MICHELIN
Tweels

Technology / Value Description

Prepared for

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of Greenville, South Carolina

MICHELIN

by T[2]RERC

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October 2005

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ACKNOWLEDGEMENT
This is a publication of the Rehabilitation Engineering Research Center on Technology Transfer, which is funded by the National Institute on Disability and Rehabilitation Research of the Department of Education under grant number H133E980024. The opinions contained in this publication are those of the grantee and do not necessarily reflect those of the Department of Education.

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SECTION A

Executive Summary

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Product Description

The Michelin Tweel™ is a non-pneumatic tire and wheel assembly designed for wheelchairs. It combines Non-Pneumatic "Bottom Loader" technology (load is supported by the bottom of the wheel) with Bias Ply Pneumatic "Top Loader" technology (load is carried by the top of the wheel) to form a Non-Pneumatic "Top Loader" tire and wheel assembly. Tweels™ have the ability to deliver performance characteristics similar to pneumatic tires but with greater damage tolerance and the maintenance reduction characteristics of non-pneumatic tires. Tweels™ are designed to accept more deflection and absorb more energy from shock loads than equivalent size pneumatic and non-pneumatic tires, thus simplifying suspensions by eliminating suspension components. Tweels™ simplify wheelchair manufacturing and final assembly thus presenting a significant overall cost savings for the manufacturer.

Key Features of Tweels™

- Very low wear rate, resulting in an estimated tire life expectancy 3 - 4 times more than other non-pneumatic tires
- In manual wheelchairs, eliminates the need for front suspension system
- In power wheelchairs, reduction in overall weight of the wheelchair due to elimination of suspension components
- Improved range due to lower rolling resistance
- Higher shock load energy absorption than equivalent pneumatic tires
- Can handle severe vertical deflections (bumps and potholes) without damage
- Capable of motion in a damaged state which allows the user to reach their destination for service
- Eliminates need for tire pressure monitoring and maintenance, thus reducing the number of service calls
- Elimination of "caster chatter/shudder"
- Non marking due to silica base and reduced amount of carbon black in material composition
- Extremely versatile, the caster and drive wheels can be manufactured in any size and thus can be customized to fit any wheelchair

Consumer Benefit

The increased cost of the Tweel™ will be offset by the decrease in need for replacement tires and the elimination of costly suspension system components both on manual and power wheelchairs. Depending on the amount of use, wheelchair users are frequently faced with replacing their tires. Standard wheelchair users replace their tires at least 1-2 times per year, and sport wheelchair users replace their tires 3-4 times per year. This can be very costly to consumers since Medicaid and other 3rd party insurers only allow reimbursement for one set of tires per year. This means that the consumer would then incur the cost for any additional tires that their wheelchair may need in a given calendar year. Tweel™ technology has the capability of reducing these costs since they are 3-4 times more durable than current wheelchair wheels. With the increased reliability and durability provided by Tweels™, tire replacements will become less frequent and, therefore, less costly to the consumer and insurance companies who provide reimbursements.

Manufacturer Benefit

On power wheelchairs, the increased cost of the Tweel™ assembly will be more than offset by the elimination of the cost of certain suspension components, thus decreasing the overall manufacturing cost of the wheelchair. With fewer suspension components subject to potential failure on the wheelchair, there will be an elimination of maintenance and warranty claims for the manufacturer on those removed components, resulting in further manufacturer savings. An additional benefit is the reduction of overall weight of the wheelchair. For example, on the iBOT, the increased weight of the Tweel™ was more than offset by the removal of 4.4 pounds worth of suspension components, resulting in a significant weight difference between the Tweel™ and the next best pneumatic alternative.

Target Markets

Tweels™ are targeted at all manufacturers of both manual and power wheelchairs. Tweels™ are also targeted primarily towards disabled consumers who purchase new wheelchairs. People who would benefit from the Tweels™ have disabilities including cerebrovascular disease, quadriplegia or paraplegia, osteoarthritis, multiple sclerosis, absence or loss of lower extremity, and cerebral palsy. Those consumers looking to replace their current wheels provide a secondary market for the Tweels™. These individuals are looking for reliability and durability in their tires, as well as versatility.

Section B

Overview

- ❑ **Background/Current Situation**

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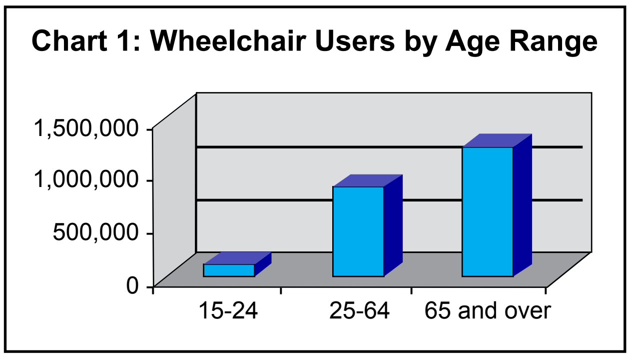
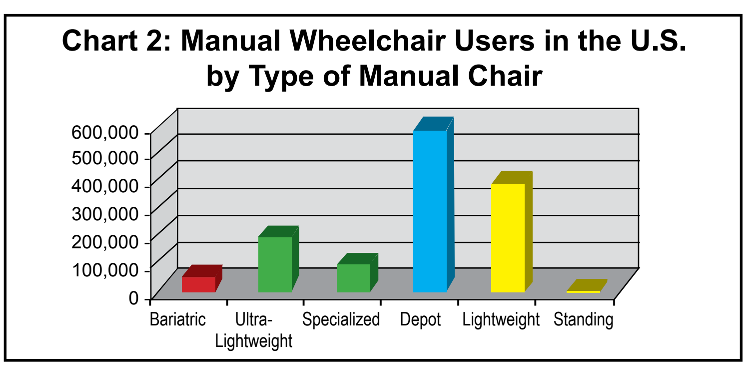
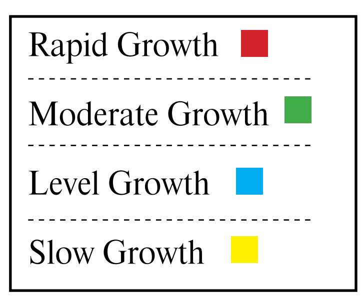
Background / Current Situation

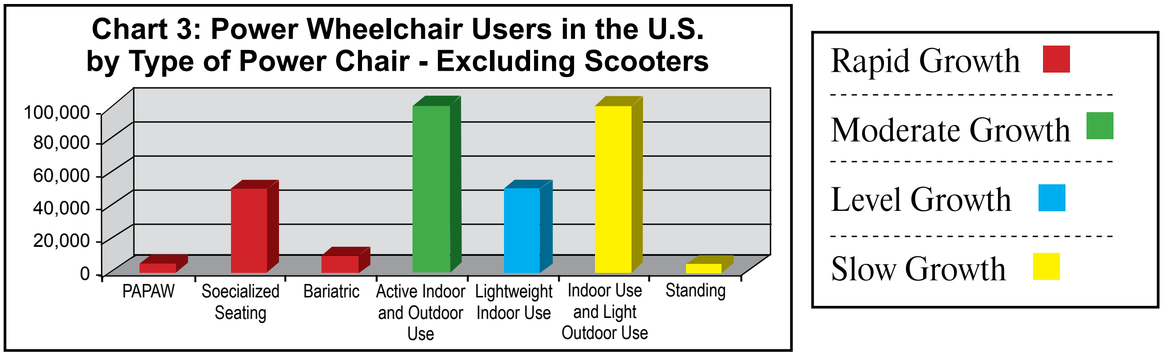
According to figures included in the 1997 Survey of Income and Program Participation, approximately 2.2 million Americans use a wheelchair (Census Bureau, 1997). An estimated 670,000 are power wheelchair users, half of whom (approximately 350,000) use electric powered scooters (Cooper & Cooper, 2003). As people age, they become more susceptible to disabilities, including mobility limitations (See Chart 1). At the present time, over 56% of all wheelchair users are aged 65 and older (U.S. Census Bureau, 1997). As America's baby-boomer generation reaches old age and joins the approximated 36 million people who are currently over the age of 65, the wheeled mobility market is expected to grow exponentially (U.S. Census Bureau, 2000).



According to figures compiled and presented by Cooper and Cooper (2003), both the manual and power wheelchair markets are seeing the majority of their growth in bariatric wheelchairs. In the manual wheelchair market, ultra-lightweight and specialized chairs follow closely behind in terms of growth. Depot chairs make up the largest portion of the manual wheelchair market, and growth is expected to remain level, suggesting that current purchases will remain stable. Scooters dominate the power wheelchair market, accounting for nearly half of all power wheelchair sales. Pushrim Activated Powered Assisted Wheelchairs PAPAW technology has been making great strides in the market. The PAPAW is increasing in both availability and ease of use. As a result PAPAW's are rapidly gaining consumer acceptance. Experts anticipate that PAPAW's will experience tremendous growth in coming years (Cooper & Cooper, 2003).







Adapted from Cooper & Cooper (2003)

Please note that some categories illustrated in chart 2 may not be mutually exclusive. For example, specialized seating could be fitted to wheelchairs that fall into other categories within the same chart.

Medicare Reimbursement

Regardless of whether a wheelchair is manual or power operated, Medicare reimburses for 80% of their allowable charges for a wheelchair, less any deductible. The remaining 20% and any additional amount due are paid by secondary insurance, or out of pocket by the con-sumer (Edmond Wheelchair Repair and Supply, 2004).

Wheelchairs fall under the “capped rental item” classification for reimbursement, which means that Medicare typically does not purchase manual wheelchairs, but rather rents the wheelchair for the beneficiary for a period not to exceed 15 months. After 15 months, no more payments will be made, and the beneficiary gains ownership of the wheelchair. Power wheelchairs differ from manual chairs in that power wheelchairs may be purchased outright, rather than rented for the 15 month period.

Should the beneficiary choose to purchase a power wheelchair, Medicare will allot a lump sum payment for 80% of the allowed charges. The beneficiary is then responsible for the remaining 20%, and becomes the owner of the wheelchair. Medicare will also pay 80% of allowed service and maintenance charges when the equipment is serviced.

If the beneficiary chooses to rent a power wheelchair, Medicare will pay 80% of the allowed rental price for a period of up to 10 months. The beneficiary is responsible for the remaining 20% of each rental payment. Medicare will also pay 80% of allowable service and mainte-nance charges every six months, regardless of whether the wheelchair was serviced or not. After that 10 month period the beneficiary may again choose to either continue renting or purchase the wheelchair.

If they choose to purchase the power wheelchair at this time, Medicare will pay for 80% of three additional months of rental. The beneficiary will pay the additional 20% of rental charges, and then become the owner of the power wheelchair.

If they choose to continue renting the power wheelchair, Medicare will pay 80% of the rental price for a maximum of five additional months. The beneficiary is responsible for the addi-tional 20% of the rental price, and the supplier will remain the owner of the power wheel-chair (Centers for Medicare and Medicaid Services, 2003a).

The maintenance allowances mentioned above for power wheelchairs also apply to rented manual wheelchairs. The standard 80% payment for maintenance and repairs is paid by Medicare for the expected life of the equipment, which is 5 years.

Special features and upgrades on a wheelchair will only be covered by Medicare if the upgrades are deemed medically necessary. Even when medical necessity criteria are met, Medicare will only pay for the least costly alternative that fulfills the medical need. For example, in order to receive coverage for a one arm drive attachment, the patient must have a condition that is expected to last at least 6 months, which renders them only able to propel their wheelchair with one hand (Peak Wheelchairs, 2003). Upgrades for leisure and recreational use are not covered by Medicare. As a result, beneficiaries must pay for these expenses out of pocket (Centers for Medicare and Medicaid Services, 2003b).

