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Trends and Issues in Wheelchair Technologies

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There is an overwhelming need for wheelchairs and the research and development required to make them safer, more effective, and widely available. The following areas are of particular importance: practitioner credentials, accreditation, device evaluation, device user training, patient education, clinical prescribing criteria, national contracts, and access to new technology. 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. Wheelchairs account for about 1% of Medicare spending. Use of assistive technology is an increasingly common way of adapting to a disability. 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. 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.

Key Words: Manual wheelchair—power wheelchair—Bariatric wheelchair—Pushrim-activated power-assist wheelchairs (PAPAW)—Independence 3000 IBOT transporter—Wheelchair usage—Wheelchair transportation—Wheelchair marketplace—Emerging trends

INTRODUCTION

The purpose of this paper is to describe emerging technologies and trends in wheeled mobility and their likely impacts on anthropometry and on design and construction. 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. Last, 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 a perspective on current wheelchair technology and where things might go in the future.

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THE WHEELCHAIR MARKETPLACE

In the United States an estimated 2.2 million people currently use wheelchairs for their daily mobility (U.S. Census Bureau, 2002). Worldwide, an estimated 100–130 million people with disabilities need wheelchairs, though fewer than 10 percent own or have access to one (New Freedom Initiative Act, n.d.). While these numbers are staggering, experts predict that the number of people who need wheelchairs will increase by 22 percent over the next 10 years (U.S. Department of Commerce, 1994). One of the leading causes of traumatic 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 (Bilukha, Brennan, & Woodruff, 2003). There is an overwhelming need for wheelchairs and the research and development required to make them safer, more effective, and widely available (Cooper, 1998a, 1998b). This was pointed out by the U.S. Veterans Health Administration (VHA) Rehabilitation Strategic Healthcare Group, which 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 (Department of Veterans Affairs, 2002b). 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 (Dun and Bradstreet Marketplace, 2003). 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 (CMS, 2003). Scooter sales reached $245 million in 2000, with a sustained growth rate of about 7% (Shalala et al., 1996). This growth has been attributed to the aging baby boomers, growing longevity (an issue facing the rapidly growing aged population), increased incidence of spinal cord injury/dysfunction, and manual wheelchairs users acquiring electric-powered wheelchairs when they start to lose function (Cooper & Axelson, 1997; Cooper, Thorman, et al., 2002; Russell et al., 1997; Schunkewitz, Sprigle, & Chung, 1989). Although this market is crowded with participants, there is little product differentiation, and further consolidation is anticipated (Attali & Pelisse, 2001). Wheelchairs account for about 1% of Medicare spending (Kaye, Kang, & LaPlante, 2000).

The U.S. Department of Veterans Affairs (VA) is the single largest supplier of wheelchairs in the United States at a cost in excess of $20 million annually (Kaye et al., 2000). There are about 25 million veterans in the United States, of whom 75% served in a major conflict (Disabled American Veterans, 2008). About 2.7 million veterans receive disability compensation or pension from the VA. In 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 combinations of using competitive bidding and direct purchase, the VA has been able to control the costs of purchasing medical devices, including assistive devices (Render, Taylor, Plunkett, & Nudent, 2003). 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 wheelchairs and seating systems that require assistance from experts (Department of Veteran Affairs, 2002a).

Use of assistive technology is an increasingly common way of adapting to a disability (Manton, 1989). 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 (Edwards & Jones, 1998). The majority of assistive device users, particularly users of mobility aids, are over age 65 (Gitlin, Levine, & Geiger, 1993). 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 to 1994, the age-adjusted use of wheelchairs increased by 82.6% (George et al., 1988). 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 expansion in design options in wheelchairs in last two decades, including lighter-weight wheelchairs, more functional motorized wheelchairs and scooters, and greater ability to customize the fit of the seat and back to the wheelchair rider (Cooper, 1999).

