Chapter 8: Appendices

Appendix A: Description of the New Power Add-On Unit (PAU)

Design Criteria

The new power attachment is designed to provide the following abilities listed in approximate order of importance:

1. The ability for a manual wheelchair user to gain an inexpensive power chair without permanently modifying their existing chair.
2. The ability to retain the portability of the folding chair and be carried in the seat of a car.
3. The ability for the wheelchair operator to independently attach and detach the PAU given sufficient upper body capabilities.
4. The ability to switch between power and manual modes of operation while the attachment is in place on the wheelchair.
5. The ability to steer the wheelchair in any direction with a simple steering and reversing mechanism.
6. The ability to retrofit the device to nearly all standard folding wheelchairs, with only simple modifications to frame extensions and attachment fittings.
7. The ability to maintain wheelchair maneuverability by enabling the chair to turn in its own length without adding to the overall wheelchair dimensions. This includes maintaining the ability to access tables and counters.
8. The ability to maintain the stability inherent in the manual wheelchair design that arises from four wheels in ground contact.
9. The ability to provide straight-line tracking on a smooth surface with no lateral adjustment required to the steering control.
10. The ability to maintain traction over uneven surfaces.
11. The ability to assist the user in rolling over obstacles.

These criteria were used as a starting point in the design process for the components of the new PAU. Through each iteration the criteria have been referenced in order to maintain compliance.

Component Specifications

The design process for the PAU was separated into several sections. These sections include design of the securing frame, tiller column, column attachment points, steering mechanism, drivetrain, and battery storage. Each of these areas is specified as it has been fabricated for the second prototype.

Securing Frame. The securing frame, composed of two crossbars, is horizontally connected to the vertical wheelchair supports via securing blocks located under the front edge of the seat. Spring-loaded poppits at the ends of each of the crossbars insert into predrilled holes located in the securing blocks (see Figure A-1). The poppits can be retracted for column movement by means of finger grips located on the crossbars. The four points of attachment provide a solid frame which is not prone to rotation as would be a single securing bar. The bars are not connected together in a single unit so that they can be positioned as needed on different wheelchairs (e.g. the vertical distance between the bars may be four inches on one chair and five inches on another).

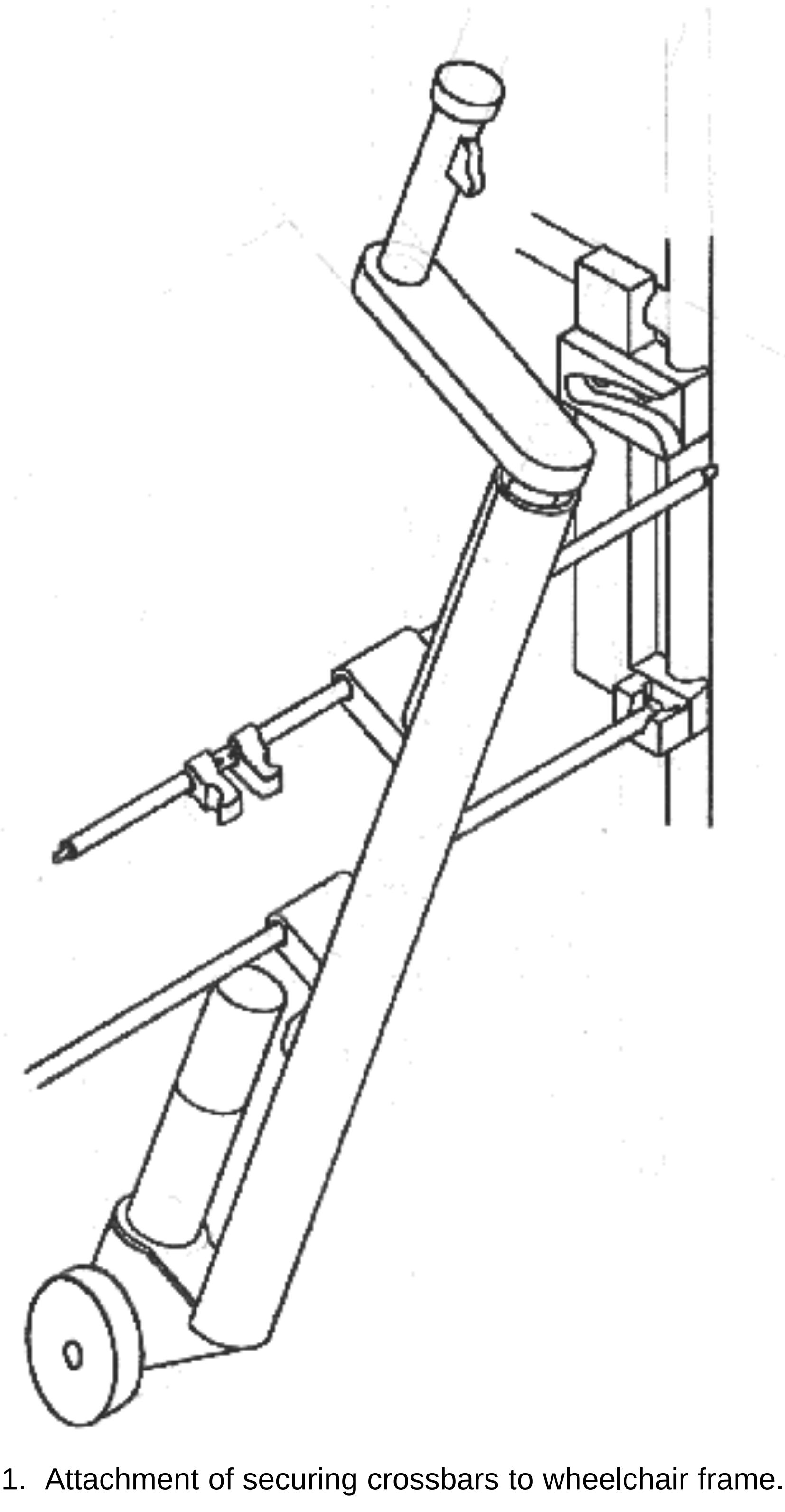


Figure A-1. Attachment of securing crossbars to wheelchair frame.

<u>Tiller Column</u>. The vertical tiller column is the central component of the PAU, consisting of two concentric tubes. The outer tube remains stationary relative to the wheelchair and serves as the connection between the drive/steer components and the securing frame. This outer tube is attached to the securing frame via friction blocks which can be adjusted vertically along the length of the outer tube.

The inner tube is connected at the top end to the steering bar by a dowel which extends through both the steering bar and the tube. At the lower end the inner tube is connected in the same manner to the drivetrain support. The tube serves as a conduit for the wiring between the controls on the steering handle and the motor located on the drivetrain support.

While the outer tube is stationary, the inner tube rotates and translates vertically to accommodate steering motions and fluctuations due to uneven driving surfaces. This is achieved by connecting the two tubes with bearings to allow motion in both the rotational and vertical directions. Bearings located at the top and at the bottom of the tubes maintain the relative position of the tubes. The juncture at the bottom includes a housing (shown in Figure A-2) which provides a downward force on the inner tube by means of a compression spring. This spring is compressed against the thrust bearing which is secured to the outer tube and a collar which is secured to the inner tube. The result is a constant pushing of the inner tube toward the ground which maintains drive wheel contact over uneven terrain. This biasing effect is also necessary to provide adequate friction for the drive wheels to propel the wheelchair.

Figure A-2. Compression spring housing.

<u>Steering Mechanism</u>. Attached to the top of the tiller column, a steering bar extends back toward the wheelchair operator (as seen in Figure A-1). The bar is attached to the inner tube of the column and is used to rotate the entire drive wheel apparatus (attached at the lower end of the inner tube). A vertical handle is connected to the end of the steering bar for the operator to maneuver the position of the bar. A finger actuator which controls voltage to the motor, on/off positions, and forward/reverse positions, is placed on the steering handle.

Steering is accomplished by rotating the bar counterclockwise for motion to the left and clockwise for motion to the right. A slip-ring placed in the plastic handle allows it to easily swivel in place so that the user does not need to regrip the handle at different positions. In addition, the handle houses the controls for the motor.

The steering bar is hollow to accommodate the wiring for the motor controls which pass from the handle to the inner tube of the tiller column. A transistor attached to the wires and the steering bar transfers any excess heat to the bar (the steering bar functions as a heat sink for the motor system).

<u>Drivetrain</u>. Figure A-3 is an exploded, two-dimensional view of the drivetrain assembly. The drivetrain support serves as the central piece for the assembly and it is connected directly to the inner tube of the column. The entire drivetrain unit rotates in conjunction with the inner tube of the column as the operator maneuvers the steering bar.

Figure A-3. Exploded view of the drivetrain housing.

In order to provide sufficient space for the wheelchair casters to rotate, the compact, 12-volt motor is oriented parallel to the tiller column. The prototype makes use of a motor taken from a cordless hand-held drill. Characteristics such as a compact power source (a single 12-volt battery), adjustable torque levels, adjustable speed, and small dimensions, make the drill motor an excellent motive source for this purpose.

