Chapter 4: Evaluation of the Power Add-On Unit Performance on a Wheelchair

Objective

The objective of the wheelchair performance evaluation with the PAU was to determine the characteristics which define its level of operation. The intended use for the information collected is to identify the weak performance areas of the power assist. These areas can be addressed in future design iterations. The following characteristics of the power assist device were evaluated in this section:

- -- Maximum Speed. The top speed the power assist device can move the wheelchair and an occupant.
- -- Grade Climbing Capability. The grade climbing capability of the wheelchair using the PAU as the only method of propulsion.
- -- Dynamic Stability. Maintenance of wheelchair stability while performing a minimum radius turn at maximum speed.
- -- Battery Life. The duration and distance the PAU will function on one battery charge.
- -- Obstacle Climbing. The ability to climb a vertical obstacle.

Many of these characteristics are adapted from the American National Standards Institute wheelchair standards outlined by McLaurin and Axelson (1990). A brief synopsis of the standards outline is provided in Appendix H: ANSI/RESNA Wheelchair Standards Outline.

In addition to the tests described above, the PAU was subjected to a variety of operating conditions while performance characteristics were observed. These situations included: operation on rough surfaces, operation on grass, operation on carpet, operation on wet surfaces, traversal of common obstacles, and ascension of several wheelchair ramp configurations.

Comparative Testing

The two PAU products currently on the market, the Damaco D90 and the Roll-Aid, were not tested against the new design in any of the evaluations. Since the new design has been developed to provide features not found in the current products, a direct comparison would not provide information useful for design improvement. The design objectives of the new PAU are different from those of the Damaco D90 and the Roll-Aid. Specifically, lightweight components, ability to operate in either manual or power modes, and a simplistic design which translates into a relatively inexpensive retail price, are design priorities with the new PAU. Further discussion contrasting the three PAUs can be found in the section titled Products Currently on the Market.

Methods

Subjects

The tests were not intended to determine human performance but the performance of the PAU in conjunction with a manual wheelchair, and therefore no special subject population was required. In order to maintain a significant and consistent load during testing, an operator was chosen who approximated (in conjunction with added weights) the load of a 165 pound user. This load was selected because it was one of the four loads proposed for testing in the wheelchair standard (see Appendix H: ANSI/RESNA Wheelchair Standards Outline). The standard recommends testing with dummies of specified weights of 55, 110, 165, and 220 pounds. The wheelchair performance with the PAU evaluation utilized an investigator as the subject in the wheelchair (in place of the dummy load). The investigator was chosen as the participant for three basic reasons:

- -- The investigator was available to perform the tests.
- -- The investigator was familiar with the power assist apparatus and therefore did not require training.
- -- There was a small risk to the participant due to the nature of the tests, and this risk was recognized and accepted by the investigator.

It is assumed that performance levels achieved by the investigator represent optimal performance. Actual product users may experience decreased levels of performance. Also, some information concerning user-interaction may have been lost utilizing the investigator as the subject. However, safety problems encountered during performance testing justified the decision not to evaluate with wheelchair operators.

<u>Recording Data</u>
Data collected from each performance test was recorded on a data sheet. In addition, each test was videotaped and analyzed to identify performance characteristics.

<u>Sequence</u>
The sequence of PAU tests was based on minimizing the likelihood of performance degradation due to possible damage in the previous performance tests. The group of tests was scheduled in the order of increasing probability of damaging the PAU. For example, obstacle climbing tasks may have unknowingly damaged the power train of the device and caused a decrease in performance on the next test. Therefore, this test was performed after the other evaluations were completed. Each test is outlined here in the order conducted with the exception of the second grade climbing test. This evaluation was conducted following the obstacle climbing test as a post hoc decision was made to conduct the evaluation. There was no apparent impact on the PAU performance due to previously conducted tests.

Maximum Speed

<u>Apparatus and Facilities</u>
The maximum speed test was performed in the hallway of the fifth floor of Whittemore Hall on the Virginia Tech campus in Blacksburg, Virginia. The hallway is straight and flat with a floor of 12-inch tiles which were utilized to lay out a straight testing run. Markers were placed on the floor to indicate the 0, 40, and 90 foot points along the testing hallway.

Apparatus which was needed for the test included:

- -- One Everest and Jennings 1987 manual wheelchair model Ultra Lite Premier with the new power assist attachment in place.
- -- Weights placed on the wheelchair to apply a load on the wheelchair of 165 pounds total (including subject weight).

- -- One General Electric VHS video camera recorder model number 9-9806.
- -- One video camera tripod.
- -- One stopwatch.
- -- One clipboard.
- -- Data sheet and pen.

Variables

Distance was defined at only one level of 50 feet, and time was the dependent variable.

Procedure

Weights were placed on the wheelchair such that the total load on the wheelchair including the operator, was 165 pounds. One investigator operated the power assist device while seated in the wheelchair which was placed with the caster wheels on the zero-foot marker on the testing run. The second investigator was located adjacent to the 40-foot marker and off to the side of the wheelchair path. In this position, the second investigator was provided the optimum view of the marker.

The first investigator operated the wheelchair with the power control at maximum voltage to the motor. The second investigator measured the time required for the wheelchair to pass between the 40-foot and 90-foot markers. As the wheelchair passed the 40-foot marker, the second investigator quickly moved to a position adjacent to the 90-foot marker, avoiding the path of the wheelchair. It was assumed that the wheelchair reached its maximum speed before 40 feet of distance. Observation of wheelchair performance supported this assumption; there was no apparent acceleration of the wheelchair after passing the 40-foot marker.

Three pretest runs were conducted prior to data collection to insure proper marker placement, optimal observation location, and to practice timing procedures. A 9 pound lead acid battery was fully charged and then used in three trials to measure speed. Then a fully charged 25 pound gel-type battery was used in three more trials to measure speed.

