of all of the wheelchairs were within 10 km of each other. In this case, the overall mass had a greater effect on the range then the speed. Due to the size of the test track, maximum speed was only attained briefly before a 90º turn was encountered. The average theoretical range of each model corresponds to the average mass. The Quickie P200 the largest average theoretical range at 32.3 km. The average mass of the three Quickies was 92.3 kg. The E&J Lancer, Invacare Action, and Pride Jazzy were next with calculated ranges of 29.7 km, 28.1 km, and 28.9 km respectively. The average masses of these wheelchairs were 111 kg, 116 kg, and 110 kg. The wheelchair model with the lowest range was the Permobil Chairman with an average of 25.9 km. The Permobil is the heaviest of the five models having an average mass of 123 kg. Overall mass is the main reason that the Quickie P200 had a significantly larger theoretical range than the Permobil.

Cooper et al performed a study to estimate the range for seven different EPWs by testing them on an ISO two-drum test machine, a motor driven treadmill, and around a tennis court [26]. The results showed that the range estimates obtained from the two-drum test were significantly different from those of the tennis court and treadmill. Simple relationships were found between all measured variables on the treadmill and tennis court test. The predicted range at maximum speed on the tennis court trials varied from 24 to 58 km.

The batteries used during this study were all gel cell lead acid batteries. These batteries contain a mixture of sulfuric acid, fumed silica, pure water, and phosphoric acid, which forms a gel pathway between plates. The advantage of these batteries is that they require no maintenance, they do not leak, discharge very low levels of gas when charging, have a reasonably long cycle life, and are approved for airline travel. They are however, heavier and more expensive than typical wet lead acid batteries and have about 10 to 20% less capacity. A study by Kauzlarich et al compared the performance of gel cell lead acid, wet cell lead acid, nickel cadmium, and nickel zinc batteries [27]. They found that the wet cell lead acid battery offered the best performance and lowest cost. However, this study was conducted in 1983 and there have been significant advances in battery technology since then.

Advances in battery technology may soon lead to smaller batteries that can hold greater charges. AGM batteries have absorbent glass mat placed between the plates. These batteries are more resistant to shocks and vibration than normal batteries and usually have lower self-discharge rates [28]. Current research has also focused on the development of nickel metal hydride (NIMH) and lithium (Li) based batteries. NIMH batteries are maintenance free and have energy densities 2-3 times that of lead acid batteries [25]. Lithium batteries also have extremely high power densities and require little or no maintenance. Nickel Cadmium batteries have long cycle lives at high rates of discharge, but are considerably more expensive than current options.

The future of wheelchair battery technology is dependent upon size, energy density, cycle life, and perhaps most importantly cost. The ability to use a small battery with extended energy output and life could change the way EPW's are designed. Currently, batteries account for anywhere from 20 to 50% of the total weight of an EPW. Reducing the weight of batteries would increase driving range considerably. Also, spare batteries could be carried with the user for emergency situations. Right now, this is impractical due to the size of lead acid batteries. However, smaller battery sizes may also discharge batteries deeper and reduce their life cycles significantly.

A recent study by Cooper et al analyzed the driving characteristics of 17 individuals who used EPWs as their primary means of mobility [29]. The study recorded the speed, distance traveled, and driving time of each subject for 24 hours over 5 days. The results showed that the EPW users were most active during the afternoon and evening and there was little variation in the speed or distance driven per day. The maximum theoretic distance that an EPW user would travel was determined to be less than 8 km per day. This value was determined by summing the maximum distance traveled each hour of the day by any subject within the study. The result yielded a maximum of 7970 m for a day. This value is approximately 29% of the average theoretical distance determined by this study. These numbers indicate that current battery capacity is sufficient for most EPW users. In fact, battery capacities may be larger than necessary and reductions in the mass and size of wheelchair batteries may be warranted. However, the effect on wheelchair stability must be considered when attempting to reduce battery weight. Since batteries account for between 20-50% of the total mass of EPWS, and are usually situated low and towards the center of the wheelchair, reducing their weight may significantly reduce both static and dynamic stability. Safety must be considered foremost when attempting to increase the other performance characteristics of EPWs.

7.0 OVERALL DIMENSIONS

7.1 Background

Section 5 of the ANSI/RESNA Wheelchair Standards is the determination of overall dimensions, mass, and turning space. The intention of this test is to determine the length, width, height, mass, and turning ability of wheelchairs. The overall dimensions are important factors to consider when selecting a wheelchair. Users must determine whether the wheelchair will fit in their home, work space, and automobile. Turning radius and turn around width are also important. Wheelchairs that make tighter turns are able to get into and out of smaller spaces. Overall mass is another important variable. Most EPW's weigh well over one hundred pounds. Batteries can weigh as much as fifty pounds apiece. Ramps and other structures must be strong enough to hold the combined weight of the wheelchair and user. Aides and other people must also be able to lift the wheelchair in and out of vehicles if the user travels frequently. Although these measurements are simple to determine, their importance should not be ignored.

7.2 Methodology

7.2.1 Overall Dimensions

1.) The overall length of the wheelchair was measured with the footrest set 50mm above the test plane and the caster wheels in the forward running position.

2.) The footrest was then removed and the overall length of the wheelchair was measured again with the caster wheels in the forward running position.

3.) The maximum width of the wheelchair was measured.

4.) The backrest was set to the vertical position and the height of the wheelchair was measured to the uppermost point.

7.2.2 Mass

1.) The mass of the wheelchair and its accessories was determined using the scale.

7.2.3 Turning Space

1.) The radius of the smallest circle inside which the wheelchair could be turned 360° was determined.

2.) The minimum width of a corridor in which the wheelchair could be turned 180° by using one backing motion was determined.

7.3 Results

The results for determination of overall dimensions, mass, and turning space are shown in Tables 28 and 29.

Table 28 Overall Dimensions and Mass

WC	Length (mm)	Length w/o Footrest (mm)	Width (mm)	Height (mm)	Mass (kg)
EJ #1	1040	750	630	915	111
EJ #2	1055	790	630	925	111
EJ #3	1075	790	630	960	111
Q #1	1030	845	595	900	92
Q #2	1065	845	570	890	93
Q #3	1055	845	610	870	92
A #1	1115	850	630	960	117
A #2	1095	850	630	770	117
A #3	1150	850	635	975	116
J #1	940	890	700	885	110
J #2	925	890	695	875	110
J #3	1005	890	690	880	110
P#1	955	830	640	1110	123
P#2	1075	830	645	1100	123
P#3	1110	830	650	1140	123

Table 29 Turning Radius and Width

WC	Turning Radius (mm)	Turn-Around Width (mm)
EJ #1	970	1105
EJ #2	971	1110
EJ #3	970	1105
Q #1	790	1070
Q #2	794	1073
Q #3	790	1070
A #1	870	1108
A #2	870	1110
A #3	872	1107
J #1	561	975
J #2	560	973
J #3	562	970
P#1	690	1121
P#2	692	1120
P#3	690	1121

7.4 Discussion

The overall dimensions of the EPW's fall within a small range of each other. An important factor to note is that the overall length of many of the wheelchairs can be reduced by removing or folding the footrests. Users often remove the footrests in order to maneuver more easily in their homes or workspaces. However, a study by Cooper et al showed that removing the footrests could result in more serious injuries during accidents [16].

The turning radius and turn around width are two of the most important tests associated with this section. Mid-wheel drive wheelchairs such as the Pride Jazzy provide excellent turning because the point of rotation is located in the middle of the wheelchair. The Pride Jazzy wheelchairs had the lowest average turning radius at 561 mm. The Permobil Chairman was next with an average turning radius of 690.7 mm. The Permobil Chairman is a front wheel drive wheelchair. The Lancer, P200, and Action wheelchairs are all rear wheel drive. The Americans for Disability Act of 1991 set specific guidelines for the construction of new public buildings [30]. The regulations call for a minimum wheelchair turning space of 1525 mm in order to make a 180º turn. The Jazzy and Permobil wheelchairs are the only two models that have turning diameters under 1525 mm. The Lancer, P200, and Storm all have turning diameters greater than 1525mm. Most individuals do not have the finances or ability to reconstruct their homes to fully accommodate an EPW. The turning radius of a wheelchair can make a big difference when it comes to maneuvering through hallways and in crowded rooms. Individuals who primarily use their wheelchairs at home or in the office can benefit greatly from mid and front wheel drive devices. Not only is less space needed for turning, but positioning the user over the front of the wheelchair also provides a better perspective for the driver. This reduces the chances that the driver will bump into walls or furniture with their wheelchair.

Most EPWs have an overall mass greater than 100 kg. The P200 was the only wheelchair in this study with a mass under 100 kg. Because of the weight of the batteries and the type and size of the metal used for the frame, EPWs can be excessively heavy. This limits the resources available to EPW users with respect to transportation. Many manual wheelchair users can simply take the wheels off of their chair and lift all of the components into an automobile. A study conducted by Mital found that the maximum acceptable dynamic lift for loading a wheelchair into a trunk was 21 kg [31]. Therefore, EPW users must use vans or buses with ramps or lifts to travel. This presents an entirely different safety issue. Bertocci et al used computer simulation to identify the magnitude, direction, and location of the loads that a wheelchair may experience during an automobile accident [32]. The results showed that different securement systems could have a significant affect on the loads experienced by the wheelchair and rider. It was also discovered that the yield strength of some wheelchair components were exceeded during the crash simulations.

Section 5 of the ANSI/RESNA wheelchair standards is useful for comparing the dimensions and turning abilities of different wheelchairs. Turning radius and turn around width are of particular interest to individuals with confined spaces. Most EPW users desire a wheelchair with the smallest possible dimensions and the smallest turning radius. Section 5 is an effective platform for determining and comparing these values between different wheelchairs.