A protective casing for the motor secures it onto the drivetrain support with screws. This casing has a wide, solid base that maintains the vertical alignment of the motor casing. Inside the casing, machined supports interlock with the motor to restrain the motor as it turns. Reaction forces would otherwise cause the entire motor to rotate while the shaft is turning. Holes drilled in the side of the casing permit the control wires to reach the motor leads and provide for ventilation.

The motor shaft extends downward into the drivetrain support and is coupled to the miter gearbox input shaft via a two-piece coupling. Two output shafts from the gearbox extend beyond both sides of the support to the drive wheels. Distance between the drive wheels has been minimized in design efforts. If a large gearbox is used in the drivetrain, the wheels will be displaced farther apart causing two additional problems. First, the additional width reduces the excursion permitted by the wheelchair casters. Second, the increased width places more strain on the wheel assembly due to the differential forces affecting the wheels when turning. There is no differential gear arrangement in the gearbox to compensate for the different rates at which the two wheels rotate while turning. This is not a significant problem if the wheels are maintained close together.

Battery Storage. The battery which provides power to the motor must be carried on the wheelchair in addition to the column unit. It is secured in a plastic battery box with a socket in the side of the box for connecting the battery leads to the control wires. This box is placed into a harness-type sling which is secured on the back of the wheelchair frame with harness straps. The sling straddles the upper wheelchair horizontal supports and can be removed by unwinding the securing straps. The sling attachment does not alter the wheelchair in any manner. It can remain on the wheelchair when the PAU is not being used and will fold with the wheelchair for storage or transporation.

The battery is placed into the sling and secured with additional harness straps fitted with quick-release clasps. Wires from the motor controls are then plugged into the box and the unit is ready to drive.

The new PAU design requires only one battery as opposed to the two batteries required for all other products on the market. It can operate with different size 12-volt, deep cycle batteries: tests were conducted with a 9 pound and a 25 pound battery. This one battery operation is a significant advantage because of the weight of the batteries (up to 25 pounds each) and difficulty of handling. Further, a wheelchair user can simply purchase two batteries for the new invention and charge one while the other is in use. This provides a constantly available energy source for the new design which is not available with other products. There is always down time while the dual batteries are charging; though this usually occurs overnight.

Component Drawings

The following set of drawings represent the unique components fabricated for the second PAU prototype.

Figure A-27. Motor cover (piece 2 of 2).

Figure A-28. Motor locking support.

Figure A-29. Motor ring support.

Figure A-30. Axle augmentation.

Figure A-31. Cloth pattern for battery sling.

Appendix B: Wheelchairs Circa 1997

Manual Wheelchairs

Manual wheelchairs have remained basically the same for more than fifty years. Figure B-1 illustrates the front and side view of an adult cross-frame folding wheelchair. The average chair has 24 inch diameter rear drive wheels, 8 inch diameter front caster wheels, and an overall length of 31 inches without the footrests in place. The general manual wheelchair design has not been altered since the 1986 reference this synopsis is based upon (McFarland and Wilson), was published.

Figure B-1. Folding manual wheelchair.

Components. The sling-type seat and backrest are screwed onto a metal tubing frame. The two sets of lower horizontal bars of the frame are secured in position while the top horizontal bar on each side raises up to pull the two sides of the chair together. As the two sets of wheels come together upon folding of the chair, each of the crossed bars rotate about their centers where a bolt connects them and serves as their axis of rotation.

Generally, the footrests and armrests are removable to allow easy transfer to and from the seat. Individual footrests rotate out away from the center of the chair and then lift vertically to disengage. Many have a release which must be triggered before the footrest will rotate. By reversing the process, the footrests are placed back on the chair. During this routine the user can hold both legs off to the side or up above the footrests with one arm. Then, with one footrest in place, the user can fold the unsupported leg over the knee of the other leg until the remaining footrest is affixed. It is a complicated transfer sequence often requiring several minutes to complete. Armrests for the chair usually lift straight up to be removed and only one is generally removed for transfer.

There is a new type of folding wheelchair that has been recently placed on the market. The new design incorporates a rigid box-like frame (no crossed bars) with a back support which folds down onto the seat for transportation. In addition, it is generally necessary to remove the wheels in order for the wheelchair to fit into a personal automobile. There does not appear to be any apparent reason why the new PAU design would not work with the box-like frame.

Electric Wheelchairs

The powered wheelchair originated as an add-on device for a manual wheelchair (Kamenetz, 1969). A motor(s), battery, and sometimes a steering device were attached to existing chairs to assist those without the ability to push a manual chair for extended periods. Over the years the apparatus was integrated into the design of wheelchairs and a unique mobility device was developed. The wheels of the chair were reduced in size, the frame strengthened to handle the additional weight, and the power components increased in size to provide more strength for a longer time in a more reliable fashion. Many chairs have integrated the battery charger on board as well as instruments to monitor charge. Steering systems, some of tremendous complexity, have been developed; almost all of them today have the settings (acceleration rate, joystick sensitivity, etc.) programmed with a microcomputer controller. The result is a very heavy (over 200 pounds) and bulky driving system which requires a special vehicle with a wheelchair lift to transport. Prices for this type of power wheelchair begin in the range of $5000.

Another type of power-driven wheelchair just recently placed on the market is a combination of the folding manual chair and the integrated power chair. It is power-driven but it can be folded for transportation. This is accomplished by removing the power supply and in some cases the drive unit when folding is required. These chairs do not have a reinforced frame and are therefore comparable in weight with auxiliary drive chairs. Several of the foldable models are available for about $4000.

Design Considerations

The add-on drive system is designed to attach to an existing self-propelled wheelchair. Different types of wheelchairs, dimensions, prescribed clearances, etc., have all had an impact on the development criteria of the new apparatus. The following section examines these aspects of wheelchairs which manufacturers are currently producing.

Dimensions. Seat dimensions for the wheelchair, as well as floor-to-seat height, define the available space for an add-on power device. Table B-1 outlines the sizes provided by major wheelchair manufacturers. Sizes other than those listed here must be obtained by placing a special order (McFarland and Wilson, 1986).

Table B-1. Wheelchair Sizes Available From Major Manufacturers (adapted from Wheelchairs; a Prescription Guide by McFarland and Wilson, 1986)

Height from floor	Width	Depth	Designation
19.5	10	8	pre-school, infant
19.5	12	10-11.5	child's/tot's, high
16.5	12	10-11.5	child's/tot's, low
21	14-14.5	11.5	growing chair
17.5-20.5	14-16	11-13	growing chair
18.5	16	14	jr. or slim adult
19.5	16-16.5	16-17	narrow adult
19.5-20.5	18	16	adult
19.5-20.5	18	17	tall adult
19.5-20.5	20-22	16	wide adult

Note: All units are in inches.

Space under the seat of the chair where the apparatus is located is further restricted by the position of the cross-brace, footrests, and the rotation range of the front caster wheels. The cross-brace is located halfway between the front and rear vertical members of the side frames. The length of the portion of the chair in front of the brace is calculated by dividing the seat depth dimension by two. For example, an average adult wheelchair will have a 16" seat depth which provides 8" of chair length in front of the brace.

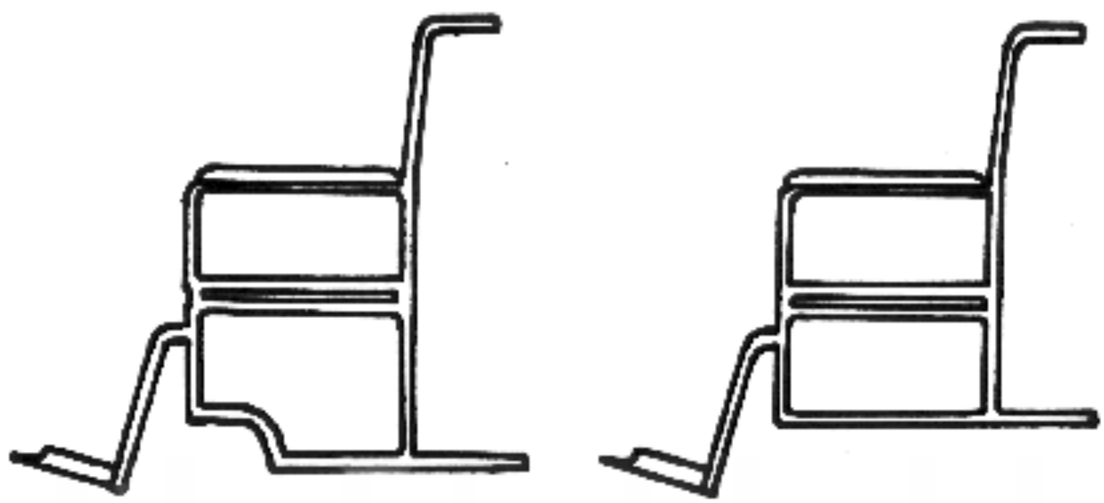
Footrests extend forward and down from the front of the wheelchair frame. While in place, supporting the operator's legs, there is little or no access to the area under the seat. Disengaged or rotated outward 90 degrees, the footrests do not impede access.

Many footrests also have a foot tray which rotates vertically out of the way while the supporting arm remains in place. This may provide further access without the need to disengage the entire footrest apparatus.