Results and Data Analysis

Results of the six testing runs are presented in Table 3.

Table 3. Results from the Maximum Speed Performance Evaluation

Trial Number	Battery Wt. (pounds)	Distance (feet)	Time (seconds)	Speed (miles/hour)
1	9	50	15.19	2.24
2	9	50	15.21	2.24
3	9	50	15.11	2.26
4	25	50	15.83	2.15
5	25	50	15.83	2.15
6	25	50	15.73	2.17

The speed was calculated by dividing 50 feet by the time measurement. This number was then converted to miles per hour. The three times for each battery weight were averaged to provide one average maximum speed over a flat tile floor. Measured times for the six runs do not indicate any degradation of speed due to battery wear during the three runs for either battery. For the 9 pound battery, the average maximum speed was found to be 2.25 miles per hour. The average maximum speed for the 25 pound battery was calculated to be 2.16 miles per hour.

Discussion

Compared with the two PAUs currently on the market, the Roll-Aid and the Damaco D90, the new PAU performs at a much slower maximum speed. The Roll-Aid advertises a speed of 4.5 miles per hour and the Damaco D90 can drive up to 5.25 miles per hour. These specifications are at least twice the maximum speed of 2.25 miles per hour achievable by the new design in its current configuration.

Normal population (nondisabled) walking speeds range from approximately 1.3 miles per hour to approximately 4.0 miles per hour (Harris and Smith, 1996). Therefore the maximum speed of the new PAU falls within the slow to moderate range of walking speeds. This capability to function at walking speed is important because the intended use of the product includes operation within the stream of pedestrian traffic.

The 25 pound battery consistently produced a maximum speed approximately 0.09 miles per hour slower than the 9 pound battery. All three speed measurements produced with the 25 pound battery and all three speed measurements produced with the 9 pound battery were grouped to within 0.02 miles per hour. This appears to indicate that larger loads produce slower maximum speeds. Further testing with variable loads would be required to support this statement.

Grade Climbing Capability

Apparatus and Facilities

The grade climbing capability test was conducted in the Industrial Ergonomics Research Laboratory in Whittemore Hall on the Virginia Tech campus in Blacksburg, Virginia. A four foot by six foot plywood ramp was placed at different angles to test the ability of the power assist to ascend the ramp in power mode. The very lightly painted plywood maintains the wood grain as the predominant surface texture.

A second set of grade climbing capability tests were conducted after securing a 40 grit rough grain resin surface to the plywood. This surface provided an increased coefficient of friction to test the maximum possible ascension angle. Similar surfaces are sometimes placed in strips on wheelchair ramps to assist in climbing the slope.

Apparatus which was needed for the test included:

- One Everest and Jennings 1987 manual wheelchair model Ultra Lite Premier with the new power assist attachment in place.
- Weights placed on the wheelchair to apply a load on the wheelchair of 165 pounds total (including subject weight).
- One four foot by six foot rectangular plywood ramp (supported and stiffened with a structure of 1 1/2 inch by 2 inch boards).
- Four cement block structures for supporting the ramp at a variety of angles.

- -- One strip of 40 grit rough resin paper measuring 4 inches by 48 inches.
- -- One General Electric VHS video camera recorder model number 9-9806.
- -- One video camera tripod.
- -- One clipboard.
- -- Data sheet and pen.

Variables

The slope of the wheelchair ramp was the independent variable. The dependent variables observed were the action of the drive wheels on the ramp surface and the distance traversed. Levels for the drive wheel variable include:

- -- The drive wheels rotating forward at a continuous rate (no slipping).
- -- The drive wheels slipping against the ramp surface.
- -- The drive wheels not rotating relative to the ramp surface.

There was a total possible distance traveled of 36 inches. Therefore, the levels for the variable of distance traveled range from 0 inches to 36 inches. This distance was measured to the nearest inch.

Procedure

Weights were placed on the wheelchair such that the total load on the wheelchair including the operator, was 165 pounds. The downward force which the drive wheels apply to the ground was adjusted to apply the maximum force possible which still permitted easy adjustment between column positions. The nine pound battery was fully charged prior to each attempt to ascend the ramp.

The wheelchair was placed facing up the ramp such that all wheels were on the ramp oriented in the direction of travel. The investigator operating the wheelchair then applied maximum voltage to the motor with the PAU controls to propel the wheelchair forward. The investigator attempted to traverse the ramp for a total drive wheel distance of 36 inches.

The angle of the ramp was adjusted after each attempt in an effort to determine the maximum possible ramp angle which the wheelchair and PAU were able to traverse. Therefore, the ramp angle was increased when the wheelchair was propelled the full 36 inches up the ramp, and decreased when the drive wheels slipped against the surface of the ramp. This procedure was continued until the maximum ramp angle which the PAU was capable of traversing, was determined for both the wood and resin surfaces.

Results and Data Analysis

The observations and videotape collected during the grade climbing capability test were reviewed and summarized. Those trials which produced results defining the grade climbing capability performance of the PAU are presented in Table 4.

Table 4. Results from the Grade Climbing Performance Evaluation

Surface	Angle of Slope (degrees)	Description of Motion
Wood	6.09	Continuously traversed the full 36 inches.
Wood	6.32	Traveled 12 inches then the drive wheels slipped continuously against the wood.
Wood	7.00	Drive wheels slipped continuously against the wood at zero inches of travel.
Resin	10.04	Continuously traversed the full 36 inches.
Resin	10.47	Very slowly traveled 15 inches then the drive wheels slipped against the resin continuously.

Against the wood surface, the PAU and wheelchair successfully climbed a ramp with a slope of 6.09 degrees, but was not able to ascend a slope of 6.32 degrees. The increased coefficient of friction, provided by the rough resin surface, permitted the wheelchair and PAU to successfully climb the ramp with an angle of 10.04 degrees. It was not able to ascend the ramp at an angle of 10.47 degrees.