8.0 MAXIMUM SPEED, ACCELERATION, AND RETARDATION

8.1 Background

Section 6 of the ANSI/RESNA Wheelchair Standards is Determination of Maximum Speed, Acceleration, and Retardation of Electric Wheelchairs. The intention of this test is to determine the maximum speed of the wheelchair as well as its maximum and average accelerations and retardations.

Most EPWs have adjustable speed and acceleration settings. A programmer can be used by the manufacturer or a clinician to adjust the value of the forward and backward maximum speed, overall and turning accelerations, and deceleration. EPWs coming from the manufacturer are usually set at mid-level default values. That was the case with all of the wheelchairs used in this study.

8.2 Methodology

1.) Any user accessible controls that influence the maximum speed, rate of acceleration, and/or retardation were set to the maximum values.
2.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.
3.) The wheelchair was driven at maximum speed on a level test plane.

4.) Braking was initiated by releasing the joystick.

5.) The maximum speed, overall acceleration and retardation, and maximum acceleration and retardation were measured and recorded.

6.) Steps #3-5 were repeated two more times.

7.) Steps #3-6 were repeated, but braking was initiated by reversing the direction of the joystick.

8.) Steps #3-6 were repeated again, but braking was initiated by turning the wheelchair power off.

9.) The wheelchair was run at maximum speed down the 3° test plane and then down the 6° test plane.

10.) The maximum speed was recorded for each slopes.

11.) Steps #9-10 were then repeated two more times.

12.) The wheelchair was then run at maximum speed up the 3° test plane and then up the 6° test plane.

13.) The maximum speed was recorded for each slope.

14.) Steps #12-13 were then repeated two more times.

The overall acceleration and deceleration of the wheelchair, A_o and R_o, were determined by using the following formulas:

$$A_o = \frac{0.9V}{T} V_m m/s^2 \quad \text{and} \quad R_o = \frac{0.9V}{T_R} V_m m/s^2$$

where T = the time taken for the wheelchair to accelerate from 5% to 95% of its maximum speed, V, and V_m is the arithmetic mean of the maximum speed for the three trials.

Likewise, the overall deceleration of the wheelchair, R_o, was determined by the same formula, but with T_R= the time taken for the wheelchair to slow down from 95% to 5% of its maximum speed.

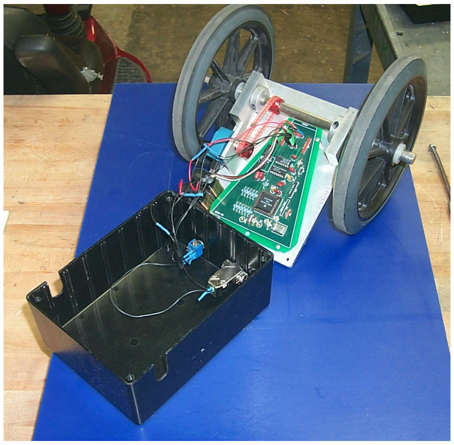

Figure 19 The Trailing Wheel Used to Record Speed and Acceleration.

Figure 20 The Trailing Wheel Attached to the Pride Jazzy During Testing.

8.3 Results

Table 30 Speed, Acceleration, and Retardation Values

	Max. Speed (m/s)				Acceleration		Retardation					
WC	Level Surface		Forward Downhill		(m/s^2)		R_m (m/s^2)			R_o (m/s^2)		
	For.	Back.	3°	6°	A_m	A_o	Rel.	Rev.	Off	Rel.	Rev.	Off
EJ #1	2.32	1.01	2.55	3.01	1.75	0.67	2.77	2.97	5.33	1.20	2.12	2.67
EJ #2	2.26	1.00	2.43	2.96	1.59	0.64	2.32	2.75	5.37	1.10	1.96	2.32
EJ #3	2.38	0.98	2.57	2.99	1.63	0.65	2.48	2.81	5.32	1.17	2.00	2.53
Q #1	3.14	2.18	3.37	3.85	2.13	1.30	3.71	4.89	5.46	2.21	2.63	2.90
Q #2	3.32	2.15	3.48	3.84	2.41	1.31	3.68	4.92	5.51	2.18	2.65	2.91
Q #3	3.10	2.15	3.44	3.79	2.33	1.28	3.72	4.87	5.47	2.22	2.60	2.87
A #1	2.77	1.30	2.89	3.41	2.37	1.22	2.82	3.91	3.99	1.40	3.42	3.30
A #2	2.79	1.28	2.89	3.42	2.48	1.1	2.83	3.81	3.95	1.42	3.44	3.31
A #3	2.45	1.30	2.83	3.36	2.35	1.03	2.79	3.86	3.88	1.33	3.41	3.12
J #1	1.79	1.00	1.89	2.08	1.85	0.98	2.54	2.59	2.94	1.52	1.95	2.03
J #2	1.81	1.02	1.93	2.15	1.93	1.00	2.52	2.51	2.89	1.49	1.95	2.11
J #3	1.92	1.97	1.97	2.19	1.89	1.10	2.53	2.56	2.91	1.50	1.99	2.05
P#1	1.87	0.84	1.83	2.03	1.65	0.88	2.51	2.76	3.10	1.22	1.98	2.26
P#2	1.85	0.87	1.81	2.06	1.68	0.89	2.55	2.77	2.93	1.26	1.97	2.31
P#3	1.88	0.85	1.81	2.10	1.76	0.94	2.48	2.68	2.94	1.20	2.11	2.09

8.4 Discussion

Cooper et al found that in a study of 17 EPW users, maximum attainable wheelchair speed was used sparingly [30]. It was theorized that maximum speed was used mainly for crossing streets, avoiding pedestrians, and other similar maneuvers. EPW users must have the ability to accelerate quickly to high speeds if the situation warrants it. Deceleration or retardation is just as important. For most instances, EPWs are not running at maximum speed and therefore do not need to stop suddenly. The method of releasing the joystick to brake the wheelchair is usually sufficient in such cases. However, if the wheelchair is running at maximum speed or needs to stop suddenly, a faster deceleration is needed. This can be accomplished by reversing the direction of the joystick or shutting off power to the controller. As observed in section 3, these two methods usually produce shorter stopping distances than by simply releasing the joystick.

The results for section 6 show that releasing the joystick produced an average overall deceleration of $1.49 m/s^2$ and an average maximum deceleration of $2.82 m/s^2$ for all of the EPWs. Reversing the joystick produced an average overall deceleration of $2.41 m/s^2$ and an average maximum deceleration of $3.38 m/s^2$. Shutting off the power produced an average overall deceleration of $2.59 m/s^2$ and an average maximum deceleration of $4.13 m/s^2$. Figures 21-23 show the acceleration curves for the Invacare Storm (A#1) using the three different braking methods. The graphs are almost identical except for the maximum deceleration values. When an EPW is stopped by releasing the joystick, current to the motor is stopped and the motors are allowed to coast down. This produces a very smooth deceleration. When the joystick is reversed, the current to the motors is switched to reverse the direction of the drive shaft. This obviously produces a shorter and more turbulent deceleration. In the most extreme case, power to the controller is shut off. This automatically engages the electromechanical brakes on the motor and creates the highest rate of deceleration.

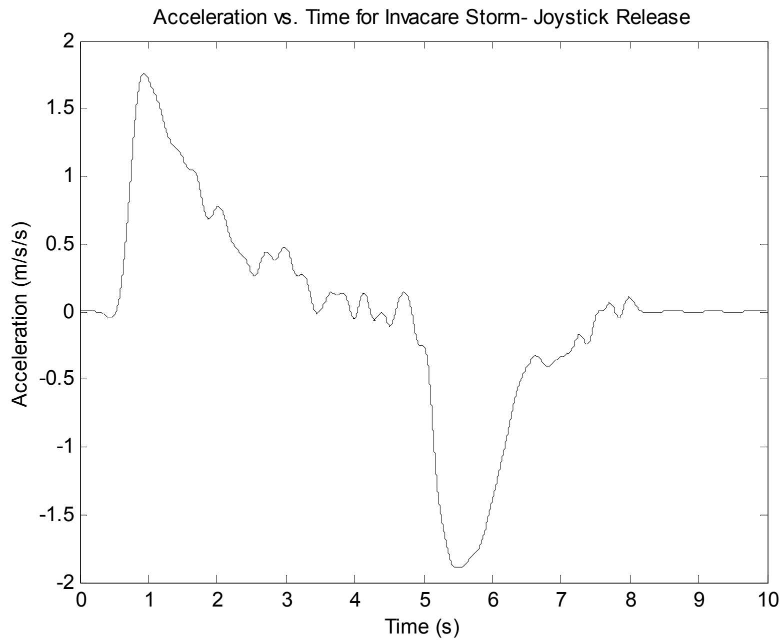

Figure 21 Acceleration Graph for Speed Trial of A#1 with Braking Initiated by Releasing the Joystick

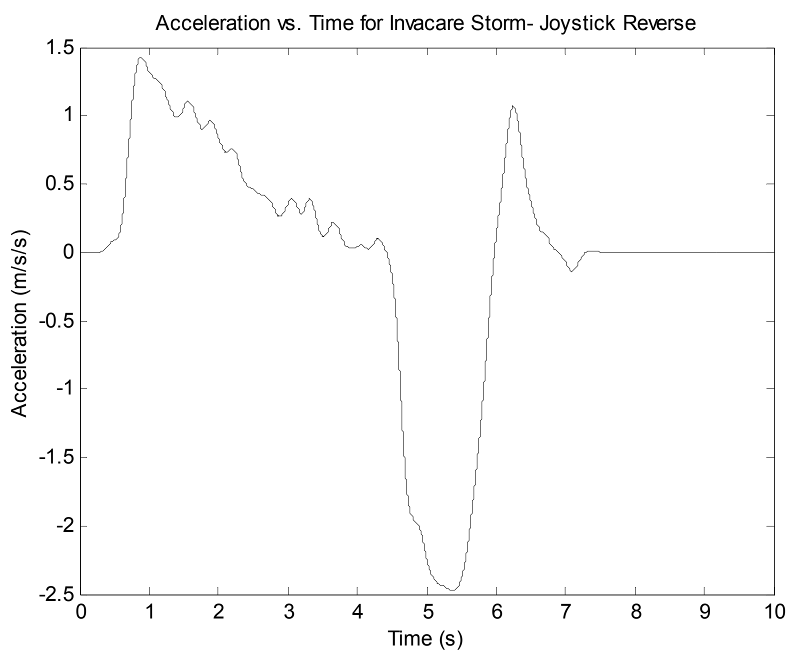

Figure 22 Acceleration Graph for Speed Trial of A#1 with Braking Initiated by Reversing the Joystick