Individuals who use wheelchairs for mobility typically receive a new wheelchair every three to five years (Cooper, Boninger, & Rentschler, 1999; Cooper, Cooper, & Boninger, 2002; DMERC, 1997; Rehab Specialties, 1998). The cost of a new wheelchair varies from about $100 to $30,000 depending on the complexity of the wheelchair and the degree of impairment of the person (Collins, Cooper, Cooper, & Schmeler, 2002; Fitzgerald, Cooper, Boninger, & Rentschler, 2001). The chances of acquiring a disability increase with age, and most persons aged 75 or older have some form of disabling condition. People over 65 represent about 43% of people with severe disabilities (Department of Veteran Affairs, 2002). 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 (Shalala et al., 1996). The proper selection of the wheelchair and related technology (including cushions) will have substantial socioeconomic costs for the people with disabilities and society (Cooper, 1998a; Fifield & Fifield, 1997; Hobson, 1992; Sprigle & Sposato, 1997). Moreover, the quality of life of the people with disabilities and their families are impacted.

In North America the number of people who are obese is growing at an alarming rate. Obesity is associated with a variety of debilitating diseases and conditions, some of which may lead to the individual requiring a wheelchair for mobility (Paluska, 2002). Unfortunately, individuals who are morbidly obese may require skilled nursing assistance, especially if they require a wheelchair (Kraus, Stoddard, & Gilmartin, 1996). 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 (Sung et al., 2002). 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. One of the most significant mobility challenges faced by 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 and out of their wheelchairs.

Obesity is a severe medical problem affecting one third of the North American population (about 58 million people). Associated with many diseases, obesity results in long-term health risks, increased health care costs, emotional difficulties, and mortality (Frisancho, 1984; Weil et al., 2002). In a 2002 study by Weil et al. [68] 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 (Janssen, van Oers, van der Woude, & Hollander, 1994). 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 (Boninger, Cooper, Baldwin, Shimada, & Koontz, 1999). 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 pushrim-activated power-assisted wheelchairs (PAPAWs). 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.

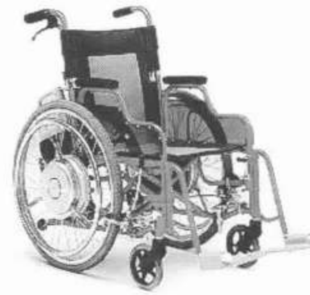

FIG. 1. Power-assist pushrim-activated wheelchair (PAPAW).

EMERGING WHEELED MOBILITY DEVICES

A pushrim-activated power-assisted wheelchair uses motors and a battery to augment the power applied by the users to one or both pushrims during propulsion or braking (Fig. 1) (Cooper et al., 2001). Applying a torque to the pushrim activates the wheelchair. The torque applied to the pushrim is amplified by the motors and gear-train. A microcontroller 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 pushrims (Cooper, Corfman, et al., 2002). A PAPAW is typically assembled by retrofitting an ultralight 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, obesity, insufficient arm strength, or the inability to maintain a posture effective for propulsion (Arva et al., 2001; Corfman, Cooper, Boninger, Koontz, & Fitzgerald, 2003). 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 electric-powered wheelchair is poised to un-

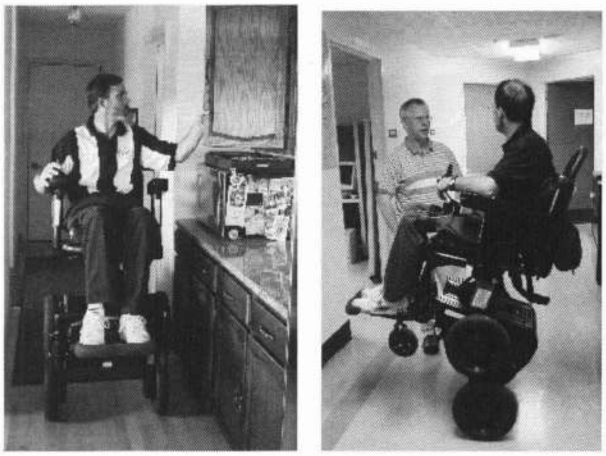

FIG. 2. An IBOT in balance function.

dergo revolutionary design changes. Although 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 (Attali & Pelisse, 2001). Indeed, people with disabilities and people who are elderly are becoming more empowered to insist on 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 becoming 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 intuitive 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 systems to be configured (e.g., wheelbase, track-width, steering interface) for the user and the activity.