2004 DMEPOS Fee Schedule for Wheelchairs

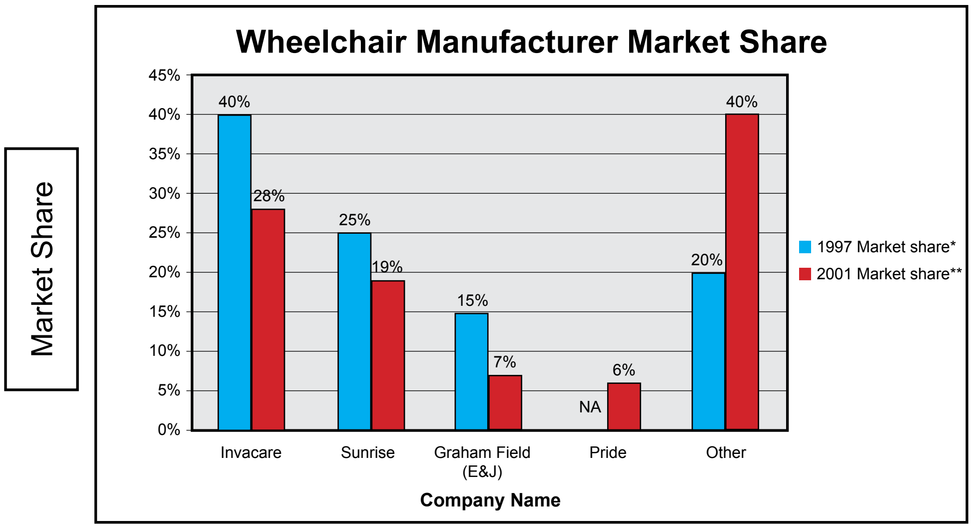
(Adapted from: 2004 Durable Medical Equipment Prosthetics/Orthotics, and Supplies (DMEPOS) Fee Schedule Public Use File (PUF). Retrieved February 24, 2004 from: http://www.cms.hhs.gov/providers/pufdownload/d04_Jan.ZIP)

HCPCS Code aand Device Description	Ceiling*	Floor*
Manual Wheelchairs		
K0001 Standard wheelchair	$54.62	$46.43
K0002 Standard hemi (low seat) wheelchair	$81.83	$69.56
K0003 Lightweight wheelchair	$89.59	$76.15
K0004 High strength, lightweight wheelchair	$133.64	$113.59
K0005 Ultra lightweight wheelchair	184.86	$157.13
K0005 Ultra lightweight wheelchair (New Purchase)	$1,848.76	$1,571.45
K0005 Ultra lightweight wheelchair (Used Purchase)	$1,386.55	$1,178.57
K0006 Heavy duty wheelchair	$125.41	$106.60
K0007 Extra heavy duty wheelchair	$178.50	$151.73
Electric Wheelchairs		
K0010 Standard weight frame motorized/power wheelchair	$425.99	$362.09
K0011 Standard weight frame motorized/power wheelchair with programmable control parameters for speed adjustment, tremor dampening, acceleration control and braking	$529.65	$450.20
K0012 Lightweight portable motorized/power wheelchair	$324.92	$276.18

* Capped rental rates unless otherwise specified in HCPCS Code and Device Description column.

Wheelchair Manufacturer Market Share Information

Despite shrinking figures for market share percentages among previous market leaders, Invacare, Sunrise, and Graham Field have maintained their lead over the competition for more than six years. However, the "other" category has grown more than any single company; now accounting for 40% of the total industry. Also, Pride Mobility has gained enough market share to enter the arena of market leaders; They attracted 6% of total market share in 2001, falling just short of Graham Field's 7% share. This changing landscape indicates that there are many smaller companies in the industry who are pulling sales away from the larger corporations, increasing competition in the industry.



Medicare Reimbursement

Regardless of whether a wheelchair is manual or power operated, Medicare reimburses 80% of their *allowable charges* for a wheelchair, less any deductible. The remaining 20% and any additional amount due (above and beyond *allowable charges*) are paid by secondary insurance, or out of pocket by the consumer (Edmond Wheelchair Repair and Supply, 2004). Special features and upgrades on a wheelchair will only be covered by Medicare if the upgrades are deemed medically necessary, which requires a prescription from a physician. Even when medical necessity criteria are met, Medicare will only pay for the least costly alternative that fulfills the medical need. For example, in order to receive coverage for a one arm drive attachment, the patient must have a condition that is expected to last at least 6 months, which renders them only able to propel their wheelchair with one hand (Peak Wheelchairs, 2003). Upgrades for leisure and recreational use are not covered by Medicare. As a result, beneficiaries must pay for these expenses out of pocket (Centers for Medicare and Medicaid Services, 2003).

Chart 4 illustrates Medicare's average allowed charges for selected wheelchairs and accessories. Rental rate ceiling and floors are the monthly payment amounts that Medicare will allow for wheelchair rentals, and are typically around 10% of total allowed purchase price. Actual coverage limits for rentals and purchases vary from state to state. Individual state ceilings and floors can be identified with the DMEPOS Fee Schedule Public Use File, which is available on the Medicare/Medicaid website (Centers for Medicare and Medicaid Services, 2004).

Chart 4: 2004 Fee Schedules for Selected Wheelchairs and Accessories

Rental HCPCS Code and Device Description	Rental Rate: Ceiling	Purchase Rate: Floor	Purchase Rate: New	Rate: Used
Manual Wheelchairs				
K0001 Standard wheelchair	$54.62	$46.43	$434.62	$325.96
K0002 Standard hemi (low seat) wheelchair	$81.83	$69.56	$682.98	$512.24
K0003 Lightweight wheelchair	$89.59	$76.15	$712.81	$534.61
K0004 High strength, lightweight wheelchair	$133.64	$113.59	$1109.86	$832.40
K0005 Ultra lightweight wheelchair	$184.86	$157.13	$1730.41	$1297.79
K0006 Heavy duty wheelchair	$125.41	$106.60	$1452.91	$834.90
K0007 Extra heavy duty wheelchair	$178.50	$151.73	$1670.76	$1253.07
Electric Wheelchairs				
K0010 Standard weight frame motorized / power wheelchair	$425.99	$362.09	$3325.32	$2493.99
Standard weight frame motorized /power wheelchair with programmable control parameters for speed adjustment, tremor dampening, acceleration control and braking	$529.65	$450.20	$4715.56	$3536.67
K0012 Lightweight portable motorized / power wheelchair	$324.92	$276.18	N/A	N/A
Wheelchair Accessories				
E0958 Wheelchair attachment to convert any wheelchair to one-arm drive	$43.63	$37.09	$408.42	$306.31
E0967 Manual wheelchair accessory, hand rim with projections (each)	$6.57	$5.58	$67.07	$50.28
E0974 Manual wheelchair accessory, anti-rollback device (each)	$8.31	$7.06	$124.75	$94.27

Adapted from Centers for Medicare and Medicaid Services (2004); North Carolina Department of Health and Human Services (2004)

Wheelchair Tires

One of the main components of wheelchairs is its tires. They are important for how comfortable the ride is, and they will have a profound effect on how much force one must use in order to propel the chair to overcome rolling resistance. Typically, wheelchair users utilize one of two different types of wheels /tires for their wheelchairs. Pneumatic, or air-filled tires, are typically more comfortable for wheelchair users because they absorb shock by distributing the force throughout the tire. However, pneumatic tires can potentially inhibit independent living due to the fact that they are subject to accidental deflation, which can result in significant inconvenience for the wheelchair user. Non-pneumatic tires are not air-filled, and they carry the load primarily at the point of contact between the wheel and the ground surface. While there is no risk of accidental deflation, the ride is much less comfortable because the force is not distributed throughout the whole tire and there is inconsistent contact with the road.

Some wheelchair users feel comfort is a priority and, therefore, add suspension systems to their wheelchairs in order to provide a more comfortable ride. These suspension systems are designed to decrease frame vibration in the chair, reducing pain and discomfort one could potentially experience when riding on rugged surfaces. However, the increased comfort comes at an increased cost to the user as these systems range from $129.00 - $299.00.

The main goal for a wheelchair tire is to improve reliability and durability of the tires without compromising comfort and safety. In order for the design to be acceptable, tires must: 1) function on a variety of surfaces such as rugs and rough surfaces and 2) be non-marking. Other beneficial features tires should have: 1) allowance for the discharge of static electricity to prevent shocks to the user and potential damage to electronics associated with power wheelchairs and 2) be lightweight and inexpensive.

Increased durability will also decrease costs for the end user. Presently, wheelchair tires cost anywhere from $50 to $150 per wheel. Considering that tires have a short lifespan and need to be replaced frequently for certain users, this can be a large expenditure for the consumer. A need exists to design a product that will decrease costs and increase the durability of the tire while maintaining reliability and comfort level.[2]

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Section C

Tweel™ Technical Information

- Product Description
- Key Features
- Technical Description
- Environmental Factors

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Product Description

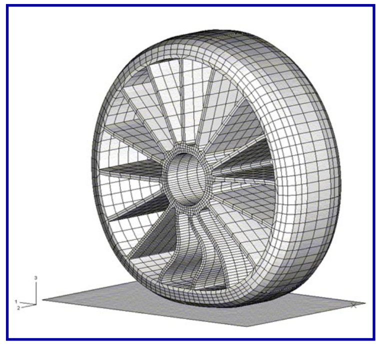

Figure 1: Model of caster Tweel™

The Tweel™ wheel replacements embody resilient, structurally supported, non-pneumatic tire technology and provide many of the performance characteristics and advantages of pneumatic tires while possessing wear and maintenance characteristics similar to non-pneumatic tires. The Tweel™ mimics the mechanics of a pneumatic tire and thus allows very low stiffness and long deflection distance. Its efficient load carrying allows the Tweel™ to have reduced mass relative to current non-pneumatic solutions in addition to allowing more deflection distance than the same size pneumatic tire. Thus, shock transmission to the chair from rough surfaces and obstacles is greatly reduced. The Tweel™ is also able to replace a front suspension system on most wheelchairs, therefore reducing weight, space, and cost.

It is important to note that there remains flexibility in design for the caster wheel in that the size and stiffness of these wheels can be tailored to specific applications.

Key Features

- Enhanced performance - traverses obstacles better than traditional tires; offers improved handling, improved stability, and lower rolling resistance. Equivalent or better traction than existing tire options on all surfaces
- Very low wear rate - lasts approximately three times longer than traditional wheel chair tires/casters
- Higher shock load energy absorption than equivalent pneumatic tires
- Can handle severe vertical deflections (bumps and potholes) without damage
- Increased comfort over traditional wheelchair tire solutions without the need for front end suspension systems
- Very little maintenance required - Tweel™ assemblies are non-pneumatic, so there is no need to monitor tire pressure or perform regular maintenance, thus reducing the number of service calls
- Eliminates chance of catastrophic failure of pneumatic tires - The vane spoke structure eliminates side walls, a vulnerable part of pneumatic tires. Reduces the number of service calls from stranded users
- Vibration reduction - eliminates “caster chatter/shudder” and reduces vibration transmission through the front casters
- Lightweight - reduced mass and weight as compared to other non-pneumatic alternatives
- Material is non-marking yet still offers the required traction performance
- Extremely versatile - the caster and drive wheels can be manufactured in any size and can be customized to fit any wheelchair

Technical Description

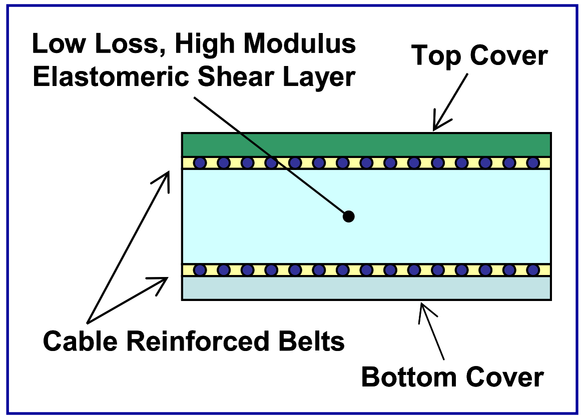

Figure 2: Shear Beam Cross Section

Michelin's resilient, structurally supported non-pneumatic assembly, the Tweel™, has performance capabilities like pneumatic tires that are a substantial improvement over any other airless tire product. The key component of the technology is a structure called the shear ring. The shear ring replaces the function of the crown belts and the air pressure that normally carry the load in a radial tire. The design of the shear ring consists of three concentric layered elements.