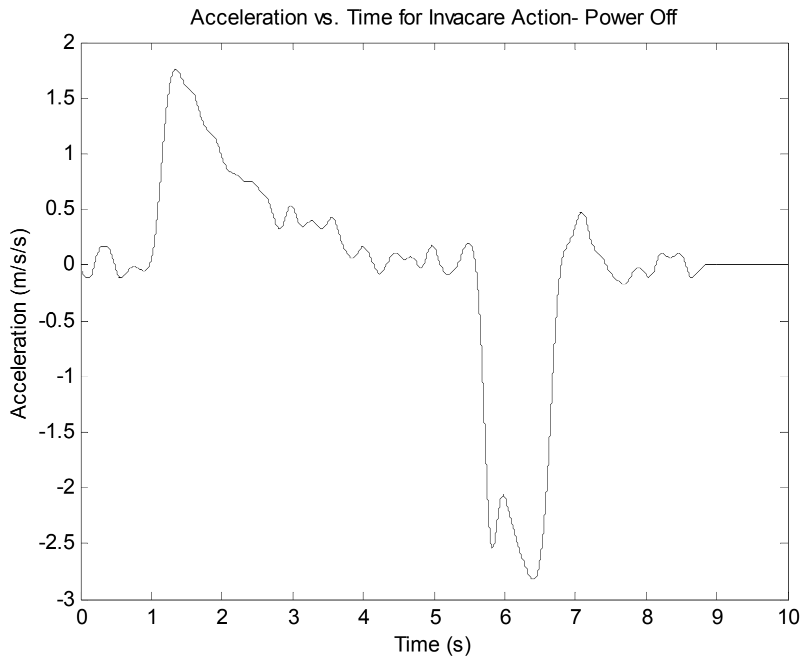

Figure 23 Acceleration Graph for Speed Trial of A#1 with Braking Initiated by Shutting Off the Power

The values for the maximum speed, acceleration, and retardation appear adequate for these EPWs. Increasing these parameters would have significant effects on the results of sections 2 and 3. Decreased dynamic stability and increased braking distances would be detrimental to the user and of small benefit compared to the inherent risks involved. Results of section 6 can be used to determine if the speed and acceleration parameters of a given wheelchair are adequate for an individual's intended use of the wheelchair. EPW users that are more active and travel outside will likely benefit from increased speed and acceleration, whereas users that spend more time indoors do not necessarily need such high values.

9.0 SEATING AND WHEEL DIMENSIONS

9.1 Background

Section 7 of the ANSI/RESNA Wheelchair Standards is the method of measurement of seating and wheel dimensions. The purpose of this standard is to disclose the various seat measurements of a wheelchair. Seating is a vital element of proper wheelchair prescription. The size of a seat, footrests, armrests, and backrest can have a significant effect on the comfort and function of a wheelchair user.

The ability of a wheelchair to accommodate different set-ups is a crucial factor for both comfort and functionality. It would be too expensive to custom build wheelchairs to the exact body specifications of each individual. Therefore, wheelchairs come in different sizes with adjustable components. Wheelchair users must evaluate how much variability they desire and determine what model will give them the ability to change dimensions as they grow or encounter new obstacles.

9.2 Methodology

1.) The wheelchair was placed on a level test plane and the reference loader gauge was positioned in the seat.
2.) The angle of the seat plane was measured.
3.) The effective seat depth was measured.
4.) The actual and effective seat widths were measured.

5.) The seat surface height at the front edge was measured.

6.) The backrest angle was measured.

7.) The backrest height was measured.

8.) The backrest width was measured.

9.) The distance from the footrest to the seat was measured.

10.) The footrest clearance was measured.

11.) The footrest length was measured.

12.) The footrest to leg angle was measured.

13.) The leg to seat surface angle was measured.

14.) The armrest height was measured.

15.) The distance from the front of the armrest to the backrest was measured.

16.) The armrest length was measured.

17.) The armrest angle was measured.

18.) The distance between armrests was measured.

19.) The front location of the armrest structure was measured.

Figure 24 An Action Wheelchair Equipped with a Reference Loader Gauge

9.3 Results

The results for the measurement of seating and wheel dimensions are shown in tables 31 and 32.

Table 31 Seating and Wheel Dimensions (dimensions in mm unless otherwise noted)

WC	Seat Angle	Seat Depth	Seat Width	Seat Hgt.	Back Angle	Back Hgt.	Back Width	Ftrst Seat	Ftrst Clear	Ftrst Lgth.
EJ #1	1.8º	415	460	470	5.8º	415	405	355	145	135
EJ #2	2.5º	415	460	455	1.4º	410	405	360	140	135
EJ #3	2.0º	415	460	455	2.3º	415	405	335	150	135
Q #1	10.2º	510	455	470	13.1º	440	400	400	90	150
Q #2	9.8º	510	455	470	10.2º	440	400	405	110	150
Q #3	10.1º	510	450	465	13.1º	440	400	390	100	150
A #1	6.5º	480	455	515	11.2º	455	400	315	230	150
A #2	5.7º	480	450	510	8.8º	455	405	310	230	150
A #3	5.2º	480	455	510	8.4º	460	405	320	230	150
J #1	9.6º	400	390	555	18.2º	345	410	460	110	185
J #2	8.3º	395	395	550	24.4º	345	415	455	95	185
J #3	9.2º	395	390	555	24.1º	345	410	460	105	185
P#1	11.7º	405	390	610	13.8º	600	310	430	150	230
P#2	10.7º	400	390	615	13.8º	600	305	410	175	230
P#3	11.7º	400	390	610	14.3º	595	305	405	160	230

Table 32 Seating and Wheel Dimensions Contd.

WC	Ftrst Angle	Leg Angle	Arm Hgt.	Arm Back	Arm Lgth	Arm Angle	B/w Arm	Front Arm
EJ #1	100.7	118.6°	260	305	280	75°	2.5	455
EJ #2	102.2	119.6°	255	300	280	75°	3.52	450
EJ #3	101.7	120.3°	255	300	280	75°	2.4	455
Q #1	90	100.6°	240	195	260	50°	7.62	455
Q #2	90	101.3°	240	190	260	50°	7.52	455
Q #3	90	101.1°	240	190	260	50°	7.8	455
A #1	107	118.6°	250	205	225	75°	4.3	450
A #2	104.6	117.4°	250	205	225	75°	4.1	445
A #3	107.4	120.7°	250	205	225	75°	4.5	450
J #1	98.4	98.8°	230	345	360	90°	0.87	450
J #2	106	99.3°	225	345	360	90°	0.9	440
J #3	103.4	100.5°	230	340	355	90°	1.2	445
P#1	97	73.4°	220	185	315	100°	8.2	460
P#2	91.4	81.4°	225	180	315	95°	7.2	460
P#3	96.2	72.1°	220	185	320	100°	6.6	455

9.4 Discussion

EPW users can best benefit from the results of section 7 by determining their own seating dimensions and comparing them to the measurements of a specific wheelchair. For instance, an individual should check if the height and length of a certain set of armrests will best fit their body. The maximum differences in armrest height and length for the wheelchairs involved in this study were 40mm and 125mm, respectively. Such sizeable differences can have a significant effect on wheelchair user comfort. All of the EPWs in this study had some degree of adjustability.

The results of section 7 demonstrate that most EPWs have small but important differences in seating dimensions. This section highlights the importance of having EPW users seek clinical assistance when attempting to choose an EPW. Seating dimensions can have a great effect on both comfort and functionality. Proper seating of an individual in their wheelchair can significantly increase their ability to function.

10.0 STATIC, IMPACT, AND FATIGUE STRENGTH

10.1 Background

Section 8 of the ANSI/RESNA Wheelchair Standards is the Requirements and Test Methods for Static, Impact, and Fatigue Strengths. The intention of this section is to determine the durability of a power wheelchair. Static and impact forces are applied to the components of the wheelchair that will experience very similar daily loads. The two-drum and curb drop machines determine if the fatigue strength of the wheelchair is adequate. The reliability of EPWs is important for many reasons. Component and frame failures can result in inconvenience and financial hardship for many users. Safety is also of paramount concern. One young individual was found dead of hypothermia after his caster fork broke and he was stuck in 5ºC temperatures [33]. EPW users depend on their wheelchairs to provide a safe and reliable means of transportation. It is important that the wheelchairs available to consumers provide this service with minimal complications.

Cooper and Fitzgerald have performed several studies to compare the fatigue life of different types of manual wheelchairs [4-6,34]. They found that the fatigue life for ultralight wheelchairs is significantly greater than for lightweight and depot wheelchairs. In one study, thirty-six percent of the ultralight wheelchairs experienced a class III failure, while 71% of the lightweight and 80% of the depot wheelchairs experienced a class III failure. Aircraft grade aluminum was used for the ultralight frames while low strength steel and composite materials were used for the other types of wheelchairs. Fatigue life has a significant affect on both the value and performance of a wheelchair. The average cost of an EPW in this study was $7,132. It has been estimated that maintenance costs for an EPW exceed $1,000 over a five-year period [35]. Many of the motor and drive system repairs often cannot be performed by technicians and require that the wheelchair be returned to the manufacturer. Most EPW users have neither the time nor the finances to deal with numerous repairs or failures. This standard helps to determine if the strength of the components, frame, and drive train is sufficient to provide the user with three to five years of reliable use.