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 (Fig. 2). The IBOT incorporates a variety of sensors and actuators for dynamic stabilization of the device, speed control, self-diagnosis, and changing operational functions (Kamen, Ambrogi, & Heinzman, 1999). 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 ensure safe operation. The IBOT command and control computers use a "voting process" (i.e., two out of three computers must agree on 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 download logs to determine whether periodic maintenance is necessary and to upload software changes. Structurally, the IBOT is based on 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 nonuniform surfaces and inclines and to climb curbs. 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 (Fitzgerald et al., 2001). 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. Its greatest strengths are outdoors and in circumstances where there is space to use balance function (Cooper, Boninger, et al., 2003). 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 (Lawn, Sakai, Kuroiwa, & Ishimatsu, 2001). Wellman, Krovi, Kuma, and Harwin (1995) described the investigation into combining the use of robotic legs with a wheeled device to provide increased mobility to people with disabilities. 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 (Jindrich & Full, 2002).

Simpson, Yoder, and Levine have reported on combining obstacle detection and avoidance with an electric-powered wheelchair (Levine et al., 1999; Simpson, Poirot, & Baxter, 2002; Yoder, Baumgartner, & Skaar, 1996). 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.

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 (Public Law 106-117, n.d.). 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 (Cooper et al., 2002). There are rear-wheel, midwheel, and front-wheel-drive electric-powered wheelchairs. 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 (Rados, 2003). However, attempting to acquire performance information from wheelchair manufacturers can be difficult and challenging.

Consumers can get the maximum benefit from their wheelchairs and seating systems by observing a few common rules:

- Use only products that comply with current ANSI/RESNA standards
- Make sure that the wheelchair has been approved by the U.S. Food and Drug Administration
- Read and understand the instructions and labeling, and know for whom the device is appropriate
- Inspect and test equipment prior to use or have it inspected by a certified technician (e.g., ATS or RET)
- Make sure that the wheelchair is properly maintained, serviced, and upgraded
- Avoid using a wheelchair that has malfunctioned, unless repaired and certified for use by a qualified technician (e.g., ATS or RET)
- Avoid using the wheelchair beyond its suggested expiration date or nominal life expectancy.

Two main conclusions can be drawn from 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 (Render et al., 2003), largely because there is a 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 last factor leads insurers to believe that there is widespread fraud and abuse when it comes to assistive technology.

Clinicians and suppliers can help remain current and better assist their clients by following several simple rules:

- Read trade publications and peer-reviewed journals on assistive technology
- Participate in professional meetings and continuing professional education
- Look for labeling changes or alerts from manufacturers and pay particular attention to "boxed" warnings
- Track "Medical and Safety Alerts" from the FDA
- Be aware of product recalls and withdraws: these are typically voluntary by manufacturers and are completed within 6 to 12 months.

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 (Kirby & Ackroyd-Stolarz, 1995). 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 (Cooper et al., 1997). In one study Frank, Ward, Orwell, McCullagh, and Belcher (2000) 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 on 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 (Vitek et al., 2002). More reliable and functional wheelchairs are needed, and they need to accommodate 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 cannot 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 (Regnier, Gordon, & Murakami, 1980; Zimmer & Chappell, 1994). 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 (NHs) 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 (Beck, 2002). Individuals in NHs are likely to use wheelchairs (Pawlson, Goodwin, & Keith, 1986). Wheelchairs serve two main purposes in NHs. Wheelchairs provide individuals with mobility and a means to participate in daily activities and social events. Residents of NHs report their mobility contributes significantly to their quality of life and feelings of well-being (Bourret, Bernick, Cott, & Kontos, 2002). In addition, wheelchairs assist NH staff in caring for residents who commonly have physical impairment, poor mobility, or 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 (Noseworthy, Lucchinetti, Rodriguez, & Weinshenker, 2000). Aronson (1997) found that reduced mobility was associated with reduced quality of life. Despite the connection between quality of life in multiple sclerosis and mobility, there is virtually no information available to guide decision making for mobility interventions in this population (Fay & Boninger, 2002). 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.

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 a 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 on the information reviewed, and our experience providing clinical services and working with various manufacturers and suppliers (including the review of annual reports and payer databases), 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.

As the market changes for wheelchairs, public policy, technical and community standards, and

TABLE 1. Current manual wheelchair usage by category and trending

	Depot[a]	Lightweight[b]	Ultra-lightweight[c]	Bariatric[d]	Standing[e]	Specialized[f]
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

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

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 40 years, the number of people with disabilities has been doubling about every 10 years. In addition, as wheeled mobility products get better they become attractive to individuals with 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.