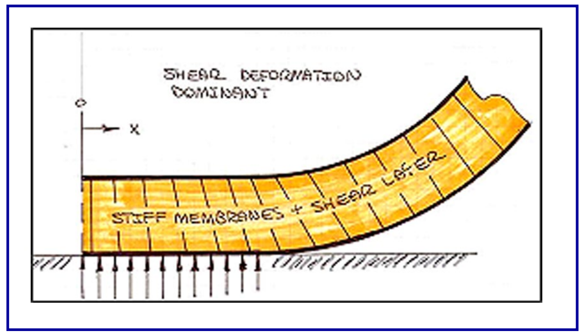

Figure 3: Shear Ring in Deflection

There is an elastomeric annular band that is called the shear layer. The shear layer is captured between two composite rings of the same width as the shear layer. The composite rings have a circumferential tensile modulus of elasticity that is substantially greater than the shear modulus of elasticity of the shear layer. The main characteristic of the shear ring is that deflecting the circular unloaded shape puts the elastomeric band in a state of shear deformation. See **Figure 3** for a depiction of shear in the deflected shear ring.

The shear deformation of the ring results in a uniform contact patch pressure distribution again indicated in **Figure 3**. This uniform contact patch pressure is the first key aspect of the technology. All prior non-pneumatic tires, which carry load via compression of structures between the contact patch and the wheel, have parabolic contact patch pressure distributions that limit a number of performance criteria, such as: traction, soft-soil flotation and tread life. The uniform contact patch pressure distribution delivered by shear rings is equivalent to that of pneumatic tires. This allows the use of conventional tread materials and tread patterns that result in traction and wear life similar to pneumatic tires. Although the current embodiment of the drive Tweel™ assembly for power chairs is 2¼″ in width, the contact area is more comparable to a 3″ wide pneumatic tire which has a rounded crown.

Further, the contact patch pressure of this technology can be low enough to offer the prospect of satisfactory mobility in marginal soil conditions. The current estimate However, any tire, pneumatic or not, that must operate continuously at a low foot print pressure must be made larger to provide the necessary footprint area without imposing excessive vertical deflection. (Excessive deflection would cause too much shear strain and lead to early ring failure.)

The shear ring transmits the contact patch load to the top of the tire like a compression arch. The ring is attached to the wheel via polyurethane spokes, which act only in tension

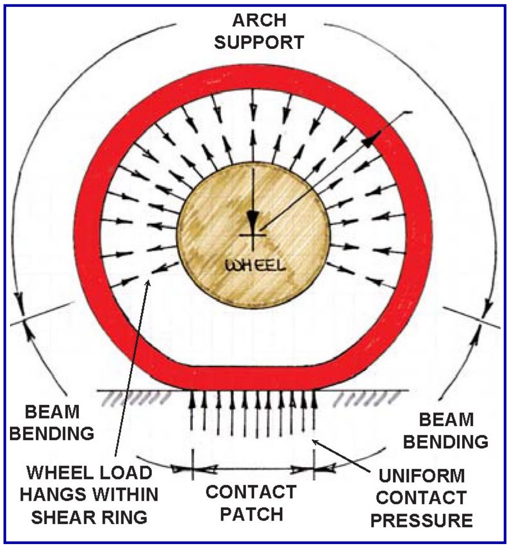

Figure 4: Structural Schematic

to transmit the ring load to the wheel. See the structural schematic in **Figure 4** to visualize the load path. The spokes buckle as they pass over the contact patch and therefore provide little load transmission via compression. The transmission of load via the top of the shear ring is the second key aspect of the technology.

The initial version of the Tweel™ assembly concept is shown in **Figure 5**. The entire structure is utilized to carry the wheel load, making the resulting tire much more efficient than classic non-pneumatic tires in the amount of load carried per unit mass of the tire/wheel system. Further, the absence of structures transmitting wheel loads directly to the road in compression allows much higher levels of deflection without causing excessive material strains. No prior non-pneumatic tire design has been able to deliver this combination of performance characteristics.

Figure 5: Early Tweel™ assembly prototype

The design of the spokes and their relationship to the wheel control the forces transmitted from the shear ring to wheel. Unlike pneumatic tires, where all the forces transmitted by the structure are proportional to the inflation pressure, the Tweel™ can be made soft in one direction and stiff in another. The lateral depth of the flat, vane style spokes contributes to the high lateral stiffness of Tweel™ assemblies. This fact removes some of the classic constraints of design that are inescapable when dealing with traditional pneumatic designs and, therefore, present a tremendous opportunity for wheel assemblies for many applications with improved handling and performance.

The shapes of pneumatic tires are dominated by the constraints of being pressure vessels. Although the belts in radial tires allow their basic shape to be flattened into low aspect ratio, low load carrying sport applications, there are currently no reasonable structures that lead to tall and narrow pneumatic solutions, such as those in the dimensional range of rear manual tires and bicycle tires. With more understanding and development of the technology, this could change in the future. Because the spoke loads allow the use of unreinforced elastomeric materials, the complexity of the spoke design is limited only by the cost of the mold. This allows substantial design flexibility in meeting the load transmission characteristics required for each vehicle application.

Further, the absence of inflation pressure loads and simple, robust connections of the spokes to the wheel allow more freedom in the wheel design. The wheel can be compliant, carrying its own share of shock loads because the spokes can be crushed against the outer wheel surface without damage. These additional degrees of design freedom available to Tweel™ designers make up the third key aspect of the technology. Tweels™ can be more easily designed to supplement or replace suspensions in most applications than can pneumatic tires and are far more tolerant of suspension bottoming shock loads.

Environmental Factors

Wheelchairs utilizing the Tweel™ assemblies will be in contact with a number of different surfaces including: pavement, concrete, grass, rocks, dirt, sand, etc. The Tweel™ assemblies are able to traverse obstacles better than other traditional tires on all different types of terrain. In addition, they significantly reduce shock transmission from the surfaces and obstacles to the chair. Both manual and power wheelchairs are exposed to a wide variety of weather conditions including rain, ice, and snow. The Tweel™ drive wheels have treads to provide comparable traction to other tires in inclement weather conditions.

Section D

MARKETING POTENTIAL

- Consumer Benefit
- Manufacturer Benefit
- Target Market
- Market Projections
- Market Growth
- Competing Products & Manufacturers

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CONSUMER BENEFIT

The increased cost of the Tweel™ will be offset by the decrease in need for replacement tires and the elimination of costly suspension system components both on manual and power wheelchairs. Depending on the amount of use, wheelchair users are frequently faced with replacing their tires. Standard wheelchair users replace their tires at least 1-2 times per year, and sport wheelchair users replace their tires 3-4 times per year. This can be very costly to consumers since Medicaid and other 3rd party insurers only allow reimbursement for one set of tires per year. This means that the consumer would then incur the cost for any additional tires that their wheelchair may need in a given calendar year. Tweel™ technology has the capability of reducing these costs since they are 3-4 times more durable than current wheelchair wheels. With the increased reliability and durability provided by Tweels™, tire replacements will become less frequent and, therefore, less costly to the consumer and insurance companies who provide reimbursements.

MANUFACTURER BENEFIT

On power wheelchairs, the increased cost of the Tweel™ assembly will be more than offset by the elimination of the cost of certain suspension components, thus decreasing the overall manufacturing cost of the wheelchair. With fewer suspension components subject to potential failure on the wheelchair, there will be an elimination of maintenance and warranty claims for the manufacturer on those removed components, resulting in further manufacturer savings. An additional benefit is the reduction of overall weight of the wheelchair. For example, on the iBOT, the increased weight of the Tweel™ was more than offset by the removal of 4.4 pounds worth of suspension components, resulting in a significant weight difference between the Tweel™ and the next best pneumatic alternative.

TARGET MARKET

Tweels™ are targeted primarily towards disabled consumers who need to purchase a new or replacement wheelchair. This includes people with cerebrovascular disease, quadriplegia or paraplegia, osteoarthritis, multiple sclerosis, absence or loss of lower extremity, and cerebral palsy. The increased durability of Tweels™ will offer increased independence to operators due to the decrease in need for servicing. Wheelchair users will also experience a smooth ride with low rolling resistance when traveling over rugged surfaces. This creates the opportunity for the individual to explore new outdoor areas, such as bike paths, which require the use of a durable, smooth riding tire.

Those consumers looking to replace their current wheelchair tires provide a secondary market for the Tweels™. These individuals are looking for reliability and durability in their tires. This would eliminate the worry and inconvenience of becoming stranded due to accidental deflation of pneumatic tires. Those individuals who have tires that need regular servicing find that it is a costly inconvenience that hinders their ability to live independently. The Tweels™ provide this durability, along with many other features that will reduce the amount of assistance provided to wheelchair users, and increase independence for those living alone.

MARKETING PROJECTIONS

The total potential market for the Tweels™, including both new manual wheelchair purchases and new power wheelchair purchases, is projected to be approximately 423,000 wheelchair users in the United States. Those looking to replace their current wheelchair tires provide a secondary market. However, an initial estimate is unknown at this time due to engineering constraints.

New Wheelchair Purchases
An estimated 400,000 manual wheelchairs and 23,000 power wheelchairs[2] are sold annually. This brings the total potential Tweel™ market for new wheelchair purchases to around 423,000 individuals.

Replacement Tire Purchases
Initially, Tweel™ technology will be included on new wheelchair builds. However, as engineering constraints decrease, there will be a large opportunity for Tweels™ to be sold as replacement tires. One such constraint is the fact that Tweels™ do not require a suspension system on the wheelchair so existing wheelchair users would have to remove those components along with their existing tires before putting the Tweel™ on the wheelchair.

MARKET GROWTH

Approximately 1 in 200 people use a wheelchair in the United States. This population of individuals is estimated to grow at a rate of 10% per year.[3] As people age, they are more likely to need assistance with mobility. At the present time, over 56% of all wheelchair users are aged 65 and older.[4] The wheeled mobility market is expected to grow exponentially as America's baby-boomer generation reaches old age and joins the approximated 36 million people who are currently over the age of 65.[5]

COMPETING PRODUCTS AND MANUFACTURERS

There are no products currently on the market that offer increased reliability and durability while decreasing cost and weight by eliminating the need for suspension systems. However, there are products that contain a few of these features currently on the market.

Cheng Shin
Cheng Shin offers a variety of foam-filled tires for power wheelchairs priced from $29.50 to $65.00. The tires never flatten and they are smooth riding, which is true of the Tweel™ assemblies as they are non-pneumatic and have built in suspension to ensure a smooth ride. Foam-filled tires are typically heavier than other non-pneumatic tires. Therefore, Tweels™ have a competitive advantage due to their decreased weight. These products can be viewed at:
http://www.southwestmedical.com/mfgsearchresults.cfm?MFG_ID=Cheng_Shin

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[2] Carlson, Wayne E., Ph.D. et al. Division of Orthopedics, RERC Project 6: The Determination of Environmental Accessibility and Wheelchair User Proficiency through Virtual Simulation. http://gait2.gait.ohio-state.edu/RERC/project6.html
[3] HCFA 1997 HME Report
[4] U.S. Census Bureau, 1997
[5] US Census Bureau, 2000

Sun Metal Products
Sun Metal Products offers caster wheels, molded wheelchair wheels, and lightweight wheelchair wheels. Some of their power wheelchair wheels are made of molded plastic that offers reliability in eliminating the hassles of flats, inserts, or foam-filled tubes. Sun Metal Products does not describe the durability of their tires, and they do not eliminate the need for suspension. These products range in price from $25 to $140 per wheel and can be found at: http://www.sunmetal.com/wheelchair_rims.htm.