10.2 Methodology

10.2.1 Wheelchair Setup

1.) The seat plane angle was adjusted as close as possible to 8°.
2.) The backrest angle was set as close as possible to 10°.
3.) The lowest part of the leg support/footrest was set as close as possible to 50mm above the test plane.
4.) All other adjustable components were set to their mid-positions.

10.2.2 Static Strength

1.) A downward force of 760N was applied to each armrest at an outward angle of 15° for 5 to 10 seconds.
2.) A force of 1000N was applied in a downward direction to each footrest for 5 to 10 seconds.

3.) A force of 750N was applied in an outward direction to each handgrip for 5 to 10 seconds.

4.) An upward force of 895N was applied at an outward angle of 10º for 5 to 10 seconds.

5.) A force of 440N was applied in an upward direction to each footrest for 5 to 10 seconds.

6.) A force of 880N was applied in an upward direction to each push handle for 5 to 10 seconds.

10.2.3 Impact Strength

1.) The back portion of the test dummy was removed.

2.) The backrest impact pendulum was set to an angle of 30° and then allowed to fall freely and strike the back of the wheelchair at a point 30mm from the top of the backrest.

3.) The test dummy was secured in the wheelchair.

4.) The test dummy was then removed from the wheelchair and the caster was aligned at 45° to the longitudinal axis of the wheelchair.

5.) The drive motors were then disengaged.

6.) The caster impact pendulum was set to an angle determined by the equation below and then allowed to fall freely and strike the caster at its midpoint.

$Cos\theta = 1 - \frac{M_d + M_w}{377}$ where θ= angle of swing in degrees, M_d= dummy mass in kg, and M_w= wheelchair mass in kg.

7.) The footrest impact pendulum was set to the angle determined by the above equation and then allowed to fall freely and strike the right footrest.

8.) Step #7 was repeated and the pendulum was allowed to strike the footrest.

10.2.4 Fatigue Strength

1.) The 100kg test dummy was placed in the wheelchair and a strap was secured around the upper leg portion of the dummy.

2.) The wheelchair was secured on a two-drum machine as specified in the standards.

3.) A 24-volt power supply was connected to the wheelchair and the batteries were replaced by weights.

4.) The wheelchair was run at a speed of 1.0 m/s for 200,000 cycles.

5.) The wheelchair was checked for damage and then placed on the curb drop machine as specified in the standards.

6.) The wheelchair was dropped a distance of 50mm 6,666 times.

7.) The wheelchair was then visually inspected for damage and operated to insure normal function.

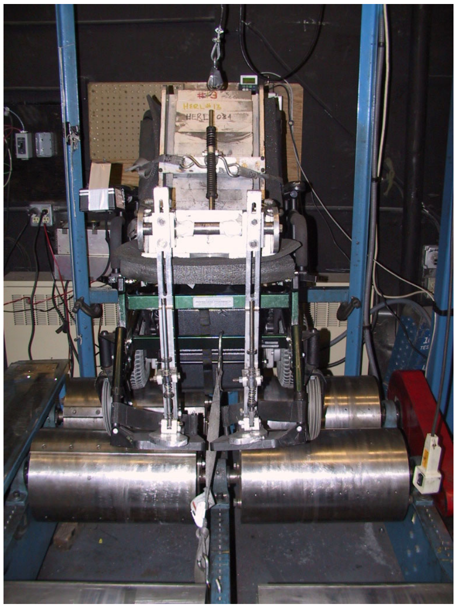

Figure 25 A Quickie P200 on the Two Drum Machine

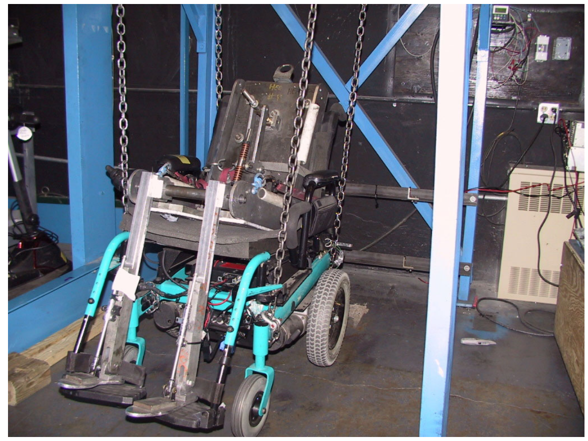

Figure 26 An Action Storm on the Curb Drop Machine

10.3 Results

Table 33 Static Strength Tests

WC	Armrests Down		Footrests Down		Handgrips Out		Armrests Up		Footrests Up		Push Handles Up	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
EJ #1	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
EJ #2	Pass	Pass	**Fail**	**Fail**	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass	Pass
EJ #3	Pass	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass	Pass
Q #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass
Q #2	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass	Pass	Pass	Pass
Q #3	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass	Pass	Pass	Pass
A #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #1	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A
J #2	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A
J #3	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A
P#1	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A
P#2	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A
P#3	Pass	Pass	Pass	Pass	N/A	N/A	N/A	N/A	Pass	Pass	N/A	N/A

Table 34 Impact Strength Tests

		Caster Impact		Footrest Impact- Long.		Footrest Impact- Lat.	
WC	Backrest Impact	Left	Right	Left	Right	Left	Right
EJ #1	Pass	Pass	Pass	Pass	**Fail**	Pass	Pass
EJ #2	Pass	Pass	Pass	**Fail**	**Fail**	Pass	Pass
EJ #3	Pass	Pass	Pass	**Fail**	Pass	**Fail**	**Fail**
Q #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass
P#1	Pass	Pass	Pass	Pass	Pass	Pass	Pass
P#2	Pass	Pass	Pass	Pass	Pass	Pass	Pass
P#3	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Table 35 Fatigue Strength Tests

WC	2-Drum Cycles Completed	Pass/Fail	Curb Drop Cycles Completed	Pass/Fail
EJ #1	200,000	Pass	6,666	Pass
EJ #2	23,712	**Fail**	-	N/A
EJ #3	200,000	Pass	6,666	Pass
Q #1	200,000	Pass	6,666	Pass
Q #2	200,000	Pass	6,666	Pass
Q #3	200,000	Pass	6,666	Pass
A #1	200,000	Pass	6,666	Pass
A #2	200,000	Pass	6,666	Pass
A #3	200,000	Pass	6,666	Pass
J #1	200,000	Pass	6,666	Pass
J #2	200,000	Pass	6,666	Pass
J #3	200,000	Pass	6,666	Pass
P#1	200,000	Pass	6,666	Pass
P#2	200,000	Pass	4,199	**Fail**
P#3	200,000	Pass	6,666	Pass

10.4 Discussion

The E&J wheelchairs experienced several failures with respect to the footrests during both the static and impact strength testing. The footrests were either permanently deformed or the mounting brackets failed. The use of stronger materials or reinforced struts could help prevent future failures. The Quickie was the only other type of EPW to experience any problems during static testing. The locking pins for the armrests did not hold when an upward force of 760 N was applied. The design of a more robust locking system may be warranted.

Only two of the fifteen wheelchairs did not make it through the fatigue testing. EJ#2 failed after 23,712 cycles on the two drum test due to a motor failure. A warning light started flashing on the joystick controller and the wheelchair would not run. A new joystick was swapped with the old one, but the same error persisted. Finally, the left motor and gearbox was replaced and the wheelchair functioned properly. The Permobil wheelchair, P#2, failed after 4,199 drops on the curb drop test. The screw for the rigid seat bar kept coming off and there were also electrical problems. The power cable to the controller kept disconnecting and one of the serial cables inside of the controller also became disconnected.

These two failures illustrate the difference between manual and EPWs. Most manual wheelchair failures that occur during fatigue testing involve the wheelchair frame or caster assembly [6, 34]. EPWs, however, are usually built to be more robust because of the increased pounding they take by being driven harder. This means that the motor assembly and electronics then become the most susceptible parts to failure. As witnessed by this study, most EPWs are built strong enough to withstand the fatigue testing of section 8. Many manual wheelchairs, on the other hand, experience failures before completing the minimum required cycles for both the two drum and curb drop tests [4,5,34].

One of the most critical aspects of EPW fatigue life is the strength versus weight ratio of the frame and components. EPWs can experience large forces and moments during normal everyday use. The maximum achievable speed and obstacle climbing ability of EPWs allow them to traverse rough terrain. Although no studies have been conducted to measure the forces and moments exerted on EPWs during everyday use, some studies have been performed on manual wheelchairs. VanSickle et al used customized wheels and casters to measure the dynamic reaction forces and moments exerted on a wheelchair during laboratory use, field-testing, and standardized testing [36]. The results indicated that wheelchairs are exposed to infrequent but high magnitude vertical forces. In addition to the high magnitude forces, a low level oscillating force was detected on the caster assembly. Although this force was only 250N, an individual that travels 3500km and pushes at a rate of 1m/s would put 3.5 million cycles on the caster. Therefore, wheelchair frames must not only be able to withstand large jolting forces, but low level sustained cyclic loading as well.

There is a need now for frame materials that can reduce weight, increase aesthetics, enable novel designs, increase durability, fit manufacturing requirements, and keep costs at a reasonable level [37]. High strength aluminum, titanium, and chromoly steel have better strength to weight ratios than traditional cold rolled steel, but are also more expensive. Composite materials utilizing carbon fiber allow for unique designs but significantly lower fatigue lives when exposed to prolonged cyclic loading. Many wheelchair manufacturers use a combination of materials to produce lighter wheelchairs. Plastics and composites can be used for low stress components.