IMPACT OF WHEELED MOBILITY DEVICES ON ARCHITECTURE

Despite the growing number of individuals who rely on 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 (Cooper, Thorman, et al., 2002; Mills et al., 2002). CE 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 because of omission of trips or trip elements, illegible handwriting, and key entry errors. 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 wheel-

TABLE 2. Current electric-powered wheelchair usage and trending

	Lightweight indoor use[a]	Indoor use and light outdoor use[b]	Active indoor and outdoor use[c]	Electric-powered scooter[d]	Bariatric[e]	Standing[f]	PAPAW[g]	Specialized seating[h]
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

[a] Lightweight indoor use: Electric-powered wheelchairs designed for primarily for indoor use (e.g., home, assisted living facility).

[b] Indoor use and light outdoor use: Electric-powered wheelchair designed for both indoor and outdoor use in ADA environments in good weather.

[c] 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.

[d] Electric-powered scooter: Three-or-four-wheeled tiller-steered electric-powered vehicle with a captain's style seat intended to provide mobility to an individual with a disability.

[e] Bariatric: An electric-powered wheelchair intended to be used by individuals with a body mass in excess of 250 pounds.
[f] Standing: An electric-powered wheelchair that holds the occupant in the standing position.
[g] PAPAW: Pushrim-activated power-assisted wheelchair.
[h] Specialized seating: An electric-powered wheelchair that includes power seat functions.

chair user, which through extended exposure can cause low-back pain, disk degeneration, and other harmful effects to the body (Nishiyama et al., 1998). 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 (Seidel et al., 1986). To date, little research has been conducted to assess the vibrations experienced by wheelchair users. Van Sickle et al. (2001) 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. Van Sickle et al. (2000) 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. DiGiovine et al. (2000a) showed that users prefer ultra-light wheelchairs to lightweight wheelchairs while traversing a simulated road course in higher comfort level and better ergonomics. DiGiovine et al. (2000b) examined the relationship between the seating systems for manual wheelchairs and the vibrations experienced, showing differences in how seating systems transmit or dampen vibrations. 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 does reduce the amount of vibrations transferred to the user (Cooper, Wolf, et al., 2003). 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 (Wolf, Cooper, & Kwarciak, 2002). Kwarciak, Cooper, and Wolf (2002) revealed that although suspension manual wheelchairs visually reduce shock vibrations the chairs are not yet ideal, possibly because of the orientation of the suspension elements. Wolf, Cooper, Dobson, Fitzgerald, and Ammer (2003) and Dobson et al. (2003) conducted an evaluation of the vibration exposure during electric-powered wheelchair driving and manual wheelchair propulsion over six selected sidewalk surfaces (Dobson et al., 2003; Wolf et al., 2003). 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 (¼″) 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, such as 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 health care 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.

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 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 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 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 because of 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 (Bertocci, Souza, & Szobota 2003). 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.

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 has 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 on our review of the literature, 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, deconditioning, vibration/shock exposure) associated with long-term wheelchair use
- 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), but 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).

The areas are in agreement with many of the recommendations of an expert panel of the Interagency Council on Disability and Rehabilitation (n.d.).

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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REFERENCES

Aronson, K. J. (1997). Quality of life among persons with multiple sclerosis and their caregivers. *Neurology, 48*(1), 74–80.

Arva, J., Fitzgerald, S. G., Cooper, R. A., Boninger, M. L., Spaeth, D. M., & Corfman, T. J. (2001). Mechanical efficiency and user power reduction with the JWII pushrim activated power assisted wheelchair. *Medical Engineering and Physics, 23*(12), 699–705.

Attali, X., & Pelisse, F. (2001). Looking back on the evolution of electric wheelchairs. *Medical Engineering and Physics, 23,* 735–743.

Beck, L. B. (2002). Rehabilitation Strategic Healthcare Group Report.

Bertocci, G. E., Souza, A. L., & Szobota, S. (2003). The effects of wheelchair-seating stiffness and energy absorption on occupant frontal impact kinematics and submarining risk using computer simulation. *Journal of Rehabilitation Research and Development, 40*(2), 125–130.

Bilukha, O. O., Brennan, M., & Woodruff, B. A. (2003). Death and injury from landmines and unexploded ordnance in Afghanistan. *Journal of the American Medical Association, 290*(5), 650–653.