The 360 degree rotation of the caster wheels also limits the options for device placement. As an example, on the most prevalent design, standard caster wheels are 8" in diameter and rotate about an off-center axis. The axis is located on the outside of the wheelchair frame which decreases excursion under the seat area. When both wheels are turned inward under the seat, 4" of caster wheel protrudes into the area under the seat on either side. For a small adult wheelchair, this decreases the available width from 16" to 8."

Wheelchair frames. There are two types of frame arrangements supporting the front caster wheels. The first type pictured in Figure B-2a is a drop-down configuration. The lowest horizontal bar in the frame starts above the caster wheel in the front and then drops down to another level behind the wheel. This arrangement makes additions to the front corners very difficult in that there is little room for attachments and the frame level is not consistent.

The second type of frame contour is called a straight-through frame and it is illustrated in Figure B-2b. In this case the lowest horizontal bar runs straight across from front-to-back and sits above the caster wheel. This bar is higher off the ground than the drop-down arrangement.



a. Drop-down

b. Straight-through

Figure B-2. Straight-through and drop-down wheelchair frame types.

Appendix C: Patents for Add-On Power Devices

Since the 1950's, patents have been issued for inventions which convert a manual drive wheelchair into a power drive wheelchair. Patents pertinent to the field of the new design have been obtained through a patent search conducted by Dr. John Casali of Virginia Tech and Sean McGinn of Whitham, Curtis, Whitham & McGinn Law Offices. These are listed in Table C-1 by name and number in order of their issue dates (Avakian, 1993; Benoit, 1975; Broadhead and Hobson, 1993; Casali, 1994; Coker, 1983 and 1991; Duke, 1950; Garin and Lusk, 1993; Goldenfeld, Mautner, and Mastov, 1988; Jones, 1990; Kaiho and Hirota, 1975; Karchak and Allen, 1975; Karlsen, 1971; Kleinwolterink, 1991; Kropf, 1992; Mastov, Mautner, Gilad-Smolinsky, and Levy, 1992; Meeker, 1994; Rabjohn, 1968; and Rosenthal, 1963). In the table, the major design and performance characteristics of the inventions and the new device (denoted by the "Casali" column heading) are outlined.

Table C-1. Patents for Add-On Power Devices

All the inventions use one of three ways to transmit power. The first type of transmission applies a torque directly to the hubs of the drive wheels. Due to their nature, these systems are relatively permanent attachments to the chair.

The second type of system applies a frictional roller to the rear drive wheels. The powered roller turns the wheels when a force is applied. Since a roller is required for each rear wheel, two motors are also necessary (this is more complicated but allows the use of joystick-type electronic steering arrangements). Rear wheel friction drives are generally placed behind the seat back on top of the wheel. In this position the roller/wheel contact surface is in a dangerous position where fingers, clothing, etc. can be pinched. This type of frictional drive system was evaluated by Gaal and Johnson (1993) and found to perform poorly in wet conditions.

Most of the inventions implemented an additional drive wheel or wheels to transmit power to the chair. Torque is applied to the additional wheel which is in frictional contact with the ground while it is secured to the wheelchair frame.

The "placement" section of Table C-1 refers to the area of the wheelchair where the main attachment components are secured. Inventions placed behind the seat back are difficult for the operator of the chair to reach or observe in case of trouble, need for adjustment, or simple attachment and detachment procedures.

Wheelchair Characteristics

Each characteristic in Table C-1 is listed such that a "yes" answer implies a positive quality in the design. These characteristics can be better understood with the following explanations:

Easily Attached/Detached. A "yes" is indicated in this row if it appears that the device can be attached or detached by an operator of sufficient upper body capabilities without assistance. The device must also be designed for temporary attachment.

No Increase in Chair Size. This statement implies that the outer dimensions of the wheelchair are not increased by the addition of the device. It is an important characteristic in that any additional size will inhibit the maneuverability of the chair.

Steering Capability. Some of the devices only apply a driving force without an additional arrangement to steer the chair. It is assumed that steering is accomplished through frictional braking applied by the operator's hands on the drive wheels in these cases. Other inventions provide for what appear to be insufficient steering means. For example, Goldenfeld number 4,759,418 (Goldenfeld et al., 1988) suggests manually manipulating one of the front caster wheels to provide for steering of the entire chair and operator.

Both Manual and Power Modes. Several of the previous inventions are unable to switch between power and manual driving modes while the attachments are in place. Both Coker patents (4,386,672 and 5,016,720) (Coker, 1983 and 1991) for instance, once attached, must be driven in power mode only.

Requires Only One Motor. This characteristic is important in that one motor is less expensive, less heavy, less bulky, and requires less maintenance than two motors.

Uncomplicated Design. The more simple the design idea, the less difficulty there will be with maintenance, adjustments, operation, and future design alterations.

No Decrease in Chair Stability. The addition of some attachments may decrease the inherent stability of the wheelchair by raising caster wheels off of the ground.

Biased Wheel Suspension. Of the inventions which make use of an added drive wheel for power transmission, some apply a downward force on the wheel and others do not (they use only gravity). Since the wheel propels the chair by frictional contact with the ground, it is an advantage to increase the downward force by some biasing means.

Can Clear Obstacles (e.g. short curbs or doorway thresholds). This characteristic is an indication of ground clearance while the attachment is in place. Those devices which comprise an additional frame (lower than the wheelchair frame) decrease the ability to traverse rough terrain.

Access to Tables. Inventions which place parts in the area above the user's knees such as Rabjohn 5,186,269 (Rabjohn, 1968), keep the chair from moving under tables and counters. These deny access to tables and counters unless there is a provision for temporarily removing the obstacle.

Appendix D: Assistive Device Consumers

Potential assistive device users are categorized by Gitlin (1995) into five groups. Specifically, she identifies the categories as follows:

1) individuals who are caring for a family member (or other acquaintance),
2) older individuals for whom device use may promote safety or reduce the risk of injury,
3) individuals who experience age-related changes or functional decline,
4) those who have a first-time disability or experience multiple chronic conditions,
5) individuals who are aging with a disability.

A wide variety of potential power assist device consumer classifications exist within these five groups. For the purpose of identifying potential market segments, the last two categories will be restructured into those who experience multiple chronic conditions, and those individuals with a first time disability or are aging with a disability.

Caregivers of Individuals with Disabilities

In many cases it is the caregiver, and not the intended assistive device user, that conducts the selection and purchasing process for the assistive device. This should be considered when targeting the consumer in advertising strategies and design issues. The standard wheelchair, for example, is designed with handles at the top of the backrest for an assistant to push the chair. If the chair was designed and advertised with only the user in mind, these handles would not exist. When the caregiver is purchasing the wheelchair, the specific aspects of this interface are very important to them.

The caregiver segment of the consumer population is an often neglected group. Certainly, they are not listed in the statistics of assistive device users. Yet caregivers need assistive devices to help alleviate the burden of care. The PAU for example, may be used to provide mobility to a person who would otherwise be pushed in a wheelchair by an assistant. Gitlin states that one segment of the disabled population; older people with long-term chronic disabilities, have family members provide close to 90 percent of their support.

Types of Caregivers. There are several different types of caregivers which may serve to use and purchase the assistive devices. Family members are the most common and obvious type of caregiver. Characteristics of this group may include a genuine concern to provide the best care for the disabled family member. The family caregiver may or may not be well informed as to what assistive devices are available and what advantages and disadvantages they may have over other available devices. Appealing to this group of consumers may involve an advertising promotion which describes the advantages of the product over others on the market. Also, the promotion can explain the device interface design for the caregiver (e.g. handles on the wheelchair) as one of the advantages. The proposed evaluations for the new PAU may provide valuable information for this consumer category.

Additional caregivers interacting with assistive devices include professional care attendants, nurses, therapists, and assistants such as drivers for disabled van and bus services. These professionals may also be involved in purchasing decisions.

Older Americans today are relying more on the assistive devices to provide support in daily tasks and less on the personal assistants (Bowe, 1995). This trend may be due in part to the recent improvements in assistive technology spurred by an increased awareness of disabled rights (e.g. the Americans with Disabilities Act).

<u>Older Individuals Who Use Devices to Reduce Risk of Injury</u>
The power assist device can be purchased by individuals that find ambulation to be a safety risk. One example of this population is older individuals afflicted with osteoporosis; a disease which results in a weakened bone structure (Stolov and Clowers, 1981). Elderly people with osteoporosis can be easily injured by a minor fall or slip. Walking and standing can therefore become extremely dangerous at times when the individual is tired or not focused. Safety becomes a larger problem for this group of people when adverse conditions such as wet or icy surfaces are present.

Another example of individuals at risk of injury with simple walking or standing are people with decrements in equilibrium. Aging can contribute to deterioration of the vestibular system resulting in vertigo, dizziness, and a decreased ability to make positional adjustments for balance. Many individuals also find that maintaining balance is difficult with conditions such as arthritis which can cause restrictions in movement (COMSIS, 1988), or other trauma which may have affected the vestibular system (e.g. head injury). Again, the power assist device may offer a safe mode of transportation without risk of falling. Because people in this category are not generally defined as disabled, they may not be included in wheelchair population statistics.

<u>Individuals Who Experience Age-Related Changes or Functional Decline</u>
This category is similar to the last in that age-related changes may be responsible for the need of assistive devices. However, Gitlin separates the two groups by the purpose for which they use an assistive device. The former category listed is for individuals who use devices as a safety precaution. While this category purchases assistive devices to enable independent performance of activities and to minimize disability. Safety is the primary concern of the previous group, and independence is the primary concern of this category experiencing functional decline.