Wheelchair vibration is an area that is receiving increased attention as new studies are revealing the magnitude and frequency that both the wheelchair and user are experiencing. VanSickle et al recorded the vibrations of 16 subjects in manual wheelchairs over a simulated road course and then sent them home with an instrumented wheelchair to record vibrations during normal daily activities [38]. Results from the road course showed that the acceleration at the wheelchair frame exceeded the 8-h fatigue-decreased performance boundary. The average peak for vertical acceleration was 8.1 Hz, much higher than the 4-6 Hz resonant peak presented in literature for seated humans. Suspension systems can help to reduce the vibrations and forces experienced by the wheelchair and the rider. The Lancer 2000 and Pride Jazzy were the only two wheelchairs with a suspension system. Both consisted of simple spring damping devices. More research is needed to determine whether specific frame designs and materials can help in reducing or eliminating vibration [38].

Fatigue analysis of EPWs can be expanded by testing the wheelchairs until failure. This involves continuously cycling the wheelchairs through the two drum and curb drop machines until the wheelchair experiences a catastrophic failure that renders it inoperable, or it experiences the same less catastrophic failure three times. Cost analysis and the overall value of different wheelchairs can be determined this way [6].

Static, impact and fatigue strength testing is one of the most rigorous and intensely scrutinized sections of all the wheelchair standards. It provides useful information to both the manufacturers and consumers. However, it may be beneficial to review some of the test procedures. The static and impact sections are intended to imitate the everyday forces and collisions that a wheelchair may experience. The standards, however, call for only a single application of the load or impact for five to ten seconds. More useful data may be obtained by performing cyclic loading of the armrests, footrests, and casters. The fatigue tests should also be re-examined. The study on the forces and moments exerted on manual wheelchairs during normal use by VanSickle et al found that the forces and moments being produced during normal use are significantly lower than those produced by the two drum and curb drop tests [36]. The laboratory testing also tends to produce asymmetrical loading patterns that may not be characteristic of actual use. Although similar studies have not been performed on EPWs, there is a significant chance that the results would be similar. A re-evaluation of the standards may prove advantageous in attempting to recreate normal wheelchair use in the laboratory.

11.0 CLIMATIC TESTS

11.1 Background

Section 9 of the ANSI/RESNA Wheelchair Standards is Climatic Tests for Electric Wheelchairs. The intention of this test is to determine whether a power wheelchair can withstand extreme environmental conditions. The technology to design and produce power wheelchairs is advancing every year. Controllers are often required to perform numerous tasks, and people use their power wheelchairs in all types of environmental conditions. It is imperative that the wheelchair and its electronics be able to withstand extreme conditions. Section 9 of the ANSI/RESNA Standards is intended to insure that a person caught in the rain or traveling outside in the winter will not be stranded due to a malfunction with their wheelchair. Unfortunately, very few laboratories have the necessary equipment to perform climatic testing. Therefore, data on this subject is not readily available to consumers. Most information that is available is outdated. The purpose of this section was to determine whether different types of popular power wheelchairs could hold up under severe conditions.

11.2 Methodology

1.) A functionality test was performed before and after each climatic test. The functions of speed control, braking, and steering were observed while driving the wheelchair on the path shown below in figure 27. Any deviation from the test path resulted in a failure for that test.

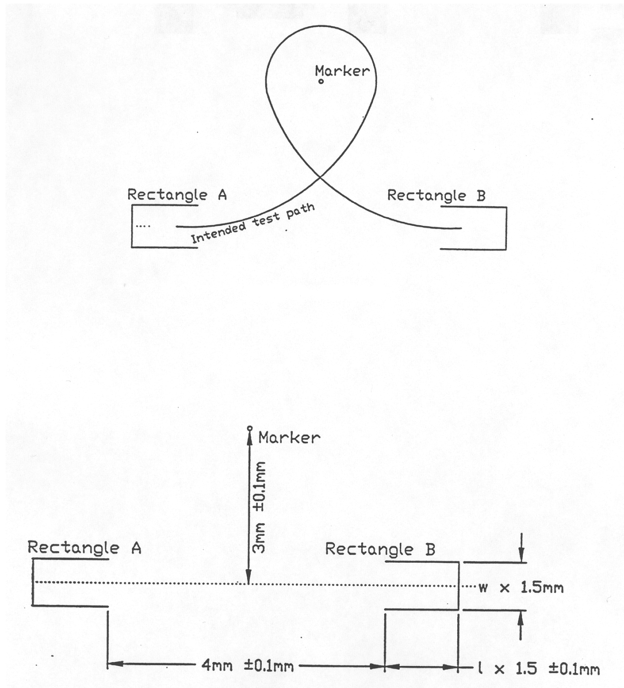

Figure 27 Test Path for the Functionality Check

1.) The functionality requirements for the wheelchair are listed below in table 36.

Table 36 Climatic Testing Functionality Requirements

Functionality Requirements
The wheelchair shall not exhibit performance, which, in the opinion of the tester, is dangerous.
The time taken to drive the wheelchair between the rectangles on the test path specified in Figure 27 shall not exceed 60 sec.
The wheelchair shall not fail to stop when commanded by its control device.
The wheelchair shall not fail to remain stationary when the control device is released.

2.) Rain Test- The wheelchair was preconditioned for 20 hours at 20 ± 5°C. A water spray was then applied to the wheelchair as specified in IEC Publication 529 (1989), Table II, second characteristic, numeral 4.

4.) Cold Operating Conditions- The wheelchair was preconditioned for 20 hours at 20 ± 5°C and a relative humidity of 50 +20%. The wheelchair was then placed in an environmental chamber (temperature range of –40°C-200°C and humidity range of 0-99%) at a temperature of –25 +2/-5°C for not less than three hours.

5.) Hot Operating Conditions- The wheelchair was preconditioned for 20 hours at 20 ± 5°C. The wheelchair was then placed in an environmental chamber at a temperature of 50 +5/-2°C for not less than three hours.

6.) Cold Storage Conditions- The wheelchair was preconditioned for 20 hours at 20 ± 5°C. The wheelchair was then placed in an environmental chamber at a temperature of -40 ± 5°C for not less than five hours.

7.) Hot Storage Conditions- The wheelchair was preconditioned for 20 hours at 20 ± 5°C. The wheelchair was placed in an environmental chamber at a temperature of 65 ± 5°C for not less than five hours.

Figure 28 The Tenney Environmental Chamber Used for Climatic Testing

11.3 Results

Table 37 Environmental Testing

WC	Rain Test	Cold Operating	Hot Operating	Cold Storage	Hot Storage
EJ #1	**Fail**	Pass	Pass	Pass	Pass
EJ #2	Pass	Pass	Pass	Pass	Pass
EJ #3	**Fail**	Pass	Pass	Pass	Pass
Q #1	**Fail**	Pass	Pass	Pass	Pass
Q #2	Pass	Pass	Pass	Pass	Pass
Q #3	Pass	Pass	Pass	Pass	Pass
A #1	Pass	Pass	Pass	Pass	Pass
A #2	Pass	Pass	Pass	Pass	Pass
A #3	Pass	Pass	Pass	Pass	Pass
J #1	Pass	**Fail**	Pass	Pass	Pass
J #2	Pass	Pass	Pass	Pass	Pass
J #3	Pass	**Fail**	Pass	Pass	Pass
P#1	Pass	Pass	Pass	Pass	Pass
P#2	Pass	Pass	Pass	Pass	Pass
P#3	Pass	Pass	Pass	Pass	Pass

A total of five of the fifteen wheelchairs tested for this study failed at least one part of the standards. Two of the Everest & Jennings Lancer 2000 wheelchairs and one Quickie P200 failed the rain test. E&J #8 appeared to function normally at first, however, after driving backwards and hitting the anti-tip bars, power was lost and could not be restored. This failure was most likely due to connector problems due to changes in the thermal response of the electronics. One hour later the wheelchair functioned normally. E&J #9 also appeared to function normally, however, after traversing a curb, the wheelchair would not drive. One hour later the wheelchair was able to drive again, however, it would also drift backwards while the joystick was in the neutral position. Quickie #6 drove backwards approximately 100mm while it was being tested for water ingress. The controller also started to beep. One hour after the test, the wheelchair did not respond to movement of the joystick and the power could not be turned off.

Two of the Pride Jazzy wheelchairs failed the cold operating test. The controller on Jazzy #13 could not be turned on until five minutes after the test. Jazzy #15 could not be turned on until ten minutes after the test.

11.4 Discussion

The results of the rain test demonstrate that it is vital for a wheelchair controller to be environmentally sealed. Two out of the three E&J wheelchairs tested failed the rain test. All of the wheelchairs that failed the rain test were outfitted with E&J PG8-55 Penny & Giles controllers.

The cold operating condition test is another very important test. If a wheelchair malfunctions due to extreme cold, the user could die due to exposure if he/she becomes stranded. Two out of the three Pride Jazzy wheelchairs failed this test.

Overall, one third of the power wheelchairs tested for this study failed at least one section of the climatic test standard. All of the wheelchairs passed the hot operating and hot and cold storage condition tests. The cold operating test is perhaps the most significant test in this standard. Failure of a wheelchair to operate under this condition can present immediate danger to the user. The rain test is another very relevant standard. If a power wheelchair fails to function after getting wet, then the user could be severely inconvenienced after going through a puddle or getting caught in a rainstorm.

People who depend on power wheelchairs for mobility need to know that their wheelchair will function properly in all situations. Power wheelchairs are now being designed to take the user wherever they want to go under any condition. Controller and wheelchair manufacturers must make sure that their products will perform to the required standards in any circumstance.