Additional Observations. It was further found that the only operator position which permitted ascension of the ramp was a forward leaning posture of the torso. This position increased the downward force at the front end of the wheelchair and therefore increased the friction force at the drive wheels which was required to move the wheelchair. When the operator was sitting back in the wheelchair seat it did not produce a friction force sufficient for propulsion up the ramp. Also, only one load size was tested, 165 pounds; operators of different weights may produce different results.

In addition, once the drive wheels of the PAU began to slip against the ramp surface, a concentrated effort was required to safely hold the wheelchair in position as voltage was decreased to the PAU. The wheelchair immediately tended to slide backward down the ramp. Upper body agility and strength, as well as the use of the operator's legs, were required to stop the wheelchair from sliding, lock the brakes, and exit from the wheelchair.

Discussion

The PAU is capable of continuously ascending a smooth surfaced ramp angled at over 6 degrees with a 165 pound operator load. This permits wheelchair users up to 165 pounds access to ramps which are in compliance with the Americans with Disabilities Act Accessibility Guidelines for Buildings and Facilities revised July 1994. The code specifies that the maximum wheelchair ramp angle permitted in new construction is a rise to run ratio of 1 to 12. This allows a slope for a given rise of approximately five degrees (personal communication, Virginia Tech University Architect Tom Tucker, May, 1996).

A large increase in grade climbing capability was observed with an increase in surface friction. The PAU is capable of ascending a slope with an additional 4 degree incline, for a total grade of over 10 degrees, on a rough surfaced ramp (with a 165 pound operator load). This finding indicates that users up to 165 pounds may be capable of ascending slopes well over 6 degrees with surfaces rougher than smooth wood (e.g. a cement ramp). The user must be capable of leaning forward in the wheelchair seat to apply a sufficient downward force on the drive wheels (it was necessary for the investigator to lean forward throughout the evaluation to produce a sufficient friction force).

It should be noted that the failure on the rough slope angled at 10.47 degrees was due to the wheels slipping. This implies that an increased downward force (applied by a stronger spring) or an increased coefficient of friction, would improve the PAU grade climbing performance by increasing the friction force at the drive wheels. The motor output torque was sufficient to continue climbing at a steeper angle. If the motor had been the reason for failure, the wheels would not have continued slipping in position.

The weights placed on the wheelchair were located behind the large wheelchair wheel axles. The weights detracted from the friction force at the front end of the chair which was needed to ascend the ramp. Therefore, the grade climbing performance provided conservative, not optimal, results.

Safety Concern. A major finding during this evaluation is the considerable safety risk encountered when the PAU drive wheels slip on the ramp. Once slipping occurs and the wheelchair will no longer move forward, the operator must apply a braking force to the large wheels of the wheelchair. The force must be applied bilaterally to both wheels simultaneously in order to avoid a backward motion of the wheelchair.

During the time required to move the PAU driving hand from the PAU handle to the large wheel, the wheelchair begins to roll down the ramp uncontrollably. The braking action inherent in the PAU motor and gear box is not sufficient to impede the backward motion. The momentum gained during this time requires that a large stopping force be applied when the hand reaches the large wheel. Even if both hands successfully reach the large wheels and stop the wheelchair momentum, the power mode configuration of the PAU precludes control of the wheelchair by manual force. This lack of manual control in power mode results from the limited inherent braking action of the PAU motor. While the PAU drive wheels remain in contact with the ground, the motor dampens any rotational input from the motion of the wheels. It was necessary for the investigator to put on the wheelchair brakes and carefully exit the wheelchair while still located on the angled ramp. This is an important safety issue which must be addressed in future design considerations.

Dynamic Stability

Apparatus and Facilities

The dynamic stability test was conducted in the Industrial Ergonomics Research Laboratory in Whittemore Hall on the Virginia Tech campus in Blacksburg, Virginia. The laboratory has a tile floor and provides an open area for testing which minimizes the opportunity to collide with walls and other obstacles.

Apparatus which was needed for the test included:

- One Everest and Jennings 1987 manual wheelchair model Ultra Lite Premier with the new power assist attachment in place.

- -- Weights placed on the wheelchair to apply a load on the wheelchair of 165 pounds total (including subject weight).
- -- One General Electric VHS video camera recorder model number 9-9806.
- -- One video camera tripod.
- -- One clipboard.
- -- Data sheet and pen.

Variables

The speed at which the wheelchair traveled was subjectively varied among below maximum speeds and maximum speed by the investigator operating the power assist device. The dependent variable recorded was the position of the wheelchair. There were three possible levels for this variable: all wheels securely on the ground, one or more wheels are lifted off of the ground while the wheelchair remains upright, and the wheelchair is turned over completely onto its side.

Procedure

Weights were placed on the wheelchair such that the total load on the wheelchair including the operator, was 165 pounds. The investigator operating the wheelchair ran several trials during which the chair was brought up to a stable speed, then turned to the left or right at the tightest possible angle. The initial trial was conducted at the slowest speed that the investigator was able to maintain. The speed was then subjectively increased by the investigator on successive trials. Throughout the trials, the investigator operating the wheelchair attempted to maintain a stable posture in the wheelchair seat so as not to influence the stability of the wheelchair.

When completed for the left and right-side turns, two trials were then conducted by turning the wheelchair sharply to one side and then immediately to the other side.

Results and Data Analysis

Several trials conducted at both maximum wheelchair speed and less than maximum speed revealed that the PAU is capable of turning the wheelchair at a minimum turning radius without lifting any wheels off of the ground. This dynamically stable performance was observed for both left and right turns, as well as successive turns. In addition, the turning angle was subjectively altered through several additional trials in an attempt to discover an unstable turning configuration. The investigator was unable to create a turning scenario which caused any wheel of the wheelchair to leave the floor.