<u>Functional Decline.</u> Age-related changes in functional ability which may influence the purchase of a power assist device include those mentioned above; osteoporosis, loss of balance, and arthritis. Another change resulting in functional decline is a decrease in strength and stamina associated with age. There is typically a mild loss of strength (10% to 20%) from ages 40 to 70 (COMSIS, 1988). After this point there is a general trend toward severe loss of strength. This over 70 age group that does not have a distinct disability brought on by a labeled pathology or trauma, may still require the use of the power assist device for mobility. Contributing to the need of such assistance devices is the increased perception of exertion that is associated with increasing age (COMSIS, 1988).

In addition to these changes with age, there tends to also be a general decrease in functional movement due to cumulative wear and natural changes in body dimensions. Flexibility, reach, and joint function can be greatly diminished as a result of age. Extreme cases can result in the need for functional assistance such as wheelchairs and the PAU. This group may or may not be defined as disabled depending on the individual cases.

The onset of these age-related limitations may be gradual. Without an acute situation which draws the attention of health care professionals, an older person may not be introduced to available assistive devices. In fact many older people are initially introduced to assistive technology during a hospitalization. Advertising efforts can be directed to reach out and educate this group of potential users before they have the need for hospitalization.

Individuals Who Experience Multiple Chronic Conditions

One study discussed by Gitlin (Zimmer and Chappell, 1994) found that "the most important determinant of the use of a mobility device was the number of mobility problems a person experienced, as opposed to the level of severity of the problem." This statement indicates that a person with several mobility limitations is more likely to purchase and use an assistive device such as the PAU, than someone with a single disability.

It is unclear what percentage of wheelchair operators have multiple chronic conditions. If they are more likely to purchase the device, it may be beneficial to identify and target this segment of the wheelchair population. The PAU design team has maintained the assumption that the user of the device may have disabilities other than ambulatory. Efforts have been made to provide a product which is easy to attach, detach, and operate in case the operator has limited capabilities in the upper body as well.

Individuals with a First time Disability or Who are Aging with a Disability

This category of assistive device consumer is the best group represented by statistics about wheelchair populations. The category is carefully broken into disability classifications in Appendix E: Wheelchair User Disability Groups. Refer to this appendix for an extensive description of these user categories which include wheelchair users with lost lower-limb function, poor postural stability, and general debilitation. It includes a description of the capabilities and limitations of wheelchair operators from a wide range of disability groups.

Appendix E: Wheelchair Disability Groups

Many conditions can lead to a disability requiring the assistance of a wheelchair. McFarland and Wilson (1986) list three groups of wheelchair users and the pathologies leading to their disability:

Lost Lower-Limb Function	Poor Postural Stability	General Debilitation
Spinal-cord Injury	Brain Damage	Aging
Arthritis	Cerebral Palsy	Alcoholism
Cerebral Palsy	Cancer of the Spine	Temporary Illness
Poliomyelitis	Other Diseases	
Multiple Sclerosis		
Muscular Dystrophy		
Stroke and Brain Trauma		
Bilateral Amputation		
Other Diseases		

The abilities and limitations of wheelchair operators will vary a great deal even within the same disability group. Capabilities of users disabled by aging, alcoholism, arthritis, illness, and brain damage may range from complete independence to complete dependence (requiring assistance in transfers, propulsion, etc.). Many of the 500,000 nursing home residents requiring the use of a wheelchair fall into these categories (Nicosia and Phillips, 1990).

Spinal Cord Injury
Spinal cord injuries account for approximately 200,000 of the wheelchair users in the United States, with an additional 10,000 injuries per year. It is estimated that two thirds of this wheelchair user group is under the age of 30 (Hall, Kupfer, and Leshner, 1996). They are categorized by indicating the lowest vertebrae with a functioning nerve root. For example, if the 6th cervical vertebrae was damaged, the disability is termed C5 quadriplegic. This indicates that the 5th cervical vertebrae, as well as those above it, have functioning nerve roots. The letters C, T, L, S stand for the cervical, thoracic, lumbar, and sacral areas of the spine respectively.

Many times spinal cord injuries will not be complete. In these cases there may be various levels of nerve function below the lesion. The abilities listed below for each spinal cord injury level assume a complete lesion; therefore, many of the wheelchair users will have more function than indicated. Background information on which the following descriptions are based may be found in the Handbook of Severe Disability (Stolov and Clowers (Eds.), 1981).

Levels C2, C3, C4. With the exception of some C4's, lesions at these levels require respiratory assistance and a full time skilled attendant. Mechanical functions are accomplished with head movement and breath control, thereby requiring an electromechanical steering mechanism for the wheelchair. These wheelchair users would not be possible consumers for the new PAU system without a specially adapted power control system.

Level C5. Mechanical functions for the C5 quadriplegic are controlled by shoulder and elbow flexion. There is no function of the hand or wrist and gross arm motions are accomplished with the use of complicated assistive devices. A joystick-type steering device is required in order to control the wheelchair. Therefore a C5 would also not be able to use the new power attachment in its most basic tiller steering configuration.

Level C6. At the C6 level there is no hand function but the wrist is capable of extension and dorsiflexion. There may also be some limitation of the strength of elbow flexion. Many times the C6 is capable of operating a manual wheelchair and may often require both a manual and an electric chair. Due to the C6's functional limitations, the steering device for the new PAU would need to be modified in such a way as to allow control by the arms and wrists (as opposed to requiring a hand grip).

One other important note about a lesion at this level is the loss of balance. The arms are the only control for the whole body and it is easy to fall over without having the muscular control for holding the torso upright. For this reason, it is doubtful a C6 would be able to attach and detach a PAU and the battery required for it to run. This problem may be obviated in some cases by the C6's need to have an attendant for some activities to assist with other functions.

Levels C7, C8, T1. With these injuries, mechanical control of the arms and wrists is quite good but the hands may still have difficulty functioning. A manual wheelchair is generally used but it is not easy to handle and may require slight modifications such as friction tape or projections on the hand wheel rims. An electric wheelchair will be required occasionally.

It may be possible for a person having functional control at these levels to operate the new add-on power drive with a steering device modified for arm and wrist control. There is still a large problem with balance at these levels and an assistant may be required to help attach and detach a PAU.

Levels T2-T12. At these levels mechanical tasks are very difficult but can generally be performed with complete independence. The wheelchair is the main form of ambulation and the hands usually function well controlling it. Individuals of this group should be good candidates for the new tiller power drive. Their ability to attach and detach the device will most likely depend on the difficulty of placing the batteries. There is still a great loss of musculature throughout the torso and this may interfere with attachment and detachment. Body control increases as the level of the lesion becomes lower.

Levels L1-L4. Those with lesions through the lumbar region have an additional option for ambulation. Though wheelchairs are still used, these individuals can also use a knee-ankle-foot orthotic which allows walking with crutches or a walker. The need for an electrical chair is based more on a general weakened condition. These levels should have sufficient body control to handle the batteries and drive mechanism.

Levels L5, S1, S2. As a general rule, wheelchairs are not used at these injury levels. Crutches can be combined with an ankle-foot orthotic to provide ambulation. The wheelchair and add-on device may be an option for those with additional complications. It may also be helpful for long trips since crutch use requires a very large energy output from the user and can cause irritation throughout the upper extremities and shoulder girdle.

From this information, it is apparent that wheelchair users with spinal cord injuries through the middle levels are the best candidates for using the new power drive/steer conversion system in its most basic configuration.

Poliomyelitis (Polio)

Permanent disabilities resulting from poliomyelitis depend on which areas of the body are affected by residual muscle paralysis. Cases which require permanent use of a wheelchair involve extreme functional loss of the lower extremities or loss of respiratory function requiring respiration assistance. Abilities vary a great deal and many of the wheelchair users may have perfect hand and arm function. In such cases the tiller steering power attachment will work well.

It should also be noted that the majority of people experiencing the residual effects of poliomyelitis are 40 to 60 years of age. This is due to the epidemics through the 1940's and 50's and the introduction of the Salk vaccine in 1955 which inhibited the spread of the virus. As this group ages, the number of wheelchair users may increase due to the susceptibility to degenerative joint disease, osteoporosis, and increased respiratory difficulty due to loss of thoracic elasticity. Two participants in the PAU usability study were post-polio wheelchair users. One subject was dropped from the study because she did not fit the consumer profile (and defined capability requirements). The second post-polio participant functioned well with the PAU and indicated that the product would be useful to her.

Muscular Dystrophy

Wheelchair users with muscular dystrophy have a weakness of the muscles in the shoulders and hips. Functional use of the arms and hands may diminish in time but can be helped by rehabilitation therapy. This level of ability may determine whether or not the new PAU can be operated. There is no possibility for independent attachment and detachment but an assistant is usually present to help with transfers.

Multiple Sclerosis

There is a great deal of variability in the multiple sclerosis population. Two subject matter experts in the Expert Information Interview Evaluation identified people with multiple sclerosis as good candidates for the new invention due to the need for varying levels of mobility assistance. The physical capabilities of people with multiple sclerosis can change greatly even within the same day. This results in the need for powered mobility when the wheelchair operator is not functioning well, and manual mobility when the operator is able to exercise.