12.0 OBSTACLE CLIMBING ABILITY

12.1 Background

Section 10 of the ANSI/RESNA Wheelchair Standards is Determination of Obstacle-Climbing Ability of Electric Wheelchairs. The intention of this test is to determine the maximum height of an obstacle that the wheelchair can effectively negotiate. The ability of a wheelchair to overcome obstacles can place limitations on where a wheelchair user is able to drive. EPW's can vary greatly in their obstacle-climbing abilities. For instance, many of the front-wheel drive wheelchairs can negotiate obstacles quite effectively because their front wheels are usually quite large and power is supplied directly to these wheels. Rear-wheel drive wheelchairs have smaller caster wheels in the front and depend on using increased speed and power to help propel the chair over obstacles. The situation is reversed when attempting to negotiate an obstacle while traveling backwards. However, speed and acceleration are usually decreased when a wheelchair runs in reverse and therefore less power is available. Front-wheel drive wheelchairs are often better suited to climb obstacles in the forward direction than rear-wheel drive wheelchairs. This is due to the fact that FWD wheelchairs pull the casters and the rest of the wheelchair over an obstacle instead of pushing them, as is the case with RWD wheelchairs. The use of antitip devices also affects obstacle negotiation. Such devices are used to prevent wheelchairs from becoming dynamically unstable, however, they also limit how high the front wheels can raise off of the ground.

12.2 Methodology

1.) A human driver was used to perform the testing. Weights were added as necessary in order to bring the overall mass to 100kg.
2.) The speed controller was set to its maximum value.
3.) The wheelchair was driven forwards, without any run-up, at a 90 angle of incidence towards the obstacle. The height of the obstacle was increased by 19mm until the wheelchair could no longer climb it.
4.) Step #3 was repeated, but the wheelchair was facing backwards.
5.) Step #3 was repeated, but the wheelchair was facing forwards and had a 0.5m run-up.
6.) Step #3 was repeated, but the wheelchair was facing backwards and had a 0.5m run-up.

12.2.1 Statistical Analysis

Analysis of variance (ANOVA) with a significance level of $p < .05$ was used to test the hypotheses. The data were fairly normally distributed and independent. The Bonferoni method was used to perform post hoc analysis with $\alpha = .05$. All statistical analyses were performed with SPSS.

12.3 Results

Table 38 Obstacle Climbing Results

	Forward Direction (mm)		Backward Direction (mm)	
WC	No Run Up	0.5m Run Up	No Run Up	0.5m Run Up
EJ #1	38	57	38	57
EJ #2	38	38	38	76
EJ #3	38	57	38	57
Q #1	76	57	57	57
Q #2	57	57	38	38
Q #3	57	76	57	57
A #1	57	57	38	38
A #2	57	57	38	38
A #3	57	57	38	38
J #1	38	57	38	57
J #2	38	38	38	57
J #3	38	57	38	38
P#1	38	57	38	38
P#2	57	57	38	38
P#3	57	57	19	38

There was a significant difference between the maximum obstacle height negotiated between the Quickie P200, the E&J Lancer 2000, and the Pride Jazzy with no run up in the forward direction. The Quickie P200 climbed a significantly higher obstacle than the other two types of wheelchairs. The Quickie P200 also climbed a significantly higher obstacle than both the Invacare Action and the Permobil Chairman when driving backwards with a 0.5m run up. There were no other significant differences between the wheelchairs in any of the obstacle climbing tests.

12.4 Discussion

Wheelchair users encounter obstacles almost everywhere they go. Curbs and sidewalks present some of the most challenging obstacles. The ADA calls for curb cuts in new sidewalks that are being constructed (see figure 29). However, many sidewalks still exist that do not incorporate curb cuts. Therefore, wheelchair users depend on the climbing ability of their wheelchair to overcome such barriers. Door thresholds, potholes, and many other obstacles are also present. EPWs must couple the ability to overcome obstacles with the concern for dynamic stability.

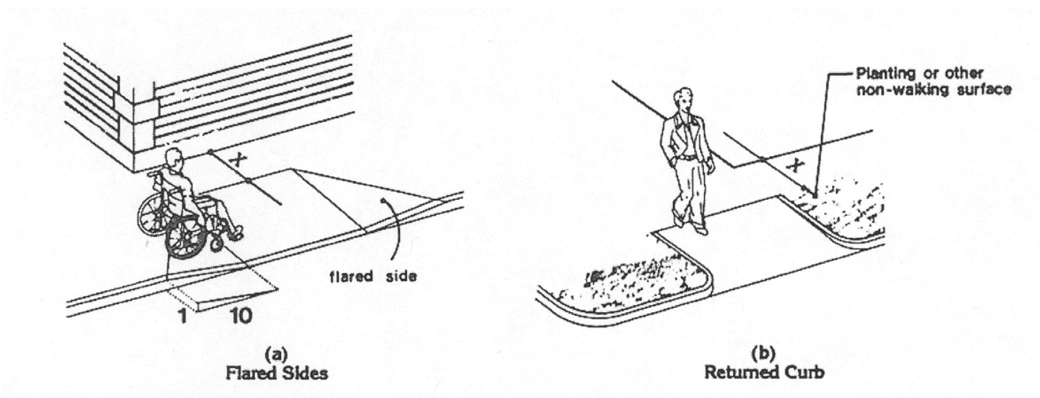

Figure 29 Drawing of Curb Cuts Required by the ADA

An EPW that will be used extensively outside should be able to climb a 50 mm obstacle without much difficulty. Even though the ADA calls for curb cuts in new sidewalks or when repairs are done, many sidewalks have no curb cuts. The height of curbs and many driveways and other common obstacles can reach 50 mm or greater. EPWs without the ability to climb these obstacles will leave the rider at a distinct disadvantage.

Speed and power are two of the most important factors involved with the obstacle-climbing ability of an EPW. The Quickie P200 was the fastest wheelchair of the five different models tested. It also performed the best on this section. The maximum height that any wheelchair was able to negotiate was 76mm. The minimum height was 38mm. This is a reasonable height for most wheelchairs to achieve. Indoor obstacles will rarely exceed 38mm. Outside, however, active wheelchair users would optimally like the ability to traverse much higher obstacles. Curbs, steps, and other obstructions can severely limit the range of a wheelchair outside. New wheelchair designs are being created to overcome such barriers. Clustering wheels, robotic arms, and treads have all been involved in research projects developed to provide greater obstacle-climbing ability for EPWs [39]. The Independence 3000 is a developmental EPW that has four drive wheels. Each set can cluster over top of the other and allow the wheelchair to traverse obstacles of up to six inches.

The obstacle climbing ability of a wheelchair also depends on the wheelbase size, antitipper height, and obstacle length. Wheelchairs with very long wheelbase lengths can get caught on short obstacles and straddle them. An EPW with low or unsuspended antitippers can also get caught on obstacles during the descent phase and effectively hang-up the wheelchair. EPW users therefore, have many factors to consider when attempting to determine the climbing ability of a wheelchair. Drive wheel placement, speed, antitipper height, wheelbase length, and obstacle dimensions must all be included in the equation. Future revisions of the obstacle climbing standard should consider using obstacles of different length in order to truly evaluate climbing ability.

13.0 POWER AND CONTROL SYSTEMS

13.1 Background

Section 14 of the ANSI/RESNA wheelchair standards is the requirements and test methods for the power and control systems for electric wheelchairs. The intention of this standard is to insure the protection of the wheelchair user during both normal operation as well as under certain failure conditions. The rapid development of microchip technology has led to the creation of more advanced electric powered wheelchairs. Wheelchair microcprocessors control the brakes, motors, and all other electronic devices that are found on wheelchairs. Not only is it important that an EPW functions safely during normal operation, but it is also imperative that they do not imperil the user when a failure or malfunction occurs.

13.2 Methodology

6.1 Battery Connection and Circuit Protection Diagram

1.) Remove any covers from the batteries. Check to see if there is a diagram present.
2.) Is the diagram attached permanently to a surface as close a s possible to the batteries?
3.) Check if the diagram contains the following: connections to the batteries with the identification of the wire and terminals; the location and pictorial instructions for use of all circuit breakers and fuses intended to be serviced by the user or an attendant; the current rating and type of any fuses.

6.2 Color and Marking of Wires Connected to the Batteries

1.) Check if all wires connected to the positive terminal of the most positive battery pack are red and permanently marked with a “+” symbol.
2.) Check if all wires connected to the negative terminal of the most negative battery pack are not red and are permanently marked with a “-“ symbol.
3.) Check if all other wires connected to the batteries are not red.

6.3 Electrical Isolation of Wheelchair

1.) Support the wheelchair so that it is secure and the drive wheels are lifted off the ground and free to revolve.
2.) Check if there is any electrically conducting part of the wheelchair frame, motor cases, gearbox, battery cases or controller cases that can be touched by the standard unjointed test finger. If there is, remove paint or other protective coatings and apply the positive connection test finger in turn to all of the electrically conductive parts of the wheelchair chassis. Check if the current is greater than 5mA.
3.) Apply the negative connection test finger in turn to all of the electrically conductive parts of the wheelchair chassis. Check if the current is greater than 5mA.

6.4 Fuses

1.) When changing fuses that do not need a tool for access, check if it is possible to touch electrically live leads or terminals exposed during this procedure to any other part of any electrical circuit.

6.5 Interchangeability of Connectors

1.) Check if it is possible that connectors provided for use by the wheelchair occupant or attendant can be connected in a manner that will cause operation different from that specified by the manufacturer.

2.) Check if the connectors use only color-coding to identify correct assembly.

3.) Check if it is possible to connect any connector intended for operation at or below the battery set nominal voltage to any socket intended for domestic or industrial power distribution.

6.6 Attachment and Positioning of Wiring

1.) Examine all wires to see if they can be snagged on furniture or any other protrusions, damaged by moving parts, or trapped in any pinch points.

6.7 Protection from Non-Insulated Electrical Parts

1.) Apply the standard unjointed test finger to all openings from every possible position with a force of 30N.