Skyway Wheels
Nylon composite "Tuffwheels" are maintenance-free, lightweight, and durable. They also come in a variety of sizes, ranging from 4˝ casters to 24˝ wheelchair tires. Suspension systems are still required with these wheels for a smoother ride. They can be found at: http://www.skywaywheels.com/products_006.htm.

Frog Leg Suspensions
Frog Leg suspension systems provide safety, comfort, and increased mobility for wheelchair users. They are also lightweight and durable. These systems range from $129.00 - $299.00 and need to be purchased separately from the wheelchair. The suspension system will add weight to the wheelchair once it is installed, which is a potential drawback. If Tweels™ were used on a wheelchair, the need for suspension systems would be eliminated, thus reducing the wheelchair's total weight. Frog Leg Suspensions can be viewed at: http://www.medaidmedical.com/catalog/page28a.shtml.

Section E

APPENDICES

- Appendix A: Facts and Figures Regarding Wheelchair Use in the United States
- Appendix B: Trends and Issues in Wheeled Mobility Technologies

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Human Engineering Research Laboratories
VA Pittsburgh Healthcare System

- Appendix C: Tweels™ Addressing Documented Unmet Needs in the Wheeled Mobility Market
- Appendix D: T² Project Overview

T²RERC

Appendix A

Facts and Figures Regarding Wheelchair Use in the United States

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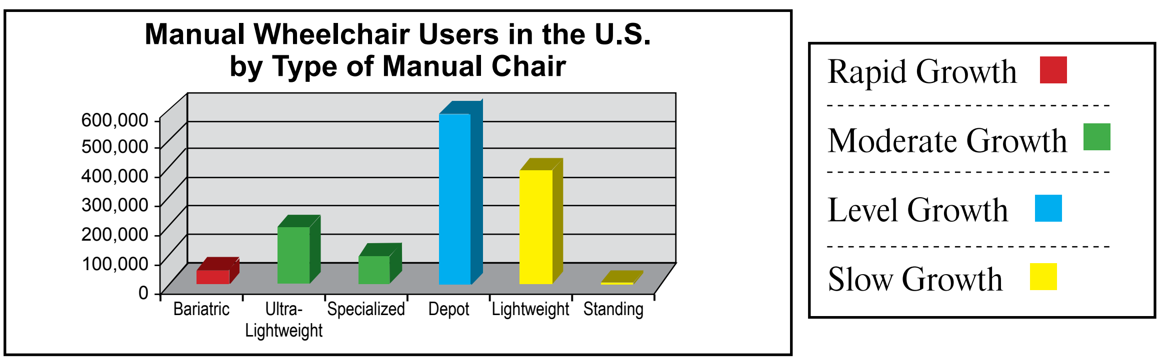
Facts and Figures Regarding Wheelchair Use in the United States

Primary causes of limitations leading to the use of wheelchairs or scooters

Total	100%	2.2 million
Cerebrovascular disease	11.05	243,100
Osteoarthritis and allied disorder	10.43	229,460
Multiple Sclerosis	5.02	110,440
Absence or loss of lower extremity	3.68	80,960
Paraplegia	3.63	79,860
Orthopedic impairment of lower extremity	3.62	79,640
Other forms of heart disease	3.30	72,600
Cerebral palsy	3.11	68,420
Rheumatoid arthritis and other inflammatory polyarthropathies	3.00	66,000
Diabetes	2.40	52,800
Other/Not Reported	50.76	1,116,720

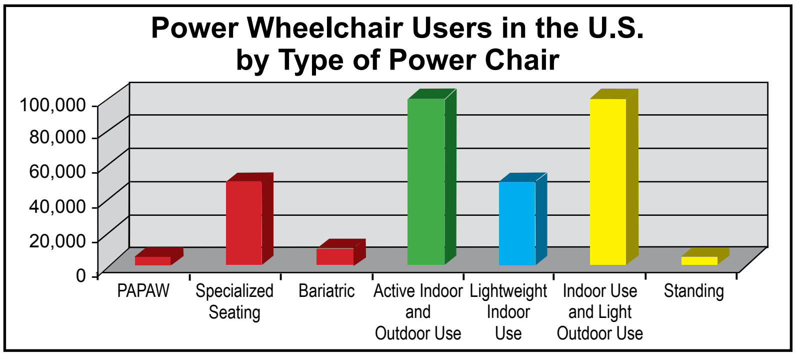
(Adapted from: Kaye, Kang, & LaPlante, 2000 & Cooper & Cooper, 2003)

Manual Wheelchair Users in the U.S.



Type of Manual Wheelchair	Bariatric	Lightweight	Ultra- Specialized	Depot	Lightweight	Standing
Current Number	50,000	200,000	100,000	600,000	400,000	5,000

Power Wheelchair Users in the U.S.
(Excluding scooters)



Rapid Growth

Moderate Growth

Level Growth

Slow Growth

Type of Manual Wheelchair	PAPAW	Specialized Seating	Bariatric	Active Indoor and Outdoor Use	Lightweight Indoor Use	Indoor Use and Light Outdoor Use	Standing
Current Number	5,000	50,000	10,000	50,000	100,000	100,000	5,000

Adapted from Tables 1 and 2 in "Trends and Issues in Wheeled Mobility Technology" (Cooper & Cooper, 2003)

Note to users of this data:
These categories are not necessarily mutually exclusive in terms of wheelchair functions and features, and there may be some overlap of categories within these estimates.

Appendix B

Trends and Issues in Wheeled Mobility Technologies

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Trends and Issues in Wheeled Mobility Technologies

Rory A. Cooper, Ph.D., and Rosemarie Cooper, M.P.T., A.T.P.
Department of Rehabilitation Science and Technology
University of Pittsburgh
And
Human Engineering Research Laboratories
VA Pittsburgh Healthcare System

I. Introduction

The purpose of the paper is to describe emerging technologies and trends in wheeled mobility and their likely impacts on anthropometry and on design and construction. We provide a concise review of the basic types of devices currently on the market and their recommend uses. Trends in the usage and development of wheelchairs are presented along with some market indicators. Promising emerging technologies are described and areas in need of further development are suggested. Lastly, we have tried to indicate the impact of new wheeled mobility technologies on the built environment and transportation. This paper is not meant to be a comprehensive review of the literature, but rather to provide our perspective on current wheelchair technology and where things might go in the future.

II. Basic Types of Wheeled Mobility Devices on the Market

Figure 1. Photograph of a K0001 depot type manual wheelchair.

The Centers for Medicare and Medicaid Services (CMS) is one of the nation's largest purchasers of wheelchairs.[1], [2] However, neither CMS's coverage nor payment of wheelchairs is always in the best interest of the patients that need them. [3] Wheelchairs are considered by CMS to be durable medical equipment (DME) and must meet the following criteria: capable of withstanding repeated use; primarily used to serve a medical purpose; not useful to person in absence of illness or injury; and appropriate for in home use. [1] The last criterion is often interpreted by Durable Medical Equipment Regional Carriers (DMERC's) to exclude payment of wheelchairs that would provide community mobility and improve function outside the home. Despite the fact that CMS has nine Common Procedure Coding System (CPCS) codes for manual wheelchairs (K0001 - K0009), only the first four codes are regularly covered. [4] Codes K0001-K0003 represent wheelchairs that are essentially designed for depot (e.g., airport, amusement park) or temporary institutional use (e.g., hospitals) and are generally not appropriate as a long-term mobility device. The obvious attraction of K0001-K0003 wheelchairs is their low purchase price, see **Figure 1**. The wheelchairs coded K0004-K0009 provide clinicians and consumers greater ability to select and adjust the wheelchair to the user and accommodate the consumer's functional needs. Ultralight manual wheelchairs are moderately adjustable or selectable manual wheelchairs intended to be used by a

Figure 2. Picture of an ultralight (K0005) manual wheelchair.

Figure 3. Picture of a lightweight (K0004) manual wheelchair.

single individual {K0005}, see **Figure 2**. Lightweight manual wheelchairs are minimally adjustable or non-adjustable manual wheelchairs intended for an individual or for institutional use {K0004}, see **Figure 3**. Depot manual wheelchairs are minimally or non-adjustable manual wheelchair intended for institutional or commercial use {K0001-K0003}.

All manual wheelchairs are not alike. There are variations in the quality and performance of manual wheelchairs. [5], [6] It is import for clinicians to realize the benefits of a proper wheelchair prescription, not only for the consumer's comfort and mobility needs but also in the quality of the wheelchair that will last with minimal repairs.[7] Although there are settings in which trained clinicians properly fit wheelchairs, many times the consumer is provided a wheelchair that is determined by what insurance (e.g., CMS, VA) will pay, not what is of benefit to the consumer's function or in considering the quality of the wheelchair itself. Currently CMS will pay only for a limited variety of wheelchairs based on medical necessity. Medicare will only cover lightweight wheelchairs (K0004) for individuals who 1) engage in frequent activities that cannot be performed in a standard or depot wheelchair or 2) requires a seat width, depth or weight that cannot be accommodated in standard or depot wheelchair. [8] Medicare will pay for K0005 wheelchairs when there is adequate justification based upon treatment of prevention of upper extremity repetitive strain injury or in order to be able to independent propel a manual wheelchair. [9] The VA uses broader criteria that include transportation of the wheelchair, mobility outside the home (e.g., school, work, community), and hence provides a higher percentage of K0005 manual wheelchairs. [10]

The terms lightweight and ultra light wheelchairs are derived from the Medicare categories of K0004 and K0005 respectively. K0004 wheelchairs must weigh less than 34 pounds without footrests or armrests, and K0005 must weigh less than 30 without foot or arm supports. K0004 wheelchairs have very limited adjustability. Like depot chairs, they can be sized to the user but many of these chairs do not offer features like adjustable axle plates, quick-release wheels, or a method to change the seat to back angle of the wheelchair. Because of the way Medicare reimburderived from the Medicare categories of K0004 and K0005 respectively. K0004 wheelchairs must weigh less than 34 pounds without footrests or armrests, and K0005 must weigh less than 30 without foot or arm supports. K0004 wheelchairs have very limited adjustability. Like depot chairs, they can be sized to the user but many of these chairs do not offer features like adjustable axle plates, quick-release wheels, or a method to change the seat to back angle of the wheelchair. Because of the way Medicare reimburse, at present it is necessary to justify the need for a K0004 or K0005 above a standard K0001. Unfortunately prior authorization, meaning the vendor is guaranteed ahead of time to be reimbursed for the wheelchair, is not always possible. As Medicare serves as an example for many insurers, their actions affect many more people with disabilities.

Powered wheelchairs can be grouped into several classes or categories. [11] The most common groupings are based upon the functions provided by the wheelchair and the intended use. A convenient grouping by intended use is primarily indoor, both indoor/outdoor, and active indoor/outdoor. Indoor wheelchairs have a small footprint (i.e., area connecting the wheels). This allows them to be maneuverable in confined spaces. However, they may not have the stability or power to negotiate obstacles outdoors. Indoor/outdoor powered wheelchairs are used by people who wish to have mobility at home, school, work, and in the community, but who stay on finished surfaces (e.g., sidewalks, driveways, flooring). Both indoor and indoor/outdoor wheelchairs conserve weight by using smaller batteries, which in turn reduces the range for travel.

Some wheelchair users want to drive over unstructured environments, travel long distances, and to move fast. [12] Active indoor/outdoor wheelchairs may be best suited for these individuals. The active indoor/outdoor-use wheelchairs include those with suspension and use of a power base design. The power base consists of the motors, drive wheels, castors, controllers, batteries and frame. The seating system (e.g., seat, backrest, armrests, leg rests, footrests) is a separate integrated unit. Often, seating systems from one manufacturer are used on a power base from another manufacturer.

Figure 4. Picture of a rear-wheel drive electric powered wheelchair.