Once a person with multiple sclerosis has reached an advanced condition, there is generally extreme weakness, spasticity (involuntary muscle reflexes resulting in uncontrollable jerky motions), and ataxia (inability to control voluntary movement). A large difficulty resulting from the spasticity is a scissoring of the legs and a tendency to lift the legs. Since the new PAU is mounted between and above the legs, this group would probably not function well with the device unless the legs are restrained. Therefore, the new invention may only be useful for people with multiple sclerosis that are in the early transition state from manual to power wheelchairs.

Cerebral Palsy

Of the many complicated conditions of cerebral palsy, there are some which allow use of a manual wheelchair. Situations vary widely with a mixture of symptoms including spasticity, ataxia, rigidity, and athetosis (uncontrollable motions of the hands and feet). If, for instance, only the lower extremities are involved and there is no problem with leg positioning, the wheelchair user may be able to use the new drive mechanism. Also, people with cerebral palsy respond favorably to physical therapy and may be trained in some cases to use the PAU product.

Amputation

Due to the difficulty and extreme energy requirement of walking with two artificial limbs, the wheelchair is the primary means of ambulation for many bilateral lower extremity amputees. Since mechanical function of the upper extremities is rarely affected, members of this population should be good candidates for the power attachment.

Appendix F: Expert Interview Questions and Responses

Each of the interview questions presented to the experts is listed here with the responses. Expert responses are listed following each question and marked with a number surrounded by parentheses. The number represents the expert number who contributed the remark. Experts one through four were interviewed individually at the location of their request. Experts numbered five through eight requested a group interview at the Virginia Department of Rehabilitation Services in Roanoke, Virginia. Their combined responses are listed together and marked as "(5-8)."

Comments surrounded by square brackets [ ] are notes contributed by the interviewer for clarification purposes. These comments are based on contextual and visual cues not apparent within the statements alone. In addition, observations made by the interviewer which may be relevant to future design considerations, are listed next to the number of the expert observed. These observations are marked by the preface "Observation:"

Interview Questions and Responses

1. Do you see any problems with the attachment/detachment procedures?

(1) Can you lock the finger controls so that both hands can be used to align and place, then release afterwards?
(2) Having the mechanisms on the right side of the chair is good because it's closest to drivers side seat of a car. Turning the chair around is hard [concerning the requirement to turn the chair around for attachment and detachment of the battery] -- better to have small batteries in the front.
(3) Chances are, will have someone attach and detach for you.
(4) I would need an assistant to attach and detach it. Consider front transfers. Possibly lay it on the ground and roll over it.
(5-8) The finger grips are different for people [people have varying capabilities for finger and hand strength/dexterity]. Consider a pull-type situation where one hand can make it work [described a u-shaped handle that can be pulled by one hand and would not require finger dexterity]. Same thing can be used for the plug in front. [Further discussed a second option for finger-pull controls: a two-bar grip where one bar remains stationary and the second pulls closer to the first when gripped by the hand (both bars would fit inside the squeezing hand).]

2. We anticipate the easiest transfer to be with the unit attached in the forward position. What types of difficulties do you foresee with that transfer scenario?

(1) Don't see inadvertent grabbing of bar.
(2) When transferring to and from the car, the post will interact with the car door. Maybe use a telescoping column.
(3) Depends on the person, most can lift the leg over. Possibly latch upper part of column to drop the column further to the ground -- look at an airplane stick. Neat to design like an airplane.

(4) Someone would need to lift my leg over the bar -- it's a big obstacle.
(5-8) Watch any type of body weight shift. [This statement refers to the trouble many users have with balance. Any time the weight of the body is shifted such as the requirement to lift one leg over the column, there is the possiblity of losing balance.]

3. What are your comments on the procedure to switch between the three column positions?

(1) Would I remember to turn the column each time? [The column must be rotated 180 degrees when moving to or from the transfer column position.] Possibly change the battery position. [This comment refers to the interaction between the drive wheels and the battery when the column is rotated into the transfer position.]
(2) Are you pulling your weight when moving into drive position? [Here there was a concern that the user would be lifting their entire body weight when moving into power drive position. It was explained that only the stiffness of the spring must be overcome.]
(3) Position of the finger pinchers is difficult. Possibly put pin movers up on the column - so you don't have to bend over and don't have to move the leg. Think of two arms pulling up together.
(4) Consider pivoting on top crossbar, that would keep it more out of the way.
(5-8) [Conversation led to consideration of adjusting the battery so that the column can drop further.]

4. Do you anticipate any problems with the maneuvering and operation of the unit?

(1) To turn right, you must move the stick left which is against intuition.
(2) No response.
(3) I feel like I want to pull back on the stick to put a brake on. Users will automatically put the [wheelchair] brakes on when they stop. I forgot about the quick take-off -- wheelchair jumps when I trigger it.
(4) Handle is nice to hold on to.
[4] Observations: She wants to turn by rotating only the handle -- requires training. She grabs the column with the non-steering hand for security.
(5-8) Too much effort in steering when it's stalled -- possibly try two handle [such as the Roll-Aid configuration], balances. [Two handles will make it more balanced.]
[5-8] Observation: He turns the handle around and uses his thumb to actuate trigger.

5. What is your impression of the operating controls?

(1) Use a rocker control switch on top of the handle for the forward and reverse positions -- matches mental image. Grip is fine. Consider joystick control.
(2) [No response.]
[2] Observations: Puts hand on top to balance, this makes it hard to see angle of steering arm. C7 quadriplegic able to use controls by pressing trigger against the medial side of the second metacarpal.
(3) Consider using the palms of hands, not finger control. Watch forward balance. The simpler the better -- try not to add brake system. Mark which [position] is forward and reverse.

(4) Right is reverse, two R's -- easy to remember. [This comment refers to the forward/reverse switch.]
[4] Observations: Takes a good effort for her hand/finger to pull the trigger. Her hands are weak so she uses two hands. In the house she has the need to shift constantly from forward to reverse and back. Maybe need an easier switch.
(5-8) Leaves out quads with controls.

6. Can you think of situations in which the power unit would cause a problem for the user (subway, elevator)?

(1) Side loading vans have a small curb to get over. Slipping friction limit -- linoleum ramp, wet pavement, will it still pull the weight? Should test sidewalk obstacles. Won't work with two ramp vehicle entry. Public busses lock wheels on floor.
(2) Center posts on tables in restaurants; gets in the way.
(3) I don't think there is a problem with the small wheels. In fact, power adds an advantage.
(4) [No response.]
[4] Observations: She had trouble traversing the threshold from carpeting to vinyl flooring. When the casters hit the threshold (before it started to traverse), the drive wheels started to spin; as the casters raised up on the threshold, this raised the drive wheels and the spinning worsened. The problem was overcome by traversing the threshold with more momentum.
(5-8) [No response.]

7. We have envisioned a user that primarily operates a manual wheelchair, but has an occasional use for a power operated wheelchair. For instance, on days when they are not feeling well or must travel a long distance. Do you foresee a particular set of users that we are not anticipating?

(1) Wheelchair users that have hand problems from pushing. Diabetics can't have/afford the open cuts from pushing. Very overweight consumers - many cannot push their own weight.
(2) Temporarily disabled may rent. Those which do not have hand strength (small women with a temporary injury). Those who need assistance with ramps, up and down.
(3) Many grades are too steep for manual, this would be great for when you get to grades like that. People with MS have extreme variation in performance from day-to-day -- this chair would be great for a bad day.
(4) MS people -- consider side and front transfers. Most MS people lose the ability to use one or more of the legs -- lower body becomes disabled first.
(5-8) Might consider the ultralightweight market. No quads. You've got a market with the paras and amputees.

8. Do you think that we have implemented features which are not necessary?

(1) No, real good battery carrying system.
(2) I don't think so.

(3) No. People get stranded in big electric chairs.
(4) No.
[5-8] Observation: Heads shake no.

9. How do you recommend that we let people know the new device is available on the market?

(1) Local support groups - they are members of bigger support groups which usually have a yearly trade show -- distributors attend these (open to solicitation and sales demos). State rehab centers -- technology demonstrations. Centers for independent living (one center hits a large geographical area) -- they are private non-profit organizations though they get state and federal money. Don't waste money with expensive electronic advertisements; those people tend to have top of the line. Veteran's Administration. Magazines.
(2) Newsletters. The little card advertisements [direct mail].
(3) Brochures and notices to rehab places. Let specialists know. Take it up to Woodrow Wilson. Magazines -- 'One Step Ahead, Independent Living.' Internet. Brochure packet -- postcards.
(4) Support groups and newsletters. The newsletters have both articles and advertisements usually.
(5-8) Check the internet and do shows. There's a bulletin board at Virginia Assistive Technology. [Discussed possible shows: RESNA show in June, Atlanta show in November, Three-state conference show (unsure of).] Team Rehab Magazine.

10. What is your critique of the appearance?

(1) Looks mechanical, a lot of straight lines. For example, grip can be more rounded and contoured. Consider matching colors of wheelchairs. Reflective tape to see you coming -- electric chairs people tend to ride into the road. Traffic violations and wheelchairs.
(2) Damn attractive. Very integrated with the chair.
(3) Good -- It would be neat if it looked like an airplane or video game.
(4) It's so small there's no problem -- it doesn't stand out.
(5-8) Very polished. Great.