Discussion

The current configuration of the PAU on a manual wheelchair does not appear to negatively impact the wheelchair's inherent dynamic stability. The limited speed and additional drive wheels of the PAU may, in fact, improve the dynamic stability of the wheelchair.

Battery Life

<u>Apparatus and Facilities</u>

The battery life test was conducted at the Human Factors Engineering Center in Whittemore Hall on the Virginia Tech campus in Blacksburg, Virginia. A 576 foot course was laid out on a flat, tile floor to provide a consistent and measurable testing track.

Apparatus which was needed for the test included:

- -- One Everest and Jennings 1987 manual wheelchair model Ultra Lite Premier with the new power assist attachment in place.
- -- Weights placed on the wheelchair to apply a load on the wheelchair of 165 pounds total (including subject weight).
- -- One clock located in a position that can be observed from track starting point.
- -- One voltmeter.
- -- One clipboard.
- -- Data sheet and pen.

<u>Variables</u>

Distance of travel, time of travel, and battery voltage, were the dependent variables used to measure the life of the nine pound lead acid battery. In addition, observations concerning the speed of the wheelchair were noted. This included observable reductions in speed which resulted in spite of consistent manipulation of motor controls (maximum voltage was applied to the motor throughout the test). The 25 pound gel-type battery was not tested due to the possible wear on the PAU which an additional battery life test would produce.

<u>Procedure</u>

Weights were placed on the wheelchair such that the total load on the wheelchair including the operator, was 165 pounds. The investigator operated the power assist device while seated in the wheelchair and recorded the observed data on a data sheet during rest breaks.

A fully charged nine pound lead acid battery was placed into the battery sling and a voltmeter was used to measure the battery voltage. A clock with a second hand was placed in view of the start/stop point along the wheelchair course and the starting time was noted. The wheelchair was then operated consistently for four laps around the defined 576 foot course at maximum speed. After completion of the four laps, the wheelchair was stopped, the time was noted, and the voltage of the battery was measured. The wheelchair remained stopped for approximately five minutes while the investigator was permitted to exit the wheelchair and break from the evaluation.

Following the break, a second four lap trial took place under the same conditions as the first trial. A second five minute break preceded subsequent trials of constant operation and breaks continued until the battery wore down and the wheelchair did not move. This schedule was designed to determine the best possible range, not the worst case.

Results and Data Analysis
Table 5 presents the results of the battery life performance test with each trial representing an attempt to complete four laps of the driving course.

Table 5. Results from the Battery Life Performance Evaluation

Trial (4 laps)	Distance (feet)	Elapsed Time	Post Trial Voltage (volts)
0	0	0 sec	13.02 (before starting)
1	2304	13 min 35 sec	12.50
2	2304	14 min 4 sec	12.37
3	2304	13 min 5 sec	12.28
4	2304	13 min 30 sec	12.16
5	2304	13 min 35 sec	12.08
6	2304	14 min 30 sec	11.95
7	2304	14 min 30 sec	11.83
8	2304	14 min 25 sec	11.69
9	2304	14 min 35 sec	11.51
10	2304	15 min 45 sec	11.20
11	2278	21 min 40 sec	7.73

The total distance traveled by the wheelchair and PAU in power-operating mode was 25318 feet which is equivalent to almost 4.8 miles. A noticeable decrease in speed occurred during trial ten after traveling a total of approximately four miles. The wheelchair and PAU continued at submaximum speed for an additional 0.75 miles. During this time period, the speed of the wheelchair decreased at a subjectively constant rate until the final 550 feet. A sharp drop off in speed occurred within this final lap. The third lap of the eleventh trial produced a split time of 5 minutes and 20 seconds (to travel 576 feet). The fourth lap of the eleventh trial, and final lap, produced a split time of 8 minutes and 17 seconds to travel 550 feet.

Figure 11 demonstrates the performance of the battery throughout the battery life evaluation. It appears that a constant linear decrease in voltage occurred through the life of the battery. At a traveling distance between approximately 4 miles and 4.75 miles, there is a sharp decrease in voltage of the battery. This decrease was associated with a noticeable decrease in operating speed as described previously.

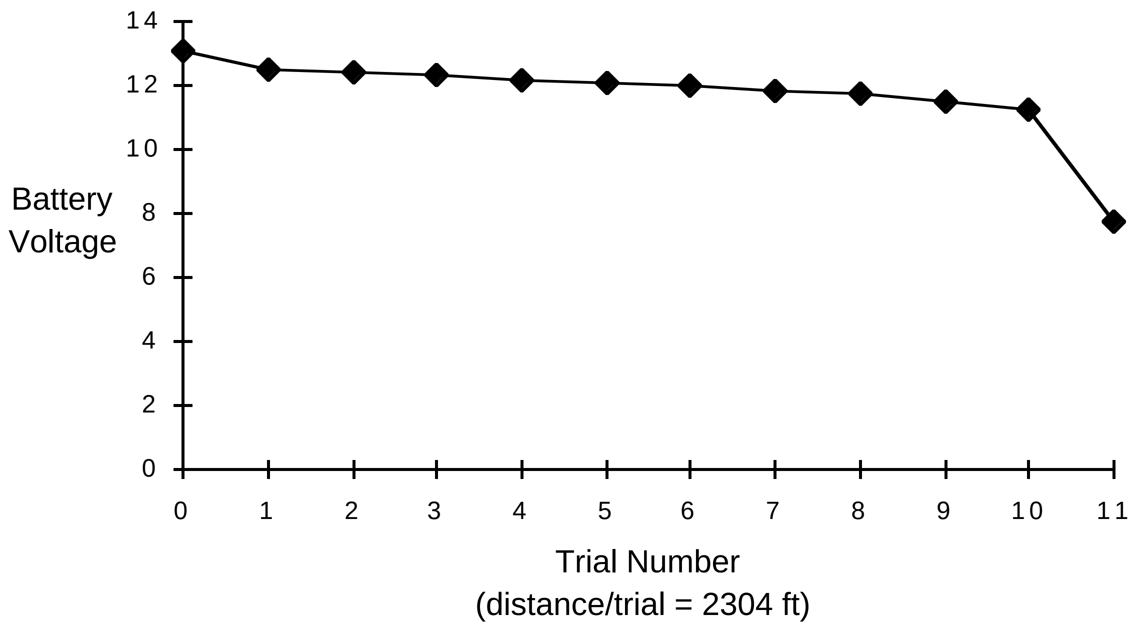

Figure 11. Battery voltage measurement versus trial (distance traveled).