Power wheelchair bases can be classified as Rear Wheel Drive (RWD), Mid Wheel Drive (MWD), or Front Wheel Drive (FWD). [13] The classification of these three drive systems is based on the drive wheel location relative to the systems center of gravity (CoG). The drive wheel position defines the basic handling characteristic of any power wheelchair. All three systems have unique driving and handling characteristics. In Rear Wheel Drive power bases the drive wheels are behind the user's center of gravity and the casters are in the front. RWD systems are the traditional design and therefore many long-term power wheelchairs are familiar with their performance and prefer them to other designs. A major advantage of RWD systems is its predictable drive characteristic and stability. A potential drawback to a RWD system is its maneuverability in tight areas due to a larger turning radius, see **Figure 4.**

Figure 5. Example of a mid-wheel drive electric powered wheelchair.

In Mid Wheel Drive power bases the drive wheels are directly blow the user's center of gravity and generally have a set of casters or anti tippers in front and rear of the drive wheels, see **Figure 5**. The advantage of the MWD system is a smaller turning radius to maneuver in tight spaces. A disadvantage is a tendency to rock or pitch forward especially with sudden stops or fast turns. When transitioning from a steep slope to a level surface (like coming off a curb cut), the front and rear casters can hang up leaving less traction on the drive wheels in the middle.

Figure 6. Example of a front wheel drive electric powered wheelchair.

A Front Wheel Drive power base has the drive wheels in front of the user's center of gravity and it tends to be quite stable and provides a tight turning radius, see **Figure 6.** FWD systems may climb obstacles or curbs more easily as the large front wheels hit the obstacle first. A disadvantage is that a FWD system has more rearward CoG, therefore the system may tend to fishtail and be difficult to drive in a straight line especially on uneven surfaces. [14]

Scooters are designed for people with limited walking ability and substantial body control. [11] They are power bases with a mounted seat and usually a tiller (e.g., handle bar) steering system, see **Figure 7**. Scooters are primarily characterized by the upholstered seat which is often similar to that used on a lawn tractor or fishing boat. Most scooter seats swivel to ease ingress and egress. The seats are often removable to simplify transport in a personal automobile. From an engineering and clinical perspective, one of the most important distinguishing features of a scooter is that speed is controlled electronically and direction is controlled manually. Most scooters allow the steering column to fold or be removed without tools in order to make the scooter easier to transport in a personal motor vehicle. There are products that use electronic steering by using a motor to change the direction of one or both front wheels.

Figure 7. Photograph of a 3-wheeled scooter.

Pressure ulcers are a costly problem in the United States. Another common problem in wheelchair users is back pain and poor posture. For both of these conditions, it is thought that tilt in space and recline may be of benefit. Tilt in space can significantly reduce static seating pressure, a key ingredient in the development of pressure sores. Sprigle & Sposato [15]. and Hobson [16] studied the effects of various seated positions and found that pressure was reduced significantly with 120 degrees of recline. In addition, using recline and tilt in space can allow for a change in position in the wheelchair and thus improve comfort. Nachemson found decreased inter-vertebral disc pressure by reclining the back from 80 to 130 degrees. [17] Others purported advantages of tilt and recline system include better swallowing,[18] and decreased leg edema, [19] Based on these arguments tilt in space and recline are widely prescribe accessories on power wheelchairs. However, there is very little research in this important area.

Figure 8. Picture of an electric powered wheelchair with a power seat recline.

Reclining wheelchairs allow the user to change sitting posture through the use of a simple interface (e.g., switch), see **Figure 8**. Changing seating posture can extend the amount of time a person can safely remain seated without damaging tissue or becoming fatigued. Reclining wheelchairs assist in performing pressure relief. Changing seating position redistributes pressure on weight-bearing surfaces, alters the load on postural musculature, and changes circulation. Changing position can also facilitate respiration. Elevating the legs while lowering the torso can improve venous return, and decrease fluid pooling in the lower extremities

Figure 9. Picture of an electric powered wheelchair with power seat tilt function.

Tilt-in-space systems allow the person to change position with respect to gravity without changing their seated posture (i.e., the joints of the body maintain their seated position) **Figure 9**. There are some difficulties with tilt-in-space wheelchairs. The wheelchairs are heavier than standard wheelchairs, they are less stable, and can require greater turning diameter when reclined. A potential problem with tilt-n-space and reclining seating systems is that the body may not remain in a stable position after transitioning through several seating orientations. Sliding or stretching during reclining or tilting in some individuals may produce undesirable shear forces, excite spacticity, and bunch clothing.

Many activities can be promoted by using a variable seat height wheelchair. Lowering seat height can make it simpler to get under tables and desks. Picking up objects from the floor can also be assisted by an adjustable seat height. Access to the floor is an important feature for promoting the cognitive and social development of children. Children often play, explore the environment, and interact with other children at ground level. Children who use wheelchairs can benefit from being able to access the ground. Some wheelchairs provide powered floor access for children. Adults who use wheelchairs may also desire the ability to lower the wheelchair seat to the floor. This can allow parents who are wheelchair users to play with their children or for people to garden. As the person is lowered to the floor by the wheelchair stability is affected. In some wheelchairs, the batteries move as the person is lowered in order to maintain the balance of the wheelchair and rider. Some seat lowering mechanisms alter the leg rest angle in order to get closer to the ground. It is important to assure that the rider has suitable range of motion to safely use this feature. Lowering the seat makes access to desks and tables easier. When retrieving items from the floor or placing them in low cabinets a lower seat height can be beneficial. Lowering the seat height tends to make the wheelchair more stable. A lower seat position can be helpful when maneuvering the wheelchair on steep ramps or slopes. The added stability of being able to lower the seat height can be of considerable benefit on cross slopes.

Figure 10. Example of an electric powered wheelchair with powered seat elevation function.

The ability to raise the seat can also provide several advantages, **Figure 10**. Raising the seat height also offers several benefits. Items on high shelves or in high cabinets can be obtained by using an elevating seat. Elevating the seat height is helpful for viewing people at eye level. Tasks such as cooking and washing can be simplified with an elevated seat height. Many powered wheelchair controllers cause the speed of the wheelchair to decrease as the seat height is raised. Increasing seat height tends to decrease the stability of the wheelchair. Most wheelchair manufacturers do not recommend elevating the seat on a slope or uneven terrain.

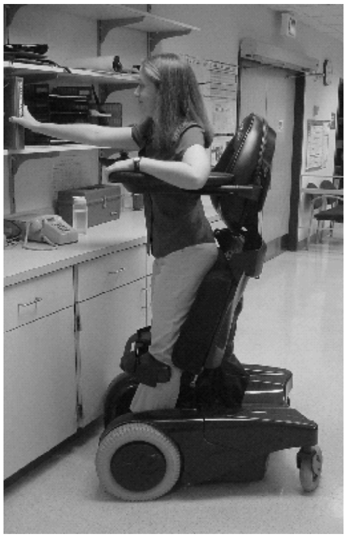

Figure 11. Example of an electric powered stand-up wheelchair.

Stand-up wheelchairs are being produced that are lightweight and transportable. Stand-up wheelchairs offer a variety of advantages over standard wheelchairs, see **Figure 11**. They provide easy access to cabinets, shelves, counters, sinks, and many windows. Many activities around the home are easier to accomplish by using a stand-up wheelchair, for example, cooking, washing dishes, and ironing clothes. Stand-up wheelchairs can reduce the need for significant home modifications. In the workplace, stand-up wheelchairs may help when making presentations using a "white board", accessing copiers, and interacting with colleagues. The ability to perform some occupations is can be enhanced by using a stand-up wheelchair. For example, machine operators or machinists can perform normal job functions with minimal modifications to the worksite and physicians and surgeons can examine patients and perform procedures safely and effectively.

Greater integration of people with disabilities into society has created new avenues for specialized technologies. Stand-up wheelchair manufacturers have benefited from the increased desire of people with disabilities to be active at home, school, work, and the community. In many cases stand-up wheelchairs allow people to perform activities without significant architectural modifications. This has tremendous potential for overcoming both physical and social barriers which have prevented wheelchair users from gaining greater access to employment, education and community services. For example, a school teacher could use a stand-up wheelchair to conduct physics experiments at a standard laboratory bench without the need to completely remodel the entire classroom. This should not be interpreted to mean that society does not have an obligation to eliminate architectural and social barriers. However, specialized technology provides greater flexibility when making individual accommodations.

Stand-up wheelchairs are more complex than most manual or electric powered wheelchairs. Several decisions must be made prior to selecting and fitting a stand-up wheelchair. The rehabilitation team must work with the individual to determine if the stand-up wheelchair should have an electric powered base or whether it should be manually propelled. Stand-up features are integrated into some power wheelchairs with minimal trade-offs (i.e., no additional weight or size). Manually powered stand-up wheelchairs are heavier than lightweight manual wheelchairs. Currently the weight of manually propelled stand-up wheelchairs is between 30 and 60 pounds (13.6 to 27.3 kilograms). Some of the weight can be attributed to the lifting mechanism. All electric powered wheelchairs with a stand-up feature use a separate electric drive system for the stand-up mechanism. Manually powered stand-up wheelchairs may use a manual lifting mechanism or an electric powered lifting mechanism. It is important to realize that many wheelchair users have access to greater financial resources than previously. Through moderate success in employment and education, some wheelchair users have the means to purchase stand-up wheelchairs. In such cases, the individual must decide whether the potential benefits justify the expense.

III. Emerging Wheeled Mobility Devices

In North America, the number of people who are obese is growing at an alarming rate. Obesity is associated with a variety of debillitating diseases and conditions, some of which may lead to the individual requiring a wheelchair for ambulation. [20] Unfortunately, individuals who are morbidly obese may require skill nursing assistance, especially if they become dependent on a wheelchair for mobility. [21] This has resulted in a significant growth in the market for bariatric wheelchairs. Typically, bariatric wheelchairs are classified as wheelchairs required for individuals who weigh over 250 pounds and who have a body-mass-index of greater than 25. [22] Bariatric wheelchairs range from a common wheelchair, manual or powered, that is built to handle the additional mass to custom products that can accommodate people who may weigh up to 1,000 pounds. The of the most significant mobility challenges for individuals who use bariatric wheelchairs is the additional width of the wheelchair, in some cases as great as 60 inches, and the inability to transfer independently. In some cases, specialized lifts are required to transfer individuals in an out of their wheelchairs.

Figure 12. Power Assist Pushrim Activated Wheelchair (PAPAW).

A push-rim activated power assisted wheelchair (PAPAW) uses motors and a battery to augment the power applied by the users to one or both push-rims during propulsion or braking, see **Figure 12**. [23] Applying a torque to the push-rim activates the wheelchair. The torque applied to the push-rim is amplified by the motors and gear-train. A micro-controller controls each of the rear wheels. Software simulates inertia (i.e., allows the wheels to coast between strokes), compensates for discrepancies between the two wheels (e.g., differences in friction), and provides an automatic braking system activated when applying a reverse torque to the push-rims. [24] A PAPAW is typically assembled by retrofitting an ultra-light manual wheelchair with the PAPAW wheels and some customized hardware. Most PAPAW wheels use quick release axles (i.e., axles that allow the wheels to be removed without tools). Most PAPAW's will accommodate standard wheelchair wheels in order to serve as a manual wheelchair as well. The PAPAW represents an entirely new class of wheelchair. There are many people who have difficulty effectively propelling a manual wheelchair because of pain, low cardiopulmonary reserves, insufficient arm strength, or the inability to maintain a posture effective for propulsion. [25], [26] Until recently, people who were unable to effectively propel a manual wheelchair would be presented with the options of using an electric powered wheelchair, using a scooter, or being pushed by an assistant in their manual wheelchair. The PAPAW provides a fourth alternative that may be of substantial benefits to some clients. The electronic controls of a PAPAW are commonly selectable. The electronic controls can be used to set the sensitivity of the push-rims (i.e., to alter the amount of assistance provided by the motors). On some devices, it is possible to adjust the sensitivity of the left and right wheel independently, which is advantageous for people with strength imbalance or motor coordination issues. It has been proposed that a PAPAW could be used for training arm movement post cerebral vascular accident in order to gain greater strength and coordination. The maximum speed, maximum braking, and acceleration are also possible to adjust with a PAPAW. Selecting the settings for the electronic controls of a PAPAW should follow a similar process to that of adjusting an electric powered wheelchair.