11. Do you have any other suggestions?

(1) Wires need to be better stored.
(2) Holder for the plug in back [when not plugged into the battery, the plug just hangs there]. Consider having adjustable lengths of bars [crossbars]; possibly threaded situation with a set screw. Test going down a grade -- very different. There might be a problem with an older person and lifting their leg over column in the middle. Car door conversation: [the column makes it hard to place both legs and feet on one side of the column (in between car door and car seat)]. But can still take [device] off chair while seated in the wheelchair before transferring into a car.

(3) Good intermediate step. Best to let users of wheelchairs use it. User would have to tell drivers of busses not to tie down on the crossbars. Hook tie downs are used for busses.
(4) Try to remove the upper column while in place.
(5-8) Consider telescoping the upper part of the column. Get good product liability insurance. Consider fraying and wear of wires -- stronger cover maybe?

12. Based on what you know, do you see this as a viable alternative? If yes, what would you be willing to pay for the device, considering the alternatives?

(1) Yes, $2500.
(2) Yes, $500 - $700. Well those are '87 prices. The Medicare agent will say they want to spend about $1000 to $1500 on a chair for someone. My new chair [manual] is $4000.
(3) Yes, $1000. There are several things on the market we would like to buy but they're too expensive.
(4) I'm not familiar with motorized wheelchair prices [told ~ $5000]. $1000- $1500.
(5-8) $2500.

Appendix G: Expert Interview Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project: "Development of Quick-Connect Wheelchair Power Assist Device"
Part 1: Expert Evaluation

Principal Investigators: J. G. Casali, Ph.D., Professor, ISE
L. L. Clark, M. S., Graduate Research Assistant, ISE

Faculty Advisor: J. G. Casali, Ph.D., Professor

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a demonstration and interview which are designed to solicit your opinions on possible design flaws and design suggestions for the Quick-Connect Power Drive/Steer Wheelchair Assist Device. As an expert in the field of wheelchairs/rehabilitation and/or a user of wheelchairs, your comments are considered important and may serve to improve future design iterations of the power assist device.

II. PROCEDURES

The procedures to be used in this research are as follows. If you wish to become a participant after reading the description of the study, then sign this form on page 3. First, the experimenter will carefully explain each aspect of the power assist device and how it functions with the device present. The experimenter will then demonstrate how the power assist device works on the wheelchair by transferring to the wheelchair and maneuvering the chair with the power assist device in place. Next, you will be asked if you would like to transfer to the wheelchair and operate the power assist device. This is strictly a voluntary procedure; you can still function as a participant without actually operating the power assist device.

If you choose to transfer to the wheelchair, the experimenter will assist you in every way possible. Once you have operated the wheelchair to your satisfaction (or declined to operate the wheelchair), the experimenter will ask you a series of questions designed to solicit your input on several issues concerning the power assist device. You may question the experimenter and/or request further demonstrations if you wish. Your responses may be written down by the experimenter and/or recorded on audio tape. After the tapes are transcribed by the experimenters, they will be erased.

III. RISKS AND BENEFITS OF THIS RESEARCH

Your participation in this demonstration and interview will provide information that will be used to evaluate and improve the quick-connect power drive/steer wheelchair assist device. It is the objective of this project to eventually manufacture the power assist device to be distributed for consumers in need of an easily transportable and affordable electrically powered wheelchair.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

It is the intent of the investigators of this project to report your statements with an explanation of your applicable background in the field of wheelchairs/rehabilitation. While it is not necessary to identity you by name, it is necessary to explain your applicable background which could possibly serve as an identifier. Please sign the appropriate statement of disclosure which describes the level of anonymity you wish to retain:

I authorize the disclosure of my name and relevant background information to be reported with my responses in materials which will be produced in conjunction with this project.

____

Signature

I authorize the disclosure of my relevant background information to be reported with my responses in materials which will be produced in conjunction with this project. I do not authorize the release of my name for any reports (or other materials) associated with this project.

____

Signature

I authorize the disclosure of my comments in materials which will be produced in conjunction with this project. I do not authorize the release of my name or background information for any reports (or other materials) associated with this project.

____

Signature

V. COMPENSATION

There will be no financial compensation for participation in this experiment.

VI. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason without penalty.

VII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial Engineering.

VIII. PARTICIPANT'S RESPONSIBILITIES

I know of no reason why I cannot participate in this study. I have the following responsibilities:

- To notify the experimenter at any time about a desire to discontinue participation.

- To carefully follow the instructions provided by the experimenter in regards to operating the power assist device.

____
Signature of the Participant

IX. PARTICIPANT'S PERMISSION

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on this page and the following page (please repeat for your copy).

Signature Page

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so.,

Signature ________________________________

Printed Name________________________________

Date ________________________________

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory and Laura L. Clark, Graduate Research Assistant. Ms. Clark will serve as the experimenter. Ms. Clark may be contacted at the following address and phone number:

Industrial Engineering Department
302 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Dr. Ernie Stout
Chair, University Institutional Review Board for
Research Involving Human Subjects
301 Burruss Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-9359

Appendix H: ANSI/RESNA Wheelchair Standards Outline

Within the United States a group called RESNA has established a series of wheelchair standards. RESNA describes itself as "an interdisciplinary association for the advancement of rehabilitation and assistive technologies" (RESNA, 1989). The organization established the American National Standards Institute Technical Advisory Group (ANSI TAG) to work in conjunction with RESNA on the standards.

It is the purpose of the standards to provide testing procedures and performance guidelines to assure durability and performance of wheelchair products. While these standards will not have a direct impact on the PAU, they may be used to test the device once it has been attached to a wheelchair. Following the standards is not required by law; however, conforming to the standards will most certainly provide a competitive edge over products which are not approved, and may prove important to defending products liability lawsuits (McLaurin and Axelson, 1990).

Standards are approved in the United States once they have been introduced to the public for comment and approved by ANSI's Standards Review Board (McLaurin and Axelson, 1990). RESNA and ANSI TAG have worked with the International Standards Organization (ISO) to establish standards which are consistent across all involved countries. The international wheelchair standard is titled ISO 7176 (Hartridge and Seeger, 1989).

The RESNA/ANSI TAG wheelchair standards can be found on the Worldwide Standards Services Plus Database. The RESNA/ANSI TAG set of standards are dated in the index; 1990 and 1991. They are based on the results of testing of the wheelchair under a variety of conditions. Seventeen tests which were under consideration for the standards are listed here (Axelson and McLaurin, 1990):

<u>Static Stability</u>. This standard tests the tipping angle in the forward, rearward, and lateral directions when loaded.

<u>Dynamic Stability of Electric Wheelchairs</u>. This standard determines if an electric wheelchair will turn over while turning at full speed.

<u>Efficiency of Brakes</u>. The stopping distance and the ability of wheel locks to hold while loaded on both level ground and on a 5-degree slope are observed.

<u>Energy Consumption of Electric Wheelchairs</u>. The electric wheelchair is tested over a course with turns and slopes while energy consumption is monitored.

<u>Overall Dimensions, Mass and Turning Space</u>. This standard includes testing of forward and reverse turning radii as well as folded and expanded dimensions.

<u>Maximum Speed and Acceleration of Electric Wheelchairs</u>. Tests wheelchair performance, user comfort and stability under loaded acceleration conditions.

Seating Dimensions. This standard studies ergonomic considerations related to seating dimensions when loaded. For example, handrim position with respect to the user.

Static Impact and Fatigue Strength. This test considers the results of impact loading and fatigue testing.

Climatic Tests for Electric Wheelchairs. Electric wheelchairs are tested under conditions simulating heavy rain and extreme temperatures.

Obstacle Climbing for Electric Wheelchairs. The ability to climb up a curb as high as 8 inches is tested. Chairs are tested from both a standing start and at a distance of 0.5 meters from the curb.

Test Dummies. This section outlines how test dummies should be constructed for the designated tests.

Coefficient of Friction of Test Surfaces. This standard specifies the method for determining the coefficient of friction of a rough surface for testing procedures.

Power and Controls. The wheelchair is observed from a safety perspective including pinch point areas and electrical exposure.

Disclosure Requirements. Information that must be included in the user manuals is explained in this section.

Burning Behavior. Ignitability characteristics of the wheelchair cloth surfaces is determined.

Overall Dimensions. This standard provides recommended maximum outside chair dimensions. It is a reference for designers of wheelchairs and environments.

Appendix I: Motor Sound Level Measurements

One third octave band noise levels and A-weighted calculations.