There is also a dip in the voltage that is slightly different from the linear pattern at the initial stages of operation. This is seen in the difference between the voltage of the battery prior to the evaluation, 13.02 volts, as compared to the voltage after the first lap of 2304 feet equal to 12.50 volts. This is a 0.52 volt decrease in voltage and the average decrease in voltage per 2304 feet traveled from trials zero to ten is 0.144 volts. In comparison, the drop in voltage through the 2278 feet traveled in the eleventh and final trial is 3.47 volts.

Additional Observations. The long duration of the battery life test produced a significant finding which is unrelated to the duration capability of the battery. The investigator operating the wheelchair and PAU experienced fatigue in the finger and hand which actuated the PAU controls. This fatigue was significant within the first lap of the first trial (576 feet) and should be considered an important issue in the next generation of design changes. In order to complete the evaluation, the investigator secured a tie to the controls which maintained maximum voltage to the motor after starting each trial. It should be noted that minor time variations within the first three trials may be due to familiarization with this control securing procedure.

Discussion

Wheelchair users up to 165 pounds can operate the PAU for over 4 miles on a flat, hard surface with one charge of the 9 pound battery. It is anticipated that this distance will decrease with users of larger size and/or operation over varying terrain. It is further expected that larger batteries will have an extended duration. Consumers can choose the battery size which will accommodate their power and handling needs.

One design requirement made apparent throughout the battery life evaluation is the need for a battery charge level gauge. A gauge incorporated into the column unit or battery box design will permit users to make knowledgeable decisions concerning battery charges and power mode excursions.

Obstacle Climbing

<u>Apparatus and Facilities</u>

The obstacle climbing evaluation was conducted outdoors on a wooden deck near Blacksburg, Virginia. This location provided a means for securing the obstacles to be traversed to the ground. Rectangular obstacles of different dimensions constructed of wood were utilized in the tests. All obstacles were one inch wide and thirty inches long. The height of the obstacles varied as described below and the four edges along the length of the obstacles were slightly rounded to eliminate sharp corners.

Each obstacle tested was nailed to the wood deck such that it obstructed the path of the wheelchair at an angle perpendicular to the path of the wheelchair wheels. All nails were driven into the obstacle so that they did not extend beyond the surface of the obstacle. The wheelchair path was oriented parallel to the wood boards of the deck so that the gaps between boards did not provide additional obstacles.

Apparatus which was needed for the test included:

- One Everest and Jennings 1987 manual wheelchair model Ultra Lite Premier with the new power assist attachment in place.
- Weights placed on the wheelchair to apply a load on the wheelchair of 165 pounds total (including subject weight).
- One piece of wood cut to 1/4"x1"x30".
- One piece of wood cut to 1/2"x1"x30".
- One piece of wood cut to 3/4"x1"x30".
- One piece of wood cut to 1"x1"x30".
- One tape measure.
- Nails to secure the obstacles.
- One claw hammer.
- One General Electric VHS video camera recorder model number 9-9806.
- One video camera tripod.
- One clipboard.
- Data sheet and pen.

<u>Variables</u>

Two independent variables were altered: the height of the obstacle and the starting distance of the wheelchair from the obstacle. The height of the obstacle was varied from 1/4 inch to the maximum possible height the wheelchair and PAU were capable of traversing in 1/4 inch increments.

The wheelchair was placed at three different starting distances from the obstacle. These distances were zero inches, six inches, and eighteen inches, measured from the front edge of the obstacle to the point where the caster wheels of the wheelchair met the ground. These distances were chosen to represent different performance scenarios.

The dependent variable for the test was whether or not the obstacle was successfully traversed by the wheelchair. A "successful" declaration was made if all six wheels of the wheelchair and PAU passed over the obstacle without destabilizing the wheelchair.

Procedure

Weights were placed on the wheelchair such that the total load on the wheelchair including the operator, was 165 pounds. The measuring tape was used to place markers at the positions of the obstacle, the six inch, and eighteen inch starting points.

For the first trial, the 1/4-inch thick obstacle was nailed to the deck so that it was perpendicular to the boards of the deck at the obstacle marker. The wheelchair with the PAU was then placed along the path of the obstacle such that it traveled parallel to the boards of the deck. For the first attempt, the six-inch starting point marker was matched with the intersection point of the caster wheels and the ground. The investigator then attempted to traverse the obstacle by applying maximum voltage to the motor with the PAU controls.

The second attempt to traverse the obstacle was initiated from the zero-inch position. This located the caster wheels up against the obstacle with no opportunity to generate momentum before climbing the obstacle. Following this starting distance, the third attempt to traverse the obstacle was conducted at the eighteen-inch starting marker. If the wheelchair and PAU did not successfully traverse the obstacle, two additional attempts were made at the unsuccessful distance.

If the wheelchair with the PAU had successfully traversed the obstacle from at least one starting position, the obstacle was then replaced with an obstacle 1/4 inch thicker. The entire procedure was repeated from the three starting points with subsequent obstacles until the wheelchair and PAU were unsuccessful at traversing the obstacle from any starting point.

Results and Data Analysis

Table 6 presents the results of the obstacle climbing evaluation by listing the height of the obstacle, starting distance from the obstacle, and the result of the attempt to traverse the obstacle.