The electric powered wheelchair is poised to undergo revolutionary design changes. While devices like the PAPAW represent important advances for people whose abilities balance between using a manual wheelchair and an electric powered wheelchair, there are many more people who could benefit from advances in electric powered wheelchairs. [27] Indeed, people with disabilities and people who are elderly are becoming more empowered to insist upon maintaining or increasing independence and mobility. This has prompted the investigation of technologies that will negotiate uneven terrain, traverse stairs, and detect obstacles in the environment.

Scooters and electric powered wheelchairs are going to become more similar. The demand for electric powered mobility devices that do not look like wheelchairs and that can provide both indoor and outdoor mobility is creating innovation in the marketplace. Improvements in seating systems that allow greater user control (much like in automotive seating), mid-wheel drive scooters that provide good indoor mobility yet have the lightweight and ease of use of a scooter will emerge, and light more transportable power products are being introduced. In the future, modular type designs may evolve that allow wheeled mobility system to be configured (e.g., wheelbase, track-width, steering interface) for the user and the activity.

Figure 13. An IBOT in balance function.

The Independence 3000 IBOT Transporter (IBOT) has probably garnered the most attention for its innovations in dynamic stabilization that provide it with a unique combination of capabilities, **Figure 13**. The IBOT incorporates a variety of sensors and actuators for dynamic stabilization of the device, speed control, self-diagnosis, and for changing operational functions. [28] The actuators and sensors allow the IBOT to respond to changes in terrain, which cause deviations in the occupant's center of gravity with respect to the device. Three redundant computers help to maintain stability, provide the user with control, and assure safe operation. The IBOT command and control computers use a "voting process" (i.e., two out of three computers must agree upon the action requested by the user and the status of the sensors in order for action to be taken, otherwise a fault is indicated) to determine the actions of the device in response to requests from the user or changes in device status. The IBOT software also records the operation of the device and maintains an operations log, useful for maintenance. An important feature of the IBOT is that the device contains an internal modem that allows communication with the manufacturer or a service representative at a distance. This provides the potential to down-load logs to determine whether periodic maintenance is necessary and to up-load software changes. Structurally, the IBOT is based upon a chair mounted through linkages to a wheeled base. The IBOT drive train includes four primary wheels, each controlled through its own set of electric motors, and two caster wheels. The two sets of drive wheels on either side of the chair form a cluster. Each cluster may rotate about its central axis while the wheels may rotate about their hubs, this flexibility allows the IBOT to traverse non-uniform surfaces, inclines, and to climb curbs. The user operates an IBOT via a position sensing joystick and a user control panel containing several buttons attached to the armrest. In a study by Cooper et al. subjects reported using the IBOT to perform a variety of activities including holding eye-level discussions with colleagues and shopping by balancing on two wheels, going up and down steep ramps, traversing outdoor surfaces (e.g., grass, dirt trails) and climbing curbs. [29] The balance and four-wheel drive functions were found to be most helpful. The IBOT required attention to control in standard function. The seat height was too high for most tables and desks and it was challenging to use the IBOT in the bathroom. The IBOT was a functional mobility device. Its greatest strengths are outdoors and in circumstances where there is space to use balance function. [29] Other stair-climbing and curb negotiating devices have also been investigated. Lawn et al. reported on an electric powered wheeled mobility device that can negotiate stairs and ingress/egress into a motor vehicle. [30] Wellman et al. described the investigation into combing the use of robotic legs with a wheeled device to provide increased mobility to people with disabilities. [31] Their device was intended to assist with climbing curbs and uneven terrain. Future advances in controls may benefit from learning from nature and how insects negotiate rough terrain. [32]

Simpson, Yoder and Levine have reported on combing obstacle detection and avoidance with an electric powered wheelchair.[33], [34], [35] They use a combination of ultrasound and infrared sensors to map the environment and provide assistance with guidance and control of an electric powered wheelchair for people who have visual as well as lower limb impairments. This line of research shows promise for helping people who are elderly to maintain independent mobility. Electric powered wheelchairs are poised to get smarter and more accommodating to provide greater mobility with a higher degree of safety.

IV. The Wheelchair Marketplace

In the U.S. an estimated 2.2 million people currently use wheelchairs for their daily mobility [36]. World wide, an estimated 100-130 million people with disabilities need wheelchairs, though less than 10 percent own or have access to one. [37] While these numbers are staggering, experts predict that the number of people who need wheelchairs will increase by 22 percent over the next ten years [38]. The leading cause of disabilities in the world can be attributed to landmines, particularly in developing nations, leading to 26,000 people injured or killed by landmines each year. There is an overwhelming need for wheelchairs and the research and development required to make them safer, more effective, and widely available. This was pointed out by the VHA Rehabilitation Strategic Healthcare Group who identified the following areas as being of particular importance: practitioner credentials, accreditation, device evaluation, device user training, patient education, clinical prescribing criteria, national contracts, and access to new technology [39]. There are over 170 U.S. wheelchair manufacturers with a total reported income of $1.33 billion. However, of these companies, only five had sales in excess of $100 million [40]. There is anticipated growth in the wheelchair market. For example, sales of power wheelchairs reached $290 million in the year 2000 up from $205 million in 1996. Scooter sales reached $245 million in 2000, with a sustained growth rate of about 7%. [41] This growth was attributed to the aging baby boomers, growing longevity (an issue facing the rapidly growing aged population), increased incidence of SCI/D, and manual wheelchairs users acquiring electric powered wheelchairs when they start to lose function. [42] While this market is crowded with participants, there is little product differentiation and consolidation is anticipated. [42] Wheelchairs account for about 1% of Medicare spending. [43] The VA provides more wheelchairs than any other U.S. funding organization. [43]

The VA is the single largest supplier of wheelchairs in the US at a cost of approximately twenty million dollars annually. There are about 25 million veterans in the U.S. of which 75%

served in a major conflict. [44] About 2.7 million veterans receive disability compensation or pension from VA. In the year 2002, the VA had nearly 4.5 million prosthetic patient visits and performed nearly 6.5 million prosthetics services at an approximate cost of $700 million. There were 1.1 million unique patients seen, which was a 7.9% increase over 2001. The VA purchases over 10,000 electric powered wheelchairs per year and over 50,000 manual wheelchairs per year (most of these are depot style wheelchairs). The CARES initiative showed that less than 65% of veterans were within 4 hr. driving time of their prosthetics or specialty care clinic, which could present problems when seeking access to more complex mobility devices that require assistance from experts. [45]

Use of assistive technology is an increasingly common way of adapting to a disability. [46] In 1995, requests to Medicare for reimbursement for durable medical equipment amounted to $6.27 million, an increase of 25.7% over the $4.99 billion level in 1994.[47] The majority of assistive device users, particularly users of mobility aids, are over age 65.[48] However, the aging of the U.S. population does not account for the increase in use of assistive technology. For example, while the U.S. population increased by 19.1% from 1980 - 1994, the age adjusted use of wheelchairs increased by 82.6%.[49] Part of the increase in use of assistive technology can be attributed to remarkable improvements in design, both in functionality and in appearance. For example, there has been an explosion in design options in wheelchairs in last 2 decades, including lighter weight wheelchairs, motorized wheelchairs and scooters, and the ability to customize the fit of the seat and back to the wheelchair rider.[50]

Individuals who use wheelchairs for mobility typically receive a new wheelchair every three to five years. The cost of a new wheelchair varies from about $100 to $30,000 depending upon the complexity of the wheelchair and the degree of impairment of the person. The chances of acquiring a disability increase with age, and most persons aged 75 or older have a some form of disabling condition. People over 65 represent about 43% of people with severe disabilities. [51] Government statistics show that 17% in the general population is over 65 years of age. Approximately 33% of the U.S. population have annual incomes of less than $20,000, and about 15% less than $10,000, and over 50% of people with disabilities fall within these income ranges. The proper selection of the wheelchair and related technology (including cushions) will have substantial socioeconomic costs for the people with disabilities and society. [52] Moreover, the quality of life of the people with disabilities and their families are impacted.

V. Trends in Usage of Wheeled Mobility Devices

The number of people using wheelchairs in the United States is estimated to be greater than 2 million [53]. Increased computing power, low cost microcontrollers, and a greater variety of sensors have produced a very complex interaction between electric powered wheelchairs and their users [54]. There are rear-wheel, mid-wheel, and front-wheel drive electric powered wheelchairs. Some wheelchairs can climb stairs and even cluster over obstacles. With so many models and features available, consumers and clinicians should consider numerous safety and performance characteristics of a wheelchair when deciding what type of device to select. However, attempting to acquire performance information from wheelchair manufacturers can be difficult and challenging.

Two main conclusions can be drawn from these studies concerning wheelchair use. First, the number of people using wheelchairs is increasing every year. As the market for wheelchairs continues to expand, manufacturers and companies will offer more varieties of wheelchairs. People will be confronted with having to attempt to discern what wheelchair bests meets their needs. In addition, insurers are looking to manage costs and view durable medical equipment as an area to target for cost containment. This is largely due to the paucity of outcomes studies (something all areas of medicine suffer from), many of the issues are related to community participation and quality of life rather than morbidity and mortality, and the service providers are not widely certified or evenly readily identifiable. The latter factor leads insurers to believe that there is wide-spread fraud and abuse when it comes to assistive technology.

When a person's wheelchair has failed, his or her ability to work, perform daily tasks, and move independently in his or her environments is significantly impacted. Sixty percent of wheelchair failures are a result of engineering factors [55]. Unfortunately, these failures can also lead to injuries that require medical attention. The number of wheelchair failures that resulted in injuries serious enough to warrant medical attention is estimated to be over 36,000 per year [56]. In one study, Frank et al. [57] interviewed 113 power wheelchair users about problems with their newly prescribed wheelchairs. Component failures were reported in 39% of those interviewed. Knowing a wheelchair's reliability and life expectancy is vital for the growing number of individuals who rely upon these devices. Further, this information would assist insurers with making cost-effective purchase decisions as well as preventing injuries and the medical expenses associated with wheelchair failures [58]. More reliable and functional wheelchairs are needed, and they need to accommodate to the increasing population of people with severe and often multiple disabilities. It has been estimated that the current population of people who use electric powered wheelchairs today, only represents about half of the perspective user population. The number would increase if technology were available to provide reliable and safe control of an electric powered wheelchair for individuals who can not operate a joystick or switch array. Adding sensors to the wheelchair to detect obstacles in the environment, improved signal processing, and alternative input systems all show promise for providing more people with independent mobility.

Problems with mobility are prevalent in the older population and they are of special importance to older persons living independently. [59], [60] Interventions to adapt to mobility disability are of three basic types: improve the individual's ability to perform the activity by mending the diseases or impairments causing the disability, eliminate the need to perform the activity or parts of the activity through use of personal assistance, or alter the way the activity is performed, for example through use of assistive technology like a cane, walker, or wheelchair.

Nursing homes (NH) anticipate an increased demand for their services as the number of people aged 65 years or older is expected to double in the next 30 years [61]. Individuals in NH are likely to use wheelchairs [62]. Wheelchairs serve two main purposes in NH. Wheelchairs provide individuals with mobility and a means to participate in daily activities and social events. Residents of NH report their mobility contributes significantly to their quality-of-life and feelings of well-being [63]. In addition, wheelchairs assist NH staff in caring for residents who commonly have physical impairment, poor mobility, poor endurance, or are at risk of falling. Therefore, assistive technology holds the promise of helping to enhance or maintain functional independence, while countering the shortage of personal care givers.

Multiple sclerosis is the most common cause of disability, other than trauma, in young adults and within 15 years of onset, 50% of individuals will require assistance with mobility [64]. Aronson [65] found that reduced mobility was associated with reduced quality of life (QoL).