Wheelchair Motor

1/3 Octave Band Noise Spectrum

1/3 OB cf	Level	10^(L/10)	a-wtg corr	A-Wtd Lvls	10^(L/10)
25	49.8	95499.2586	-44.7	5.1	3.23593657
31.5	48.1	64565.4229	-39.4	8.7	7.41310241
40	47.3	53703.1796	-34.6	12.7	18.6208714
50	48.2	66069.3448	-30.2	18.0	63.0957344
63	41.8	15135.6125	-26.2	15.6	36.3078055
80	37.1	5128.61384	-22.5	14.6	28.840315
100	34.5	2818.38293	-19.1	15.4	34.673685
125	34.5	2818.38293	-16.1	18.4	69.1830971
160	31.8	1513.56125	-13.4	18.4	69.1830971
200	29.8	954.992586	-10.9	18.9	77.6247117
250	30.0	1000	-8.6	21.4	138.038426
315	28.6	724.43596	-6.6	22.0	158.489319
400	25.1	323.593657	-4.8	20.3	107.151931
500	26.1	407.380278	-3.2	22.9	194.98446
630	30.1	1023.29299	-1.9	28.2	660.693448
800	26.2	416.869383	-0.8	25.4	346.73685
1000	25.3	338.844156	0	25.3	338.844156
1250	29.4	870.96359	0.6	30.0	1000
1600	25.6	363.078055	1	26.6	457.08819
2000	25.9	389.045145	1.2	27.1	512.861384
2500	30.0	1000	1.3	31.3	1348.96288
3150	25.1	323.593657	1.2	26.3	426.579519
4000	38.6	7244.3596	1	39.6	9120.10839
5000	29.6	912.010839	0.5	30.1	1023.29299
6300	23.7	234.422882	-0.1	23.6	229.086765
8000	28.7	741.310241	-1.1	27.6	575.439937
10000	23.7	234.422882	-2.5	21.2	131.825674
12500	23.7	234.422882	-4.3	19.4	87.096359
16000	23.5	223.872114	-6.6	16.9	48.9778819
20000	23.5	223.872114	-9.3	14.2	26.3026799
dB(linear)	**55.1**	325436.542	**dBA**	**42.4**	17340.7396

Ambient

1/3 Octave Band Noise Spectrum

1/3 OB cf	Level	10^(L/10)	a-wtg corr	A-Wtd Lvls	10^(L/10)
25	48.9	77624.7117	-44.7	4.2	2.63026799
31.5	47.9	61659.5002	-39.4	8.5	7.07945784
40	47.8	60255.9586	-34.6	13.2	20.8929613
50	48.3	67608.2975	-30.2	18.1	64.5654229
63	41.4	13803.8426	-26.2	15.2	33.1131121
80	35.9	3890.45145	-22.5	13.4	21.8776162
100	33.9	2454.70892	-19.1	14.8	30.1995172
125	33.5	2238.72114	-16.1	17.4	54.9540874
160	31.1	1288.24955	-13.4	17.7	58.8843655
200	29.2	831.763771	-10.9	18.3	67.6082975
250	29.0	794.328235	-8.6	20.4	109.64782
315	27.6	575.439937	-6.6	21.0	125.892541
400	23.8	239.883292	-4.8	19.0	79.4328235
500	23.9	245.470892	-3.2	20.7	117.489755
630	28.7	741.310241	-1.9	26.8	478.630092
800	24.3	269.15348	-0.8	23.5	223.872114
1000	24.2	263.026799	0	24.2	263.026799
1250	29.0	794.328235	0.6	29.6	912.010839
1600	23.7	234.422882	1	24.7	295.120923
2000	24.7	295.120923	1.2	25.9	389.045145
2500	29.6	912.010839	1.3	30.9	1230.26877
3150	23.5	223.872114	1.2	24.7	295.120923
4000	23.5	223.872114	1	24.5	281.838293
5000	27.9	616.595002	0.5	28.4	691.830971
6300	23.5	223.872114	-0.1	23.4	218.776162
8000	25.5	354.813389	-1.1	24.4	275.42287
10000	23.5	223.872114	-2.5	21.0	125.892541
12500	23.5	223.872114	-4.3	19.2	83.1763771
16000	23.5	223.872114	-6.6	16.9	48.9778819
20000	23.5	223.872114	-9.3	14.2	26.3026799
dB(linear)	**54.8**	299559.214	**dBA**	**38.2**	6633.58143

Appendix J: Usability Evaluation Informed Consent Form

(Note: Some sections of this consent form have been adapted from Lefkowicz, 1993).

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project: "Development of Quick-Connect Wheelchair Power Assist Device"
Part 2: Usability Evaluation

Principal Investigators: J. G. Casali, Ph.D., Professor and Department Head, ISE
L. L. Clark, M. S., Graduate Research Assistant, ISE

Faculty Advisor: J. G. Casali, Ph.D., Professor and Department Head

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a usability evaluation of a new wheelchair power assist device developed at the Human Factors Engineering Center at Virginia Tech. The purpose of the evaluation is to determine design problems with the invention and solicit input from possible consumers of the device concerning the "usability" of the product. Your input is considered important and may serve to improve future design iterations of the power assist device. It is anticipated that eight to ten subjects total will be participating in the usability evaluation.

II. PROCEDURES

The procedures to be used in this evaluation are as follows. If you wish to become a participant after reading the description of the study, then sign this form on page 5. First, the experimenter will carefully explain each aspect of the power assist device and how it functions. The experimenter will then demonstrate how the power assist device works on the wheelchair by transferring to the wheelchair and maneuvering the chair with the power assist device.

You will be asked to perform a series of tasks and answer questions involving the power assist device. You will be asked to perform the following tasks:

1) While seated in your personal wheelchair, lift and secure a wheelchair battery onto the testing wheelchair. The wheelchair battery weighs approximately nine pounds and is encased in a plastic box equipped with a handle for lifting.

2) While seated in your personal wheelchair, unsecure and lift the wheelchair battery from the testing wheelchair and place it on the floor.
3) While seated in your personal wheelchair, lift and secure the power assist device onto the testing wheelchair.
4) While seated in your personal wheelchair, unsecure and lift the power assist device from the testing wheelchair and place it on the floor.
5) From a seated position on a stable padded bench , transfer into the testing wheelchair with the power assist device in place on the testing wheelchair. A transfer board will be provided.
6) Transfer out of the testing wheelchair onto the padded bench with the power assist device in place on the testing wheelchair.
7) While seated in the testing wheelchair, manipulate the power assist device to different operating modes including power-drive mode, manual-drive mode, and transfer mode.
8) While seated in the testing wheelchair, drive through a defined course operating the wheelchair power assist device in power-drive mode. You will be provided an opportunity to practice driving with the power assist beforeattempting the course.

You will be provided instruction on each of the tasks to be performed. In addition, the investigator will demonstrate each task for you and give you an opportunity to practice the task prior to evaluation. The demonstration, practice session, and evaluation performance of the tasks will all be videotaped.

After a set of tasks are performed, the investigator will ask you to review the videotape of the task performances and explain what you were thinking while performing the tasks. This information will be used by the investigator to identify problems with the power assist design. At this time, you will get a break during which time you may visit the restroom, get a drink of water, or just relax. Water is provided at the evaluation site for your convenience.

Next, the investigator will ask you short questions concerning the problems identified during the videotape review session to help determine what aspect of the design needs improvement. These videotape review and questioning sessions will be recorded on audiotape for future reference.

Once the tasks and review sessions are completed, you will be asked to fill out a short questionnaire to receive your input on the power assist device. You may choose to not participate in any part of the evaluation at any time.

III. RISKS AND BENEFITS OF THIS RESEARCH

Your participation in this usability evaluation will provide information that will be used to evaluate and improve the quick-connect power drive/steer wheelchair assist device. It is the objective of this project to eventually manufacture the power assist device to be distributed for consumers in need of an easily transportable and affordable electrically powered wheelchair.

There are two small risks to which you will expose yourself in this evaluation:

1. There is the slight risk of a fall in transferring to or from the testing wheelchair to be used in the evaluation. This risk should be no greater than that associated with a transfer under normal conditions to your own wheelchair. A transfer board will be provided.

2. There is the slight risk of a collision of the powered testing wheelchair with one of the walls of the evaluation room. This risk will be minimized by training you first in the center of the room. Only after you demonstrate proficiency, will you be permitted to drive along the evaluation course. In addition, this course is a reasonable distance from any of the walls, so there is tolerance for error.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

It is the intent of the investigators of this project to report the findings of this evaluation. The information you provide will have your name removed and only a subject number will identify you during analysis and any written reports of the evaluation.

V. COMPENSATION

If you decide to participate in this evaluation, you will be paid $6.00 per hour for the time you participate. The evaluation is expected to last approximately three hours total.

VI. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason without penalty.

VII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial Engineering.

VIII. PARTICIPANT'S RESPONSIBILITIES

I know of no reason why I cannot participate in this study. I have the following responsibilities:

- To notify the experimenter at any time about a desire to discontinue participation.

- To carefully follow the instructions provided by the experimenter in regards to operating the power assist device.

____

Signature of the Participant

IX. PARTICIPANT'S PERMISSION

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on the previous page and the following page (please repeat for your copy).

Signature Page

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so.,

Signature ______________________________

Printed Name______________________________

Date ______________________________

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory and Laura L. Clark, Graduate Research Assistant. Ms. Clark will serve as the experimenter. Ms. Clark may be contacted at the following address and phone number:

Industrial Engineering Department
302 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Tom Hurd
Director of Sponsored Programs
301 Burruss Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-9359

Appendix K: User Evaluation Questionnaire and Subject Responses

User Evaluation Questionnaire (and Subject Responses)

Subject Number _______ Date ________________

1. Was there one aspect of the power assist unit which you found particularly bad? If so, please describe the problem.

(3) Yes, in trying to control it when I was going in reverse. I felt that it was kind of difficult in trying to control what direction it was going in.
(4) Loading and unloading battery. Reverse.
(6) I would forget to lean the control down to lock it in place.
(7) In reverse when the handle is turned to more than 45 degrees it tends to want to pull out of your hand and turn you 90 degrees.
(8) The finger grips need to be wider and maybe where the thumb could fit into it so it would be easier to squeeze.
(9) Operating in reverse.
(11) Ability to transfer in and out.