Table 6. Results from the Obstacle Climbing Performance Evaluation

Obstacle Height (inches)	Distance from Obstacle (inches)	Successfully Traversed
1/4	6	yes
1/4	0	yes (slipped first)
1/4	18	yes
1/2	6	yes
1/2	0	no
1/2	18	yes
3/4	6	no
3/4	0	no
3/4	18	yes
1	6	no
1	0	no
1	18	yes
1 1/4	18	no

<u>Discussion</u>
The PAU and wheelchair are capable of traversing a one inch high vertical obstacle in power operating mode. This implies that the product will be capable of traveling over most obstacles encountered in typical daily operation. Sidewalk gaps, raised thresholds, small curbs, etc., should not stop the PAU and wheelchair while in power mode. Those obstacles greater than one inch in height can be negotiated by switching the PAU to manual operating mode and proceeding as usual when encountering obstacles in a manual wheelchair.

The evaluation demonstrated the importance of adequate momentum when approaching an obstacle. As the starting distance from the obstacle was increased from zero inches, to six inches, to eighteen inches, the momentum achieved at the obstacle contact point increased. Subsequently, the capability to traverse higher obstacles increased. A starting distance of zero inches permitted traversal of a 1/4-inch high obstacle. From a 6-inch starting distance an obstacle of 1/2-inch was successfully traversed, and the 18-inch starting distance permitted the PAU and wheelchair to crossover a 1-inch high obstacle.

Additional Performance Observations

In addition to the tests described above, the PAU was subjected to a variety of operating conditions while performance characteristics were observed. These situations included: operation on rough surfaces, operation on grass, operation on carpet, operation on wet surfaces, traversal of common obstacles, and ascension of several ramp configurations. Results of these minor evaluations are presented here with investigator observations.

Wheelchair Ramps

The wheelchair and PAU attempted to climb three outdoor wheelchair ramps located on the Virginia Tech campus in Blacksburg, Virginia. The first ramp, which is exceptionally long, is located at the entrance to Hancock Hall and consists of four rising sections, two turns, and three resting platforms (short flat sections), two of which are on the turns. The ramp is quite long and steep with a total length of 92 feet and an average slope of approximately 5 degrees (not including the flat sections). It is constructed with wood boards oriented perpendicular to the path of travel which result in a small dip in the ramp approximately every six inches where the boards meet. The entire surface of the ramp is uniformly painted with a thick coat, covering any wood grain surface texture.

The slopes of two of the four rising sections of the ramp were measured with a level, a large protractor, and a 24 inch straight edge. The first measured section was found to have a slope of approximately five degrees which is in compliance with the new construction wheelchair ramp code. The second measured section of the ramp was found to have a slope of approximately seven degrees. This section of the ramp was measured because it appeared to be steeper than the others and, in fact, exceeds the Americans with Disabilities Act code (personal communication, Virginia Tech University Architect Tom Tucker, May, 1996).

The second ramp ascended by the PAU and wheelchair is located at the entrance to the main parking lot for the Virginia Tech university. This ramp is constructed with a rough cement surface and includes two rising sections and a flat resting platform on a turn between the rising sections. The total length of the ramp is measured at 65 feet and the average slope is measured to be approximately 2.6 degrees.

The third ramp attempted is located at the entrance to Patton Hall on the Virginia Tech campus. This ramp is also constructed with a rough cement surface and consists of one short rising section (20 feet long with a slope of approximately 2.4 degrees). The three selected ramps represent a variety of lengths and conditions presented by different wheelchair ramps.

Prior to ascending each ramp, the nine pound lead acid battery was fully charged. Weights were also placed on the wheelchair to increase the operator load to 165 pounds (with the exception of the third ramp in front of Patton Hall). In addition, measurements were taken on voltage draw for the Hancock ramp (the longest ramp) to assess the impact of the extensive length and steep angles of the ramp. The wheelchair operator applied full voltage to the motor throughout all ramp climbs.

Hancock Hall Ramp. Battery voltage prior to one climb on the Hancock Hall ramp was measured to be 13.04 volts. The wheelchair and PAU successfully ascended all four sections of the ramp at a continuous pace. The investigator subjectively observed that the rate of travel was less than the maximum speed of the wheelchair powered by the PAU. A battery voltage reading following one climb of the ramp measured 12.80 volts. This is a decrease of 0.24 volts from the battery which is over half of the voltage decrease resulting from the first battery life test trial (0.52 volts) of 2304 feet traveled over a flat tile floor. Voltage drop was measured for the Hancock ramp to determine the impact that such a long and steep ramp has on the wheelchair battery.

It was necessary for the investigator to lean forward in the wheelchair to continue moving up the ramp. A second attempt to climb the ramp was made with the investigator resting against the back of the wheelchair seat. In this position, the drive wheels of the PAU immediately slipped in place and the wheelchair was not propelled forward. The wheelchair did not slip backward down the ramp, but maintained its position while the wheels slipped. It was also observed that the handle of the PAU vibrated with the slipping motion.

Parking Lot Ramp. Two attempts were also made to climb the cement ramp leading to the university parking lot. In the first attempt, the investigator leaned forward in the seat which resulted in a slow and continuous ascension. Throughout the second attempt, the investigator rested against the wheelchair seatback. With this operator position, the wheelchair and PAU were able to climb the full length of the ramp with slipping occurring temporarily in only two places before continuing upward.

The investigator also descended the cement ramp and found that the wheelchair remained in control throughout the trial. Some braking was contributed by the drive wheels but it was not sufficient to stop the wheelchair from continuing downward due to gravity (without pressing the finger trigger). The braking did maintain a constant speed which provided a safe descent without acceleration. However, an unexpected need to stop would require removing the operating hand from the PAU handle and placing it on the wheelchair drive wheel in conjunction with the other hand and drive wheel. It should also be noted that the ability to steer the wheelchair with the PAU was maintained while traversing the ramp downward.