Despite the connection between quality of life in MS and mobility, there is virtually no information available to guide decision-making for mobility interventions in this population [66]. Clinicians and patients require more information about when to prescribe assistive technology such as wheelchairs and what type of mobility device intervention is most appropriate. The fear of loss of strength and dependence on technology likely leads to delays in prescription, which can adversely affect quality of life and participation in vocational and social activities.

Obesity is a severe medical problem affecting 1/3 of the North American population (about 58 million people). Associated with many diseases, obesity results in long-term health risks, increased healthcare costs, emotional difficulties, and mortality. [67], [68]. In a 2002 study by Weil et al. [69] almost 25% of people with disabilities were obese as compared to 15% of people without disabilities. After acquiring a disability, the amount of physical activity is found to decrease rapidly which leads to a loss of muscle mass and diminished level of strength. [70] It is likely that at a certain weight, even individuals with normal strength are no longer able to functionally propel a wheelchair. Because rolling resistance is related to weight, a person with a disability who weighs more will require greater effort to propel a manual wheelchair. [71] Despite this known relationship, obesity is currently not considered an acceptable reason for a power wheelchair.

Alternatives to manual wheelchair propulsion include an electric powered wheelchair, scooter and push-rim activated power assisted wheelchairs (PAPAW). PAPAWs provide greater physical activity, are easier to transport and may be an excellent alternative for the obese population. Identifying ways to overcome barriers to mobility and improving wheelchair prescription for overweight individuals with disabilities, and people with upper extremity pain, injury, impairment or weakness could lead to increases in functional independence, self-esteem, and community participation.

People with disabilities are living longer, and expecting to remain more active than ever before. The demand to maintain an active lifestyle despite aging with a disability will present both challenges and opportunities for wheelchair manufacturers and insurers alike. For example, the life expectancy of an individual with spinal cord injury is approaching that of the general population. Another interesting indication is that people with disabilities, especially people who have reached retirement age when acquiring a disability may have more discretionary income or may be better insured. An important consideration is that as wheelchair users age, they are more susceptible to secondary conditions (e.g., repetitive strain injuries, vibration exposure injuries, and decreased cardiovascular capacity). Products and services need to be available to accommodate and where possible prevent or delay these conditions.

Unfortunately, there are no readily available statistics on the sales of wheelchairs and scooters, and it is even more difficult to estimate the size of specific market sectors such as stand-up wheelchairs. A wide variety of wheelchair models are available to consumers. Based upon the information reviewed, and our experience providing clinical services and working with various manufacturers and suppliers, we developed Tables 1 and 2, which provides estimates for the current U.S. market sizes for selected wheelchair categories. We have also provided indications as to their growth potential. In our estimates, we excluded sales to institutions (e.g., airports, amusement parks, grocery stores) for transport of people.

Table 1. Current manual wheelchair usage by category, and trending.

	Depot	Lightweight	Ultra-Lightweight	Bariatric	Standing	Specialized
Current Number	600,000	400,000	200,000	50,000	5,000	100,000
Trend	Level	Slow Growth	Moderate Growth	Rapid Growth	Slow Growth	Moderate Growth

Depot: Designed for indoor and institutional use.
Lightweight: Designed for individuals who are inactive and who do not require specialized seating.
Ultra-Lightweight: Designed for individuals who independently propel or require features to accommodate their disability.
Bariatric: Designed for individuals who weight more than 250 pounds.
Standing: A wheelchair that holds the occupant in the standing position.
Specialized: Growth chairs, manual tilt and/or recline, manual seat elevation.

Table 2. Current electric powered wheelchair usage and trending.

	Light-weight Indoor Use	Indoor Use and Light Outdoor Use	Active Indoor and Outdoor Use	Electric Powered Scooter	Bariatric	Standing	PAPAW	Special-ized Seating
Current Number	50,000	100,000	100,000	350,000	10,000	5,000	5,000	50,000
Trend	Level	Slow Growth	Moderate Growth	Moderate Growth	Rapid Growth	Slow Growth	Rapid Growth	Rapid Growth

Lightweight Indoor Use: Electric powered wheelchairs designed for primarily for indoor use (e.g., home, assisted living facility).
Indoor Use and Light Outdoor Use: Electric powered wheelchair designed for both indoor and outdoor use in ADA environments in good weather.
Active Indoor and Outdoor Use: Electric powered wheelchair designed for daily use in both indoor and outdoor environments in all kinds of weather. May also be used in on natural surfaces.
Electric Powered Scooter: Three or four wheeled tiller steered electric powered vehicle with a captains style seat intended to provide mobility to an individual with a disability.
Bariatric: An electric powered wheelchair intended to be used by individuals with a body mass in excess of 250 pounds.
Standing: An electric powered wheelchair that holds the occupant in the standing position.
PAPAW: Pushrim activated power assisted wheelchair.
Specialized Seating: An electric powered wheelchair that includes power seat functions.

As the market changes for wheelchairs, public policy, technical and community standards, and clinical practice will need to change as well. The demand for wheelchairs is likely to continue to grow for the foreseeable future. For the past forty years, the number of people with disabilities has been doubling about every ten years. In addition, as wheeled mobility products get better they become attractive to individuals lower levels of impairment further expanding the market. Medical care should continue to improve further increasing the number of people who could benefit from wheeled mobility.

VI. Impact of Wheeled Mobility Devices on Architecture

Despite the growing number of individuals who rely upon wheelchairs every year, very few studies have been undertaken to collect data describing the actual driving behavior of wheelchair users and their participation in everyday and social activities. Most studies have used self-report survey methods or laboratory-based testing, rather than portable instrumentation. [72] Lab-based data collection does not necessarily reflect how wheelchair users drive chairs in their daily lives, and questionnaire and interview methods are error prone due to omission of trips or trip elements, illegible handwriting, and key entry errors etc. This information is critical as an objective guide for designing wheelchairs and wheelchair components, battery design and specification for power wheelchairs, studying risk exposure (e.g. risk of injury because of component failure), and examining quality of life in wheelchair users.

While propelling a wheelchair, users encounter obstacles such as bumps, curb descents, and uneven driving surfaces. These obstacles cause vibrations on the wheelchair and in turn, the wheelchair user, which through extended exposure can cause low-back pain, disc degeneration and other harmful effects to the body [73]. The International Standards Organization (ISO) and the American National Standards Institute developed a standard for whole-body vibration measurement. It includes the amplitudes of vibrations that are considered harmful and the exposure times for vibrations to be dangerous. The standard also discusses some of the physical effects that can occur from whole-body vibration exposure [74]. To date, little research has been conducted to assess the vibrations experienced by wheelchair users. Van Sickle et al. recorded the forces when using the ANSI/RESNA standards double drum and curb drop tests and compared them to the road loads during ordinary propulsion [75]. Van Sickle et al. also showed that wheelchair propulsion produces vibration loads that exceed the ISO 2631-1 standards at the seat of the wheelchair as well as the head of the user [76]. DiGiovine et al. showed that users prefer ultra-light wheelchairs to lightweight wheelchairs while traversing a simulated road course in higher comfort level and better ergonomics [77]. DiGiovine et al. examined the relationship between the seating systems for manual wheelchairs and the vibrations experienced, showing differences in how seating systems transmit or dampen vibrations.[78] Based on the exposure magnitudes of vibrations defined in the ISO-2631 standard, wheelchair companies added suspension to their wheelchairs to reduce the level of vibrations that are transmitted to wheelchair users.

Cooper et al. found that in the natural frequency of humans (4-15 Hz) the addition of suspension caster forks do reduce the amount of vibrations transferred to the user [79]. Wolf et al. have shown that suspension manual wheelchairs are approaching significance in reducing the amount of shock vibrations transmitted to wheelchair users during curb descents [80]. Kwarciak et al. revealed that although suspension manual wheelchairs visually reduce shock vibrations the chairs are not yet ideal, possibly due to the orientation of the suspension elements [81]. Wolf et al. and Dobson et al. conducted an evaluation of the vibration exposure during electric powered wheelchair driving and manual wheelchair propulsion over six selected sidewalk surfaces [82], [83]. When treating the poured concrete sidewalk as the normative standard, all of the surfaces compared most favorably in terms of shock and vibration exposure with the exception of the (1/4″) beveled edge interlocking concrete surface, which produced mixed results.

New advances in wheelchairs are likely to have some interesting effects on the built environment. For example, devices like the PAPAW and IBOT are designed to provide people with greater access to the built environment and to overcome the barriers that persist in confronting wheelchair users. Other devices, for example bariatric wheelchairs, require much more space than is accommodated by current architecture or city planning. Special consideration may be required for bariatric wheelchair users, especially within healthcare facilities. Smart wheelchairs should expand the population of wheelchair users moving independently throughout the community. Potentially, people who are mobility and visually impaired will have greater community mobility. This may necessitate changes in architecture and public space design. With the exception of bariatric products, the trend in wheelchairs and other wheeled mobility products is to make them more capable in the community.

VII. Transportation Issues Associated with Wheelchair Use

Transportation has been identified as one of the most significant barriers to employment and full community participation by wheelchair users. For individuals who can drive a private vehicle, the most significant issues are the cost of vehicle modifications, the lack of widely acceptable and versatile securement systems, the need for consensus on restraint placement and easily usable restraints, and lift or kneeling systems that are reliable and simple to operate. The only probable of means of making the necessary changes to accessible vehicle design for wheelchair users is to form a consortium of wheelchair transportation engineers, automobile manufacturers, insurers, wheelchair users, wheelchair modification manufacturers, and appropriate government agencies. Much of the problem lies in the disassociation between wheelchair manufacturers, automobile manufacturers, and manufacturers of vehicle modifications. Some of the lack of cooperation seems to stem from liability concerns, but market pressures and public perceptions certainly play a role as well. Federal standards certainly provide a step in the right direction, but there are several examples of products being provided that are not in compliant with standards, and by and large the standards are voluntary with few consequences for noncompliance. The new products being developed will likely only complicate vehicle modifications to facilitate transportation in a privately owned motor vehicle. On the other hand, wheelchair designs seem to be moving in a direction where more people will be able to transfer into the automobile seat and load the wheelchair into their motor vehicle. However, the individual will need the ability to transfer from their wheelchair to the motor vehicle in order to take advantage of the compact or flexible design advances in wheelchairs or scooters.

Public transportation provides entirely different opportunities and challenges for wheelchair users. In areas where reliable and efficient public transportation is available, it can be a convenient and effective means of getting around. However, many wheelchair users object to bus drivers invading their personal space when attaching securement systems or personal restraints. Drivers complain of the difficulty in securing wheelchairs into their buses, and the time that it takes often aggravating other passengers and delaying their schedules. In practice, securement systems are frequently not used on buses or the drivers simply make excuses as to why the wheelchair using passenger can not be transported. Securement in public buses is orders of magnitudes more complex than for private vehicles due to the lack of agreement on a standardized attachment point or even the need for securement of the wheelchair in a bus. Shaw et al. showed that in a survey of wheelchair related accidents between 1988 and 1996, about 0.3 percent (170 incidents) involved a wheelchair aboard a motor vehicle. [84] Only

6 percent of the accidents involving a wheelchair in a motor vehicle were the results of the collision, and in no cases did people receive injuries severe enough to require hospitalization. Further analysis of the data indicated that school and public buses were the safest form of transportation for wheelchair users. Most of the risk associated with injury while in a public transportation system is related to tips, falls or undesired movements during vehicle maneuvers that may result in injury to the wheelchair user or other passengers. An approach that contains the wheelchair and user within a limited area of the bus or large transit area may be the most reasonable approach. This would also likely accommodate the changes and advances taking place in wheelchair design.