2.) If the finger enters any openings, use the standard jointed test finger to determine if any non-insulated electrical parts can be touched.

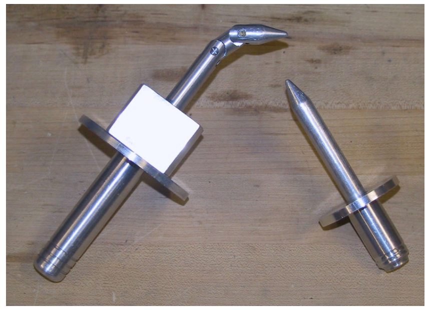

Figure 30 Jointed and Unjointed Test Fingers

6.8 Short Circuit Protection

1.) Examine the circuit protection devices and determine if they are of the type that need to be reset or replaced manually.

2.) Disconnect the controller and any other electrical devices from each battery pack but leave the main leads in place.

3.) Connect the positive and negative wires of the battery pack to the circuit breaker.

4.) Close the contacts of the circuit break and check if the circuit protection device operates correctly.

5.) Open the contacts of the circuit breaker and check if the circuit protection device resets automatically.

6.9 Safety When Charging Batteries

1.) Connect the battery charger to the battery set and supply mains in accordance with the manufacturer's instructions and switch it on.

2.) Switch on the wheelchair controller and attempt to drive the wheelchair. Record any movements.

3.) Disconnect the battery charger from the supply mains and switch on the wheelchair controller. Attempt to drive the wheelchair and record any movements.

6.10 Reversed Polarity at the Battery

1.) Disconnect the battery set and connect the circuit breaker with the wires from the battery set.

2.) Connect the battery set in reversed polarity.

3.) Switch on the wheelchair controller and operate all of the control devices. Record any unwanted or uncontrolled movements.

4.) Switch off the wheelchair controller and disconnect the battery set. Check for any damage to the electrical system other than blown fuses.

5.) Reconnect the battery set in the original configuration. Replace or reset any circuit protection devices that have operated. Does the wheelchair still operate according to the manufacturer's specification?

6.11 Controller Over-Voltage Protection

1.) Disconnect the battery set and connect a dc power source that has a voltage 1.25 times the nominal voltage of the battery set.

2.) Support the wheelchair with the drive wheels lifted off the ground and free to revolve.

3.) Switch on the dc power source and operate all the control functions. Record any unwanted movement of the drive wheels.

4.) Switch off the dc power source and place the wheelchair on a horizontal test plane.

5.) Switch on the dc power source and record any unwanted or oncontrolled movement of the wheelchair.

6.) Operate all the controls and record any malfunctions.

7.) Check if any of the circuit protection devices were tripped.

8.) Remove the dc power source and reconnect the wheelchair's battery set. Reset any of the circuit protection devices that have operated.

9.) Switch on the power and operate all of the controls, including brake operation. Record any malfunctions.

6.12 Controller Command Signal Processing Failures

1.) Connect the circuit breaker between the battery set and the wheelchair controller.

2.) Identify the conductors from the control device that are involved in the speed and/or direction control, power supply, and reference signals to the control device.

3.) Switch off the controller and disconnect it from the battery set. Disconnect the conductors identified above and connect them via a switch back to their original connections.

4.) Close the switches and reconnect the battery set.

5.) Drive the wheelchair at half speed toward a marker on the horizontal test plane. Open one switch when the marker is reached and measure the stopping distance without releasing the speed controller. Repeat for the rest of the conductors.

6.) Repeat step 5 above, but release the speed controller when the switch is opened.

7.) Switch off the controller and connect two conductors together via a switch. Open the switch and drive the wheelchair at half speed toward a marker on the horizontal test plane. Close the switch when the marker is reached and measure the stopping distance without releasing the speed controller. Repeat for all other combinations.

8.) Repeat step 7 above, but release the speed controller when the switch is closed.

6.13 Controller Output Device Failure

1.) Switch off the controller and disconnect it from the battery set.

2.) Connect a suitably rated switch to simulate a short circuit in the device that carries the current to a driving or steering motor.

3.) Switch on the controller and drive the wheelchair at half speed down a 5° slope toward a marker.

4.) Close the switch when the marker is reached and measure the stopping distance without releasing the speed controller.

5.) If the wheelchair does not stop in the required distance, repeat step 4 but release the speed controller after the switch is closed.

6.) Connect a suitably rated switch to simulate an open circuit in the device that carries the current to a driving or steering motor.

7.) Switch on the controller and drive the wheelchair at half speed down a 5° slope toward a marker.

8.) Open the switch when the marker is reached and measure the stopping distance without releasing the speed controller.

9.) If the wheelchair does not stop in the required distance, repeat step 8 but release the speed controller after the switch is closed.

6.2 Stalled Condition Protection

1.) Mechanically lock the position of the wheelchair so that movement of the drive wheels is prevented when full drive power is applied in the forward direction.

2.) Connect a current meter to the wheelchair to measure the current flowing to the right motor.

3.) Put the control device in the maximum forward position and hold it there for three minutes or until the current to the motor is cut off.

4.) Record the current cut off time.

5.) If the wheelchair is fitted with manual reset protective devices, reset them and repeat the test as many times as possible, up to a maximum of five test cycles.

6.) If the wheelchair is fitted with automatic reset protective devices, take the steps necessary to permit the devices to reset and repeat the test as many times possible, up to a maximum of five test cycles.

7.) Remove the means of locking the position of the wheelchair and replace or reset any circuit protection devices that triggered.

8.) Operate all of the controls and examine all parts of the drive system. Record any damage or abnormal operation.

6.2 Ability to Stop When Power is Switched Off or Lost

1.) Position a marker on a 6° slope and record the braking distance while traveling downhill (Limax).

2.) Connect a circuit breaker between the battery set and the wheelchair controller.

3.) Drive the wheelchair at maximum speed down the test plane. When the marker is reached, open the circuit breaker with the speed control still in its maximum position. Record the distance.

4.) If the distance is greater than 1.3*(Limax) then repeat the test but open the circuit breaker before the marker is reached.

6.3 Controller Microprocessor Watchdog

1.) Measure the braking distance of the wheelchair at maximum speed while traveling on a level test plane (Lh).

2.) Connect the microprocessor clock input to the microprocessor ground via a switch.

3.) Drive the wheelchair at half speed on the level test plane and close the switch and put the speed control to its stop position. Record the distance.

6.4 Safety with Discharged Battery

1.) Charge the battery set to between 10% and 30% of its rated capacity.

2.) Drive the wheelchair up a 6° slope for a distance of 4 meters. Then drive the wheelchair backwards down the slope. Repeat this test until the wheelchair does not move.

3.) Switch off the controller. After three minutes, repeat the test again until the wheelchair does not move after the three-minute wait.

4.) Recharge the battery set to between 10% and 30% of its rated capacity.

5.) Repeat the above steps, except with the wheelchair facing down the slope.

7.3 Non-Power Mobility Test

1.) Disconnect the battery set from the wheelchair controller.

2.) Check if there is any provision for the drive or automatic braking system to be disengaged.

3.) If yes, check if any components must be detached, if the transmission is affected, or if any tools are required.

4.) Record the force needed to operate any means for disengaging the drive or braking system.

5.) Disengage the drive or braking system.

6.) Slowly increase the pushing force applied at the back of the wheelchair until the wheelchair starts to move. Record this value.

7.) Reconnect the battery set to the wheelchair controller.

8.) Determine if it is possible that electric power can be restored with the automatic brakes still engaged.

9.) If yes, operate all of the drive controls and observe whether the wheelchair drives and if there is a visual and/or auditory alarm.

8.3 Safety Guard Test

1.) Apply the unjointed standard test finger, with a force of 30N, to all openings and places where an occupant or attendant may contact or be pinched by a moving part. Determine if it is possible to touch the following: any power driven parts of the propulsion system, except the wheels and up to 50mm of their axles; any gears, drive belts, pulleys, chains, or other drive mechanisms that create a pinch point or could injure a user or trap loose clothing; any shaft which rotates more than two revolutions during its total cycle of operation.
2.) Repeat the above steps using the jointed standard test finger.

10.3 Forces Needed to Operate Control Devices

1.) If there are any levers to control speed and/or direction of the wheelchair, determine the force needed to move the lever to the maximum extent of its travel.
2.) If there are any push button, rocker, or keypad switches, determine the force needed to operate the switch.
3.) If there are any toggle switches, determine the force needed to operate the switch.
4.) If there are any pneumatic switches, determine the force needed to operate the switch.
5.) Does the manufacturer disclose the forces necessary to operate all control devices?

13.3 Results

Table 39 Power & Control Systems Results

WC	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	6.10
EJ #1	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
EJ #2	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
EJ #3	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #1	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	Pass
Q #2	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	Pass
Q #3	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	Pass
A #1	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	**Fail***
A #2	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	**Fail***
A #3	**Fail**	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**
J #1	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #2	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #3	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
P#1	**Fail**	**Fail**	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass
P#2	**Fail**	**Fail**	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass
P#3	**Fail**	**Fail**	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass

*- Testing was not performed because prior testing indicated failure.

Table 40 Power & Control Systems Results (continued)

WC	6.11	6.12	6.13	6.14	6.15	6.16	6.17	7.3	8.3	10.3
EJ #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
EJ #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
EJ #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Q #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #1	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #2	Pass	Pass	**Fail***	Pass	Pass	Pass	Pass	Pass	Pass	Pass
A #3	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
J #3	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
P#1	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass
P#2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass
P#3	Pass	Pass	**Fail**	Pass	Pass	Pass	Pass	**Fail**	**Fail**	Pass

*- Testing was not performed because prior testing indicated failure.

All three of the E&J Lancer 2000 wheelchairs failed sections 6.1 and 6.2. There were no listings for the current rating or type of fuses used by the wheelchair.