Patton Hall Ramp. The third ramp is much shorter and not as steep as the previous two attempted. An actual wheelchair user operated the PAU up and down the short ramp. It is estimated that this operator weighs approximately 140 pounds (no weights were added to the wheelchair). In three attempts to climb and descend the ramp, the PAU and wheelchair were successfully maneuvered up and down the ramp with excellent control. Through each attempt the operator remained seated against the backrest of the wheelchair and no attempt was made to lean forward. The drive wheels did not slip at any point and control was maintained even during descension.

Operation on Carpet

The wheelchair and PAU were maneuvered in power mode over several different carpet surfaces. Each carpet provided different characteristics including low, medium, and high pile depths, one area and several wall-to-wall carpets. In all cases the PAU was able to maneuver the wheelchair in a controlled manner as it does on smooth surfaces. One difference noted is an increase in the strength required to turn the unit on the deeper pile carpets. This difference is exaggerated when the wheelchair is moving at slower speeds. Observations up to this point indicate that the PAU can be considered a reliable means of mobility in power operating mode over carpeted surfaces.

Operation on Grass

The PAU was able to propel the wheelchair in power mode, turn, and operate in reverse on a grass surface. However, the drive wheels of the PAU slipped often and in several instances within a two-minute period, the wheelchair became stuck as the wheels slipped continuously on the grass. While the PAU may provide some assistance in power mode on optimal grass surfaces, it should not be considered a reliable form of transportation on grass.

<u>Operation on Rough Surfaces</u>
Several different rough surface conditions were tested to determine if the PAU is capable of propelling and maneuvering the wheelchair over such terrain. The first surface the PAU was tested on was a gravel parking lot with dirt underlying the gravel. This surface did not prevent the PAU from propelling the wheelchair forward or in reverse. The investigator was able to maintain control of the wheelchair and steer as usual despite the gravel. It was observed that occasionally the drive wheels slipped due to the uneven terrain inherent with gravel, but momentum assured continuous operation. Another notable observation was the small deviations in the position of the steering handle of the PAU when the drive wheels struck the gravel pieces. The motions were not significant enough to affect driving performance, but were definitely detectable by the investigator.

A second rough condition was tested with very small gravel distributed over a flat cement platform. The wheelchair and PAU were maneuvered over the small gravel without any noticeable impact on performance. Control of propulsion and steering were unaffected, with only small detectable vibrations resulting in the steering handle as the gravel met with the drive wheels.

The third condition tested involved maneuvering the wheelchair and PAU over a cement walkway which has been damaged. Surface texture was very rough with shallow cavities randomly located throughout the walkway. The drive wheels of the PAU passed over these holes without any apparent change in performance. Again, small vibrations were detectable in the steering handle of the PAU as the drive wheels met the holes in the cement.

<u>Operation on Wet Surfaces</u>
The wheelchair and PAU were maneuvered through a large puddle of water approximately one quarter of an inch deep. Handling and propulsion characteristics of the PAU were maintained without any detectable slipping or loss of control. Also, the ramp to the university parking lot was ascended under both dry and damp conditions. There were no apparent changes in performance.

In addition, the wheelchair and PAU were driven in a gravel parking lot in wet conditions which provided an underlying dense mud terrain. This test found that the PAU maintained propulsion and steering capabilities (with the occasional slipping as described above) as long as the gravel separated the drive wheels from the mud. On two occasions when the drive wheels moved into predominantly mud areas, the drive wheels immediately began to slip and the wheelchair did not move despite increased voltage input to the motor. It should be noted that the wheelchair was maneuverable in these muddy areas when placed in manual driving mode.

A test conducted on a wet grass surface found that the drive wheels of the PAU were unable to produce any forward motion. The wet grass provided a surface with very little friction and the wheels slipped continuously in the same location when voltage was applied to the motor.

Traversal of Common Obstacles

Several obstacles which a wheelchair user might encounter on an average day were tested to see how the PAU and wheelchair function when attempting to traverse the obstacles. The wheelchair and PAU were evaluated traveling over an elevator doorway gap, indoor and outdoor thresholds, and sidewalk gaps and curb ramps (small cement ramps in sidewalks designed to make curbed areas accessible to wheelchairs).

Elevator Doorway Gap. Two attempts were made to traverse the gap at an elevator doorway. The gap measures approximately 1.333 inches wide with a rise from the elevator to the floor of approximately 0.375 inches. Moving from the elevator to the floor, the first attempt was made with a slow approach (sub-maximum speed) and the second attempt applied full voltage to the motor from approximately three feet of distance.

The slow approach resulted in the three inch drive wheels of the PAU getting stuck in the gap and spinning continuously. When the gap was approached with full voltage applied to the motor, the wheelchair and PAU traversed the gap without slipping or delay.

Indoor Threshold. The PAU and wheelchair attempted to traverse an indoor threshold which bridges carpet and linoleum flooring. With a slow approach from either side, the drive wheels of the PAU slipped in position and the wheelchair did not cross over. This resulted when the caster wheels of the wheelchair started to climb the threshold and the drive wheels of the PAU were lifted off of the ground. This problem was easily overcome by approaching the threshold with more momentum (but not requiring maximum speed). At moderate speed the wheelchair and PAU passed easily over the threshold.

Outdoor Threshold. A threshold 0.75 inches high and 5 inches long was approached at slow, moderate, and full speeds. The PAU and wheelchair successfully traversed the threshold which bridges two sections of concrete sidewalk, at all speeds. There was no indication of wheelchair instability or damage to the PAU.

Sidewalk Gaps and Curb Ramps. The PAU was operated over several cement sidewalks and experienced no difficulty passing over gaps and raised sections. When a raised section of sidewalk was encountered, the PAU experienced a slight jolt when passing over the discontinuous segment. This jolt was also present for all other obstacles tested in the performance evaluation and no apparent damage occurred.