Boninger, M. L., Cooper, R. A., Baldwin, M. A., Shimada, S. D., & Koontz, A. (1999). Wheelchair pushrim kinetics: Weight and median nerve function. *Archives of Physical Medicine and Rehabilitation, 80*(8), 910–915.

Bourret, E. M., Bernick, L. G., Cott, C. A., & Kontos, P. C. (2002). The meaning of mobility for residents and staff in long-term care facilities. *Journal of Advanced Nursing 37*(4), 338–345.

CMS. (2003, June). Power wheelchair coverage overview. Center for Medicare and Medicaid Services. Retrieved August 17, 2003, from http://www.cms.hhs/medlearn/PowerWheelchair.pdf

Collins, D., Cooper, R., Cooper, R. A., & Schmeler, M. (2002). Strengthening justification for assistive technology with research findings: A case study. *RESNA News, spring,* 1.

Cooper, R. A. (1998a). Wheelchair research and development for people with spinal cord injury: Guest editorial. *Journal of Rehabilitation Research and Development, 35*(1), xi.

Cooper, R. A. (1998b). *Wheelchair selection and configuration.* New York: Demos Medical Publishers.

Cooper, R. A. (1999). Engineering Manual and electric powered wheelchairs. *Critical Reviews in Biomedical Engineering, 27*(1–2), 27–74.

Cooper, R. A., & Axelson, P. W. (1997). Powered to perform. *Home Health Care Dealer, 9*(3), 49–56.

Cooper, R. A., Boninger, M. L., Cooper, R., Dobson, A. R., Schmeler, M., Kessler, J., et al. (2003). Technical perspectives: Use of the Independence 3000 IBOT transporter at home and in the community. *Journal of Spinal Cord Medicine, 26*(1), 79–85.

Cooper, R. A., Boninger, M. L., & Rentschler, A. (1999). Evaluation of selected ultralight manual wheelchairs using ANSI/RESNA standards. *Archives of Physical Medicine and Rehabilitation, 80*(4), 462–467.

Cooper, R. A., Cooper, R., & Boninger, M. L. (2002). 20 years and still going strong: 20th annual survey of lightweight wheelchairs. *Sports 'N' Spokes, 28*(2), 35–45.

Cooper, R. A., Corfman, T. A., Fitzgerald, S. G., Boninger, M. L., Spaeth, D. M., Ammer, W., et al. (2002). Performance assessment of a pushrim activated power assisted wheelchair. *IEEE Transactions of Control Systems Technology, 10*(1). 121–126.

Cooper, R. A., Fitzgerald, S. G., Boninger, M. L., Prins, K., Rentschler, A. J., Arva, J., et al. (2001). Evaluation of a pushrim activated power assisted wheelchair. *Archives of Physical Medicine and Rehabilitation, 82*(5), 702–708.

Cooper, R. A., Gonzales, J., Lawrence, B., Renschler, A., Boninger, M. L., & VanSickle, D. P. (1997). Performance of selected lightweight wheelchairs on ANSI/RESNA tests. *Archives of Physical Medicine and Rehabilitation, 78,* 1138–1144.

Cooper, R. A., Thorman, T., Cooper, R., Dvorznak, M. J., Fitzgerald, S. G., Ammer, W., et al. (2002). Driving characteristics of electric powered wheelchair users: How far, fast, and often do people drive? *Archives of Physical Medicine and Rehabilitation, 83*(2), 250–255.

Cooper, R. A., Wolf, E., Fitzgerald, S. G., Boninger, M. L., Ulerich, R., & Ammer, W. A. (2003). Seat and footrest accelerations in manual wheelchairs with and without suspension. *Archives of Physical Medicine and Rehabilitation, 84*(1), 96–102.

Corfman, T. A., Cooper, R. A., Boninger, M. L., Koontz, A. M., & Fitzgerald, S. G. (2003). Range of motion and stroke frequency differences between manual wheelchair propulsion and pushrim activated power assisted wheelchair propulsion. *Journal of Spinal Cord Medicine, 26*(2), 135–140.

DiGiovine, M. M., Cooper, R. A., Boninger, M. L., Lawrence, B. L., Van Sickle, DP & Rentschler, AJ. (2000a). User assessment of manual wheelchair ride comfort and ergonomics. *Archives of Physical Medicine and Rehabilitation, 81,* 490–494.