The Quickie P200 wheelchairs failed sections 6.1, 6.2, and 6.9. The failures for sections 6.1 and 6.2 were the same as for the E&J wheelchairs. The wheelchairs failed section 6.9 because when the battery charger cord is plugged into the wheelchair, but not the wall outlet, the wheelchair can still drive in all directions.

The Invacare Action Storm wheelchairs failed sections 6.1, 6.2, 6.10, and 6.13. The failures for sections 6.1 and 6.2 were the same as for the other wheelchairs. The Action wheelchairs failed section 6.10 because a voltage regulator was burned out during the reverse polarity test on wheelchair A #3. The other two Action wheelchairs were not tested because it was determined that the same failure would occur. Two of the Action wheelchairs (A #1 and A #3) experienced controller failures during the short circuit testing for section 6.13. It was determined that the third wheelchair would fail the same way and therefore it was not tested.

All three of the Pride Jazzy wheelchairs failed section 6.1 due to the absence of information concerning the location and rating of fuses. Wheelchair J#3 also failed section 6.10 because the battery charger needed to be connected to the wheelchair in order to turn it on.

All of the Permobil Chairman wheelchairs failed sections 6.1, 6.2, 6.4, 7.3, and 8.3. The failures for 6.1 and 6.2 were the same as for the other wheelchairs. The Permobil wheelchairs failed section 6.4 because live leads were exposed when changing the fuse. The wheelchairs failed section 7.3 because the average force required to disengage the drive mechanism was greater than 60N. There is a pinch point present on each of the Permobils when the seat bar is tilted either forward or backward and this led to a failure for section 8.3. Wheelchairs A #1 and A #3 also failed section 6.13 because they did not stop in the required distance during the test.

13.4 Discussion

All of the EPW's involved in this study failed at least one part of section 14. Most of the failures that occurred would not result in serious injury and can be easily corrected. All of the wheelchairs failed section 6.1 because the location and type of fuses used by the wheelchairs were not listed. This is simply a matter of convenience for the users and attendants. If a fuse is blown, a diagram with both the location and rating of the fuse would allow the users to replace the fuse quickly and easily. The Pride Jazzy EPW's were the only wheelchairs that did not fail section 6.2. The reason for failure by the other wheelchairs was the absence of permanent plus and minus markings on the positive and negative wires going to the battery. This is intended as a safety feature to insure that the battery set is not connected in reverse polarity with the controller. It involves a simple fix that would be of minimal cost to the manufacturers.

The Quickie P200 EPW's were the only wheelchairs to fail section 6.9. The danger in having the wheelchair able to drive with the battery charger connected is twofold. First of all, the user may drive away not knowing that the charger is still connected and may damage the charger or entangle the cord. Secondly, most users are accustomed to having an EPW rendered inoperable when the charger is connected. Therefore, accidentally hitting the joystick could result in movement of the wheelchair that could injure the user or those around the device.

The Invacare Action EPW's were the only wheelchairs to fail section 6.10. The reverse polarity test was developed to insure that if the batteries were connected in reverse, the controller would not catch fire or produce any unwanted or unexpected movements. The voltage regulator that was burned out on the Invacare wheelchair presented no hazard to the user. It simply rendered the wheelchair inoperable and required the controller to be repaired. Correct marking of the battery wires and the insertion of a fuse or circuit breaker should prevent this type of accident.

The Invacare Storm and Permobil Chairman wheelchairs experienced failures during the short circuit testing of section 6.13. The Invacare wheelchairs stopped within the required distance during the testing, but then experienced controller problems afterward. The two wheelchairs that were tested would not function and had to have a wire and diode replaced. The Permobil wheelchairs failed to stop within the required distance during this test. If current to one or both of the drive motors is lost, a wheelchair must be able to stop immediately and safely since the driver will have no control over the device. Unlike an automobile, an EPW uses the motors to steer and a loss of power effectively renders it inoperable.

The release mechanism for the drive system on the Permobil wheelchairs requires more than 60 N of force to disengage. Both the user and any individual assisting them should be able to easily disengage the drive train in case it is necessary to manually propel the wheelchair in certain situations. The Permobil wheelchairs also failed section 8.3 because a pinch point was created when the seat was tilted. This creates a danger to children and adults who may be around the wheelchair when the user is tilting the seat. Plastic safeguards can be employed to cover any pinch points or moving parts.

The goal of section 14 is to insure the safety of the wheelchair user if any part of the electronics or control system malfunctions. EPW control modules are based on microprocessors.

Most controllers utilize feedback to sense whether the motors are responding properly to the joystick input [35]. The controller also regulates the motor torque in order to maintain constant speed with a varying load due to changes in the terrain [35]. With such an intricate control system, there are several different components that could cause failures. Two of the most important sections with regard to user safety are the controller command signal processing failures and the controller output device failure tests. These sections determine the behavior of the wheelchair when certain circuits fail while it is in motion. The Invacare Storm and Permobil Chairman were the only two types of wheelchairs that experienced complications during the controller output device failure test. The failures that these wheelchairs had should be remedied to prevent any possible injuries or complications to the user.

The majority of failures recorded during testing for the power and control system section were simple problems that are easily corrected. Overall, the controllers performed adequately when designed to malfunction at critical times. The safety of EPWs in the future with respect to electronics and control systems will depend on the ability of the wheelchair standards to keep pace with technology. The continual increase in processing power of microchips, coupled with the decreasing cost of production, is already leading to the design and fabrication of multitasking EPWs [39]. Wheelchairs are being developed that can efficiently climb stairs, traverse rugged terrain, and even balance on one axle [40]. Control systems are becoming more involved and there are more opportunities for failures and malfunctions that could lead to injurious results. Navigation systems have been developed to help produce autonomous EPWs that can detect and avoid obstacles without the aid of the user [41]. An array of different joysticks have also been designed. Brienza and Angelo developed an active joystick with force feedback that can indicate obstacles in the surrounding environment [42]. A force sensing joystick has also been developed that can filter out tremors or unwanted movements [43]. These projects are just the beginning of what is sure to be an explosion of digital control and detection that will significantly change the function and abilities of EPWs. Section 14 is the one part of the wheelchair standards that will have to adapt most rapidly to changing technology. Advances in control systems must be recognized and evaluated in a timely fashion in order to protect EPW users.

14.0 SUMMARY

The future of EPWs will depend heavily on the development of faster and smarter microchips and controllers. Many of the different performance characteristics of EPWs can be improved to produce safer and more efficient devices. The Independence 3000 uses a combination of gyrometers and tilt sensors to balance on a single axle. This technology could be used to monitor the stability of regular EPWs. If a wheelchair is traveling downhill at angle and the rider attempts to turn the device sharply, the sensors could detect that the wheelchair would tip during such a maneuver and therefore override the joystick command. New battery technology could produce smaller and more powerful battries. EPWs could power more functions and components with a stronger and longer lasting energy supply. New lighter and stronger materials could reduce the overall weight of EPWs. Composite materials could lead to low cost custom fitted frames and wheelchairs. Materials may also be incorporated into the frame to act as a suspension system. Controllers and electronics should also become more robust and reliable. Back-up or redundant systems could help provide added safety to complex devices.

The results from this study provide an in depth look at the performance, safety, and general characteristics of the five different types of EPWs tested. The information gleaned from this study shows how similar looking and comparatively priced EPWs can perform quite differently. Most individuals who use an EPW do so on a daily basis. They depend on their wheelchair to function safely and reliably at all times to provide a source of independence not otherwise available. Currently, wheelchair standards are the best source of information to determine exactly how an EPW will perform and what its limitations are. Unfortunately, the results of EPW testing are not always readily available and consumers and even clinicians depend mainly on experience and word of mouth to select the best wheelchair for a given situation. This study demonstrates that the information gathered from the standards testing is essential when attempting to compare different wheelchair makes and models.

The specific sections in the wheelchair standards each provide valuable information about different performance and safety factors. It is important to consider all of the results as a group when evaluating a particular wheelchair. For instance, the Quickie P200 may be the fastest of the five types of wheelchairs and have the greatest acceleration and deceleration, but it also has the longest braking distances and some of the lowest dynamic stability scores. The E&J Lancer 2000, on the other hand, had strong static and dynamic stability scores, but experienced the most failures during strength testing and was not the best obstacle-climbing wheelchair in the group. The wheelchair standards allow people to examine what factors are most important to them and possibly sacrifice performance in a less important area for a better performance in a more relevant one depending on their preferences and driving style.

This study also illustrated the strengths and weaknesses of each section of the wheelchair standards. Many of the sections provide useful and detailed information about EPWs. However, wheelchair technology, both manual and powered, is progressing at a much faster rate than it ever has before. Areas such as rolling surface, wheelchair design and configuration, environmental conditions, and operator error could lead to new and helpful standards. It is important that the standards keep up with technology and are continuously adapted to ensure the safety of those who use wheelchairs and supply them with the information that they need to make the best informed choice about what wheelchair will best complement their lifestyle. The standards were created in order to insure the safety of new products as well as provide information to the consumers.

Continued research in the field of EPWs is necessary to keep consumers, clinicians, and manufacturers informed about the ever-increasing variety of wheelchairs and devices available to the public. One way to accomplish this is to continue testing as many EPWs as possible according to the ANSI/RESNA wheelchair standards. The bigger the database to draw on, the more information available to people to help them make an often life changing decision. Computer simulations is another area that could prove to be quite beneficial to wheelchair design and technology. A variety of modeling software is now available that could assist in the development and testing of current and new wheelchair designs. It is easier and more cost effective to develop a dynamic computer simulation to run multiple tests than to perform the actual physical testing. For instance, component adjustments can be made on static or dynamic stability models and the trials can be run over and over again in a matter of minutes. Repeating this process in the laboratory takes much longer and can cost much more. The more tools available to help test and evaluate wheelchairs, the safer and more customized they will become.

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