VIII. Summary and Conclusion

The emergence of advanced mobility devices shows promise for the contribution of engineering to the amelioration of mobility impairments for millions of people who have disabilities or who are elderly. The application of advances in power electronics, telecommunications, controls, sensors, and instrumentation have really only just scratched the surface. Advancing mobility technology for people with disabilities and people who are elderly represents a significant career and business opportunity for engineers who want to serve the public good in a meaningful and tangible way. In other areas, manufacturers of mobility devices are increasing the use of manufacturing technologies to reduce product line complexity. Recent examples include use of molded plastic shrouds, expanded use of outsourcing, and globalization of original equipment suppliers. It also appears that the market is going to experience another period of consolidation, with companies with funds purchasing new technologies through acquisition of smaller companies during this period of economic downturn. The United States and Europe appear to be the regions with the most potential for economic growth in mobility products, while Asia seems the likely focus of future outsourcing to reduce production costs. The growth of some companies (e.g., Invacare), and the introduction of large companies (e.g., Johnson & Johnson, Yamaha Motor Corporation) are likely to change the business of producing wheelchairs. It is likely that wheelchair manufacturing will begin to mirror the automotive and computer industries. Wheelchair manufacturers will probably begin to focus more on the development of new designs and sub-system specifications for their suppliers. The large manufacturers will then assemble and test the final wheeled mobility products.

Based upon our review of the literature, our estimations of market trends, and information provided by consumer groups, manufacturers and suppliers, we were able to identify the following areas for further investigation or product development:

- Research focused on reducing the incidence of secondary conditions (e.g., upper extremity pain, de-conditioning, vibration/shock exposure) associated with long-term wheelchair user.
- Research focused on determining the actual usage patterns of wheelchairs (i.e., what are the exposure rates to hazards, where are wheelchairs used, how frequently are wheelchairs used). The impact of the built environment on mobility and activity needs to be studied.
- Improved outcomes measures to enhance the provision of wheelchairs and to determine who benefits most from existing and emerging technologies.

- Epidemiological and market data are needed to reduce the error in current data to more accurately direct research and development.
- Mobility technology development that accommodates people with severe and/or multiple disabilities to live comfortably, effectively, and as independently as possible in the community.
- Mobility technology to address the needs of emerging or rapidly growing groups of wheelchair users (e.g., active elderly, obese individuals, people with multiple sclerosis).
- Research to support technological standards, architecture and community standards, and clinical practice guidelines.
- Research and development to incorporate technologies and manufacturing techniques from other fields (e.g., rapid prototyping, computer simulation, robotic manufacturing, digital signal processing, robust controls).
- Research and development to improve the safety of wheelchair users during a wide-range of activities (e.g., prevention of tips-and-falls, safety when using wheelchairs as a seat in a motor vehicle, safety when using a wheelchair as a seat in public transportation).

There appears to be a steady advance in wheelchairs despite the restrictions imposed by insurance providers. Some changes result in costs savings, whereas others are expanding the capabilities of the user. Some of the trends in wheelchairs are going to require new service delivery mechanisms, changes to public policy, and certainly greater coordination between consumers, policy makers, manufacturers, researchers, and service providers.

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Appendix C

Tweels™ Addressing Documented Unmet Needs in the Wheeled Mobility Market

T2RERC

Tweels™ Addressing Documented Unmet Needs in the Wheeled Mobility Market

The Technology Transfer Rehabilitation Engineering Research Center (T^2RERC) is a federally funded organization whose mission is to introduce new and unique technologies into the assistive technology marketplace. In 1999 the T^2RERC began work on a project focused on the U.S. Wheeled Mobility industry.

In order to determine consumer needs that were not being met by available products, the T^2RERC called upon the expertise of knowledgeable individuals within the wheeled mobility industry. Manufacturers, technology developers, and leading researchers were formally interviewed to determine the highest priority unmet needs in this industry. These experts were then joined by informed consumers and caregivers to take part in a set of focus groups discussing wheelchair materials and components, as they relate to the needs identified in the preceding interviews. The T^2RERC used the information captured from the focus groups to develop a problem statement that details the needs and wants of wheelchair users, based on the opinions of all experts involved in the process. The following is the Tires/Wheels Problem Statement generated by the T^2RERC's 1999 Stakeholder Forum. The Michelin Tweel™ meets or exceeds nearly every need outlined by the aforementioned problem statement. The chart following the Problem Statement displays Tweel™ performance and material characteristics (bullet points) as they relate to the defined needs (bolded headings).

Tires/Wheels

Statement of the Problem

There is a need for improved tire wear without compromising ride and traction. Tires must be functional on varied surfaces - sand, rugs, snow, and smooth and rough surfaces - and must be non-marking. Tires should allow discharge of static electricity to prevent shocks to the user and damage to the electronics associated with power chairs. At the same time, tires and wheels should be light and inexpensive. In a 1994 study related to power wheelchairs, users reported that tires were the second most frequent repair behind batteries. Wheels have yearly maintenance problems 24% of the time. Although significant research has had a positive impact on manual wheelchair tires, little advancement has occurred with power chairs tires. This problem stems from the varied wheel diameter and the design and performance parameters associated with power chairs. Also, power wheelchairs introduce much larger stresses on the wheels and tires than manual chairs due their heavier loads.

Current Solutions

Common materials used include rubber, urethane, polyurethane, composite nylons, and kevlar-reinforced thin tubes. Research is in process on solid polyurethane foam tires, which combine the best features of the pneumatic (comfort, low rolling resistance) and solid tires (low maintenance). These materials have a microcellular structure that reduces weight while maintaining wear and rider comfort. One problem with the new solid tire designs is the tendency for the tire to become unseated from the rim. Radial tires, semi-pneumatic designs, and inserts are also being researched.

Issues to Consider

In the area of tire and wheel performance, the main issues are reliability and durability without losing comfort and safety. Pneumatic tires provide great comfort but are a potential inhibitor of independent living, due to flat tire etc. The goal is to achieve the comfort level offered by pneumatic tires along with the reliability and durability offered by solid tires. Increase in durability will also provide economic relief to the end-user. At present, power wheel chair tires cost almost $100. This is a big expenditure considering that present tires have a short life span and are therefore replaced quite frequently. There is a need to innovate or use materials and design that can bring down the cost of the tire, increase the durability of the tire while maintaining reliability and comfort level. And most importantly, tires should be non-marking. Black tires meet most of the requirements of an ideal tire but suffer from the big disadvantage that they are marking and are therefore not used in the industry.

- Are the problem of static charge build up and durability more critical to the power wheelchair industry than manual wheelchair industry?
- Are the newer solid urethane and polyurethane foam tires meeting users' needs adequately? If not, why not?

An issue relating to wheel improvement brings into question if it is beneficial to reduce the wheel weight for power chairs. Spoke wheels perform well but requires a lot of maintenance. Probably an ideal wheel will be one that has the weight and power of spoke wheels, while the cost and maintenance of plastic wheels. A misaligned wheel requires a lot more effort to push. It is frame structure that mainly controls wheel alignment. For manual wheelchairs, wheels should require minimum effort to push. Technology innovation, like geared hub wheels, is required to make the wheels easier to push. Though considerable improvements have been done in the wheel bearing, it is still a high maintenance item. Further improvement is required in this field.

- For power chairs, is weight irrelevant? Is the goal for wheel materials to merely match the weight and strength of spoke wheels but improve in the area of cost and maintenance?
- Wheel misalignment affects tires wear rate as well as rolling resistance. Is this a serious problem?

In the literature we found articles that cited the major barrier in the area of tires and wheels as the fact that the total market is not large enough to support investment in R&D by traditional tire and wheel manufacturers. Some believe that development of better tires will require government funding for research at universities. Another concept discussed in the literature is that all wheelchair manufacturers should cooperate to develop a specification with a single tire supplier who could then address the industry's problem.

- Is an industry consortia on tires and wheels feasible as a means to develop adequate R&D to meet the industry's needs?
- Are varied customer needs a problem inherent in tire and wheel product selection? Could modularity apply to tires/wheel systems?

Tweel™ Performance and Material Characteristics *(bullet points)* Relating to the Defined Needs *(bolded headings)*

Performance Aspects
Offer rider comfort (adequate shock absorption) • Higher shock load energy absorption than equivalent pneumatic tires • Decreased weight of tires (as compared to foam filled pneumatic alternatives) • Elimination of suspension components decreases weight to increases ease of propulsion and/or range
Low turning resistance • Improved obstacle avoidance performance due to compliant nature of the wheel
Smooth and quiet ride • Improved stability due to assembly compliances allowing for all wheels to be in contact with the ground on less than smooth surfaces • Eliminates "caster chatter/shudder" at high speeds • Auto-aligning properties improve handling
Maintenance free (self cleaning; puncture proof) • Self cleaning as debris are removed due to dynamic spoke architecture • Puncture proof • No pressure to monitor; can not be over or under inflated
Capable of some motion even in damaged state • Very capable of motion in a damaged state due to novel architecture and dynamic performance
Low rolling resistance • Possesses the potential to reduce rolling resistance - further testing is required
High traction on all surfaces • Currently performs nearly as well as pneumatic tires on soft soil surfaces
Material Properties
Durable - to enable at least 1000 miles between service (1 year of typical use) • 3 to 4 times more durable in heavy wear circumstances than its pneumatic counterpart • Can handle severe deflections (bumps and potholes) without damage
Non-marking • Non-marking
Be electrically conductive to eliminate static charge buildup • Conductive material eliminates static charge buildup
Offer sidewalls with high coefficient of friction for gripping • Eliminated sidewalls in favor of a vane spoke structure to increase durability
Be functional in all season environments (traction and durability should be maintained in hot and cold) • Functional in all seasons and environments. • Potential for improved off-pavement performance

Appendix D

T^2 Project Overview

T²RERC

REHABILITATION ENGINEERING RESEARCH CENTER ON TECHNOLOGY TRANSFER

Who we are...

The Rehabilitation Engineering Research Center on Technology Transfer (T^2RERC) is a funded project of the National Institute on Disability and Rehabilitation Research (NIDRR) of the U.S. Department of Education. The T^2RERC is charged with looking at the unmet needs of end users and industry in the assistive technology marketplace and searching the scientific and technology infrastructure to find the technology to meet those needs.

Our Mission Statement is: “The T^2RERC advances methods, technologies, and products, through collaboration with all stakeholders, to improve assistive technology devices and services. The goal is to improve the quality of life for people with disabilities through new or improved assistive technology devices.”

The T^2RERC has three primary objectives: 1) advance the methods of technology transfer through research projects, 2) transfer technologies into products through development projects, and 3) facilitate the commercialization of new and improved assistive devices through utilization projects.

We accomplish these three objectives through collaborations with academic, industrial, consumer, and government stakeholders. Facilitating and improving the process of technology transfer requires us to integrate three forms of expertise: a) technical engineering and design, b) market and business analysis, and c) end-user assessments. The T^2RERC is designed to function as an intermediary resource for technology transfer in assistive technology by combining these three forms of expertise within one program.

The T^2RERC is comprised of two organizations. The Center for Assistive Technology, or CAT, at the University at Buffalo, who performs all administrative functions of the grant, undertakes the technical evaluations of devices and technologies, determines their projected refinements and uses in assistive technology, examines a device or technology’s market potential, develops vital marketing information on the device or technology’s marketing segment, and performs the licensing of devices.

The second partner of our organization is the Western New York Independent Living Project, or ILP. This group brings the consumer focus to submitted devices. The ILP has consumers with disabilities evaluate the submitted device through moderated discussions. They then determine the degree of need for the device and evaluate how well the submitted device performs the function for which it is intended. They bring the consumer perspective to bear as to what features and qualities the submitted device may be lacking in order to make it a useful device that truly fulfills the needs of the consumers. Essentially, the results of our Consumer Team’s evaluation tell us of a device’s potential to address a currently unmet or poorly met need in the marketplace

The work performed by these two organizations results in a document package of technical, marketing, and consumer data. For additional information on the mission of the T^2RERC and the services the agencies of this partnership provide, contact James A. Leahy, Co-PI, Project Administrative Officer at jimleahy@buffalo.edu or by telephone at 716-829-3141.