2. Do you have any suggestions that you would like to make concerning future design changes in the power assist?

(3) To try and keep an eye out for a battery that is lighter but with just as much power. Also, if the finger grips were possibly moved up to the rod it might be easier to switch from transfer to manual, to power, etc.
(4) More accessible features of loading.
(6) The control is fixed too close to the body.
(7) Velcro fastener for battery case. This would allow user to attach battery with one hand. Relocate battery so that the wheels of power drive unit won't hit.
(8) Have longer armrests for more support once you're into the chair.
(9) Maybe battery pack could be on back of chair or in, or on, a sliding rack under chair.
(11) Yes. [specified in his earlier discussion]

3. As a potential consumer, would this product be useful to you? Why or why not?

(3) Yes, in case I got too tired pushing in my manual chair or walking on my crutches.
(4) No, does not fit my needs.
(6) Yes, because it could get me places that I would have to have help.
(7) Not at this point in my life. I am very active and really don't have a problem getting around. I could see it being very useful for someone with less upper body strength or for the aging.
(8) Absolutely! Because it would be less strain on my body and be very useful in going up hills or inclines that takes hard extra effort. It would eliminate the wear and tear on one's body.

(9) Yes because it would be less expensive than an electric chair, and because it would be easier to transport.
(11) Not at this stage in my life: too active.

4. Please circle the most appropriate response.

How easy was the power assist device to operate?

Easy --------------------------------------I-------------------------------------- Difficult

1	2	3	4	5	6	7

(3) 3
(4) 2
(6) 2
(7) 5
(8) 1 This is a fantastic product and in my opinion a whole lot of people will benefit from it because it's much easier to use than your regular run of the mill electric wheelchairs. This is great! Thank you!
(9) 2
(11) 1

Appendix L: Time Data Statistical Comparisons

Battery Attachment Task

Subj #	Pre Task	Observed	Post Task
3	300	27	90
6	300	32	60
7	300	78	78
9	900	32	300
11	60	25	60

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	1860	372	97920
Obs	5	194	38.8	489.7
Post	5	588	117.6	10558.8

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	303251.73	2.00	151625.87	4.17	0.04	2.81
Within Groups	435874.00	12.00	36322.83			
Total	739125.73	14.00				

Battery Detachment Task

Subj #	Pre Task	Observed	Post Task
3	300	15	60
6	300	11	60
7	300	15	15
9	900	20	300
11	60	7	60

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	1860	372	97920
Obs	5	68	13.6	23.8
Post	5	495	99	13005

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	350454.53	2.00	175227.27	4.74	0.03	2.81
Within Groups	443795.20	12.00	36982.93			
Total	794249.73	14.00				

Column Attachment Task

Subj #	Pre Task	Observed	Post Task
3	300	71	120
6	600	34	300
7	300	14	120
9	900	22	300
11	300	10	300

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	2400	480	72000
Obs	5	151	30.2	604.2
Post	5	1140	228	9720

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	508248.13	2.00	254124.07	9.26	0.00	2.81
Within Groups	329296.80	12.00	27441.40			
Total	837544.93	14.00				

Column Detachment Task

Subj #	Pre Task	Observed	Post Task
3	300	20	60
6	300	30	300
7	660	10	120
9	900	10	180
11	300	5	300

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	2460	492	76320
Obs	5	75	15	100
Post	5	960	192	11520

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	581430.00	2.00	290715.00	9.92	0.00	2.81
Within Groups	351760.00	12.00	29313.33			
Total	933190.00	14.00				

Transfer Into Wheelchair Task

Subj #	Pre Task	Observed	Post Task
3	180	8	30
4	30	17	30
6	600	6	300
7	60	10	60
9	300	15	300
11	120	5	10

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	1290	215	44790
Obs	6	61	10.17	23.77
Post	6	730	121.67	19336.67

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	126200.11	2.00	63100.06	2.95	0.08	2.70
Within Groups	320752.17	15.00	21383.48			
Total	446952.28	17.00				

Transfer Out of Wheelchair Task

Subj #	Pre Task	Observed	Post Task
3	180	5	30
4	30	32	45
6	600	5	300
7	60	6	60
9	180	15	180
11	120	5	10

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	1170	195	43110
Obs	6	68	11.33	117.87
Post	6	625	104.17	12784.17

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	101204.33	2.00	50602.17	2.71	0.10	2.70
Within Groups	280060.17	15.00	18670.68			
Total	381264.50	17.00				

Switching - Transfer to Manual Task

Subj #	Pre Task	Observed	Post Task
4	15	20	30
6	600	7	300
7	60	8	20
9	300	14	180
11	10	3	5

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	985	197	64970
Obs	5	52	10.4	44.3
Post	5	535	107	16620

ANOVA

Source of Variation

	SS	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	87085.20	2.00	43542.60	1.60	0.24	2.81
Within Groups	326537.20	12.00	27211.43			
Total	413622.40	14.00				

Switching - Manual to Power Task

Subj #	Pre Task	Observed	Post Task
3	90	7	20
4	5	4	5
6	300	4	300
7	30	3	15
9	180	4	180
11	5	2	5

Anova: Single-Factor   alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	610	101.67	13886.67
Obs	6	24	4	2.8
Post	6	525	87.5	15427.5

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	33423.44	2.00	16711.72	1.71	0.21	2.70
Within Groups	146584.83	15.00	9772.32			
Total	180008.28	17.00				

Switching - Power to Transfer Task

Subj #	Pre Task	Observed	Post Task
3	90	11	30
6	300	15	300
7	30	4	15
9	180	13	180
11	7	3	5

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	5	607	121.4	14439.8
Obs	5	46	9.2	29.2
Post	5	530	106	16842.5

ANOVA

Source of Variation

	SS	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	36993.73	2.00	18496.87	1.77	0.21	2.81
Within Groups	125246.00	12.00	10437.17			
Total	162239.73	14.00				

Driving Clockwise Task

Subj #	Pre Task	Observed	Post Task
3	300	50	120
4	60	21	30
6	600	21	300
7	40	28	30
9	360	35	120
11	60	22	30

Anova: Single-Factor

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	1420	236.67	50466.67
Obs	6	177	29.5	130.7
Post	6	630	105	11070

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	131908.78	2.00	65954.39	3.21	0.07	2.70
Within Groups	308336.83	15.00	20555.79			
Total	440245.61	17.00				

Driving Counterclockwise Task

Subj #	Pre Task	Observed	Post Task
3	300	37	120
4	60	21	30
6	600	19	300
7	40	28	30
9	360	30	120
11	60	19	30

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	1420	236.67	50466.67
Obs	6	154	25.67	52.67
Post	6	630	105	11070

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	136301.78	2.00	68150.89	3.32	0.06	2.70
Within Groups	307946.67	15.00	20529.78			
Total	444248.44	17.00				

Maneuvering Forward Task

Subj #	Pre Task	Observed	Post Task
3	120	25	90
4	15	27	40
6	300	12	300
7	30	17	17
9	300	23	90
11	60	12	30

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	6	825	137.5	17137.5
Obs	6	116	19.33	43.47
Post	6	567	94.5	11081.5

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	42924.78	2.00	21462.39	2.28	0.14	2.70
Within Groups	141312.33	15.00	9420.82			
Total	184237.11	17.00				

Maneuvering in Reverse Task

Subj #	Pre Task	Observed	Post Task
3	300	180	300
4	60	130	45
7	60	28	28
11	300	17	60

Anova: Single-Factor alpha = 0.10

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Pre	4	720	180	19200
Obs	4	355	88.75	6288.92
Post	4	433	108.25	16512.25

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	18473.17	2.00	9236.58	0.66	0.54	3.01
Within Groups	126003.50	9.00	14000.39			
Total	144476.67	11.00				

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VITA

Previous Employment

1992 to 1997	Graduate Research Assistant Virginia Polytechnic Institute and State University Blacksburg, Virginia
1990 to Present	General Manager and Instructor American Martial Arts Center Blacksburg, Virginia
1989 to 1990	Technical Production Supervisor Alcatel Cable Systems Blacksburg, Virginia
Summers of 1986, 1987, 1988	Engineering Assistant Life Cycle Engineering Arlington, Virginia

Education

1997	Doctor of Philosophy in Industrial and Systems Engineering Human Factors Engineering Option Virginia Polytechnic Institute and State University Blacksburg, Virginia
1993	Master of Science in Architecture Industrial Design Option Virginia Polytechnic Institute and State University Blacksburg, Virginia
1989	Bachelor of Science in Mechanical Engineering Virginia Polytechnic Institute and State University Blacksburg, Virginia

Affiliations

Member of the Human Factors and Ergonomics Society

Member of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA)

Certified Engineer in Training, July 1989