Several curb ramps were ascended and descended with the PAU in power mode. These are the small cement ramps built into sidewalks where a curb must be made wheelchair-accessible. Ramps which were constructed with a continuous rough cement surface and smooth transitions to the sidewalk posed no problems for the PAU and wheelchair. The investigator was able to maneuver to and from these sidewalks while seated against the wheelchair seatback (not leaning forward). No destabilization of the wheelchair was experienced, and the PAU maneuvered consistently on the asphalt as well.

One poorly constructed curb ramp did pose a significant problem and was considered an important safety concern. The PAU and wheelchair were not able to successfully negotiate the ramp located at the service entrance to Whittemore Hall on the Virginia Tech campus. The ramp has a steep transition which must be traversed between the angled ramp surface and the adjacent flat sidewalk. When the steep transition area is encountered by the caster wheels of the wheelchair, the PAU drive wheels are lifted out of contact with the ground. This causes the drive wheels to slip continuously in the air while no control is exerted over the direction of the wheelchair. The wheelchair begins to either fall backward (ascension), or forward into the opposite steep bank of the ramp (descension). The resulting motion can pose a difficult situation for the operator as he/she attempts to control the wheelchair manually. There is a tendency toward potential loss of manual control as the PAU drive wheels come back into contact with the ground. The problem is exacerbated by the extreme surface texturing of the ramp which has peaks and valleys purposefully carved into the cement. This ramp must be negotiated for access to the building and this scenario is indicative of real-life circumstances.

Additional Observations

One minor negative aspect of the PAU performance consistently observed is a high pitched whine produced by the motor when operated at submaximum voltage. The sound is in addition to the expected operation noise produced by the motor and it is only produced when the motor is operated at less than maximum voltage. This occurs when the finger trigger control is actuated partially (not full depression). The sound can be avoided by adjusting the voltage applied to the motor at the finger trigger control.

Sound Pressure Level Measurements. The sound pressure level of the motor whine was measured in an attempt to compare the sound to common noise sources. Voltage to the motor was adjusted to consistently produce the whine and a Rion model SA-27 one-third octave band real-time analyzer was used to measure the one-third octave band 30-second Leq (level average over a 30-second period). The microphone was placed at the height, angle, and position of the wheelchair operator's ear. A 30-second measurement, taken in the Auditory Systems Laboratory at Virginia Tech, produced a broadband sound pressure level of 42.4 dBA. The broadband ambient noise level in the laboratory was measured and calculated to be 38.2 dBA (sound pressure level calculations are shown in Appendix I: Motor Sound Level Measurements). This was very close to the motor whine level of 42.4 dBA which was below the sound pressure level of voice conversation (Berger, Ward, Morrill, and Royster, 1986).

The motor one-third octave band noise spectrum was contrasted with the laboratory ambient noise spectrum. Figure 12 shows the decibel levels for the one-third octave band center frequencies of the two sets of measurements.

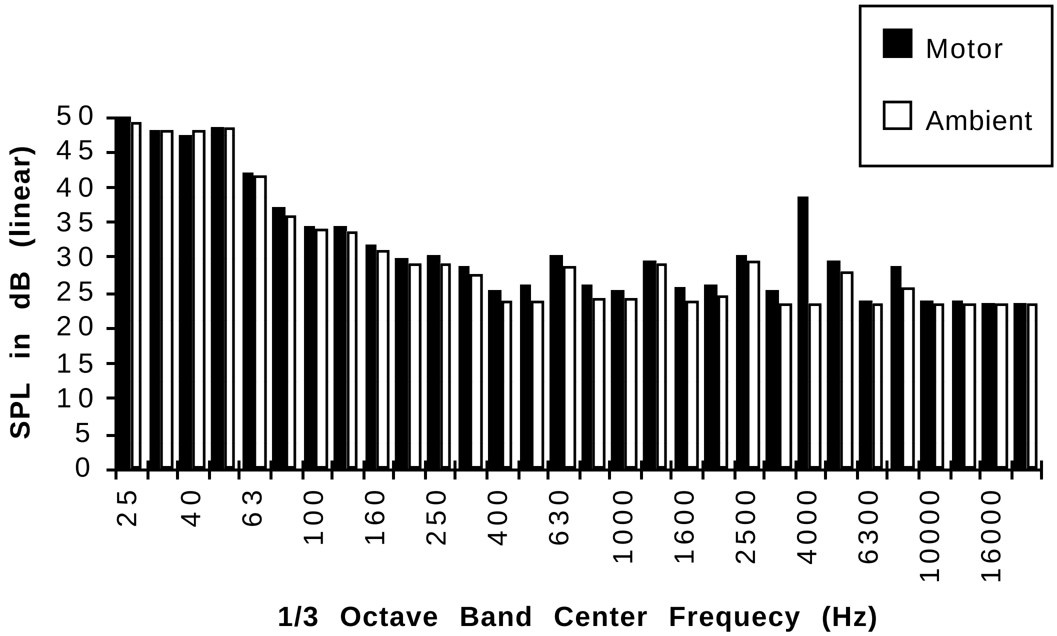

Figure 12. Wheelchair motor spectrum compared to the ambient noise spectrum.

The figure illustrates the predominant differences between the motor and ambient sound spectrums at the center frequencies of 4000 Hz and 8000 Hz. The spike at 4000 Hz represents a 15.1 dB (linear) difference between the motor and ambient sound pressure levels (38.6 dB for the motor noise versus 23.5 dB for the ambient noise). The broadband sound pressure level of the motor whine was quite low at 42.4 dbA (below voice conversation). The tonal nature of the motor whine, predominantly at 4000 Hz, probably contributed to the annoyance factor of the noise.