DiGiovine, C. P., Cooper, R. A., Wolf, E. J., Hosfield, J., & Corfman, T. (2000b). Analysis of vibration and comparison of four wheelchair cushions during manual wheelchair propulsion. *Proceedings of the RESNA 2000 Annual Conference,* 242–244.

Disabled American Veterans. 2008. Retrieved March 3, 2008, from http://www.dav.org

Dobson, A., Cooper, R. A., Wolf, E., Fitzgerald, S. G., Ammer, W. A., Boninger, M. L., & Cooper, R. (2003). Evaluation of vibration exposure of power wheelchair users over selected sidewalk pavement surfaces. *Proceedings of the RESNA 2003 Annual Conference.*

Dun and Bradstreet Marketplace. (2003, January–March). Accessed January 3, 2003, through subscription services.

Durable Medical Equipment Regional Carrier (DMERC). (1997). Region D supplier manual. CIGNA Health Care.

Edwards, N. I., & Jones, D. A. (1998). Ownership and use of assistive devices amongst older people in the community. *Age & Ageing, 27*(4), 463–468.

Fay, B. T, & Boninger, M. L. (2002). The science behind mobility devices for individuals with multiple sclerosis. *Medical Engineering and Physics, 24*(6), 375–383.

Fifield, M. G., & Fifield, M. B. (1997). Education and training individuals involved in delivery of assistive technology devices. *Technology and Disability, 6,* 77–88.

Fitzgerald, S. G., Cooper, R. A., Boninger, M. L., & Rentschler, A. J. (2001). Comparison of fatigue life for three types of manual wheelchairs. *Archives of Physical Medicine and Rehabilitation, 82*(10), 1484–1488.

Frank, A. O., Ward, J., Orwell, N. J., McCullagh, C., & Belcher, M. (2000). Introduction of a new NHS electric-powered indoor/outdoor chair (EPIOC) service: Benefits, risks and implications for prescribers. *Clinical Rehabilitation, 14,* 665–673.

Frisancho, A. R. (1984). New standards of weight and body composition by frame size and height for assessment of nutritional status of adults and the elderly. *American Journal of Nutrition, 40,* 808–819.

George, J., Binns, V. E., Clayden, A. D., & Mulley, G. P. (1988). Aids and adaptations for the elderly at home: underprovided, underused, and undermaintained. *British Medical Journal, 296*(6633), 1365–1366.

Gitlin, L. N., Levine, R., & Geiger, C. (1993). Adaptive device use by older adults with mixed disabilities. *Archives of Physical Medicine and Rehabilitation, 74*(2), 149–152.

Hobson, D. (1992). Comparative effects of posture on pressure and shear at the body seat interface. *Journal of Rehabilitation Research and Development, 29*(4), 21–31.

Interagency Council on Disability and Rehabilitation. n.d. Overview of NIDRR's Long Range Plan. Retrieved March 3, 2008, from http://www.ncddr.org/new/announcements/lrp/fy2005-2009/index.html

Janssen, T. W., van Oers, C. A., van der Woude, L. H., & Hollander, A. P. (1994). Physical strain in daily life of wheelchair users with spinal cord injuries. *Medicine & Science in Sports & Exercise, 26*(6), 661–670.

Jindrich, D. L., & Full, R. J. (2002). Dynamic stabilization of rapid hexapedal locomotion. *Journal of Experimental Biology, 205,* 2803–2823.

Kamen, D., Ambrogi, R., & Heinzman, R. (1999). U.S. Patent 5,975,225. November 2.

Kaye, H. S., Kang, T., & LaPlante, M. P. (2000). Mobility device use in the United States. Disability Statistics Report no. 14. National Institute on Disability and Rehabilitation Research, U. S. Dept. of Education, June 2000, http://dsc.ucsf.edu/pdf/report14.pdf

Kirby, R. L., & Ackroyd-Stolarz, S. A. (1995). Wheelchair safety-adverse reports to the United States Food and Drug Administration. *American Journal of Physical Medicine & Rehabilitation, 74,* 308–312.

Kraus, L. E., Stoddard, S., & Gilmartin, D. (1996). Chartbook on disability in the United States. U.S. Department of Education report no. H133D50017. Washington, DC: National Institute on Disability and Rehabilitation Research.

Kwarciak, A. M., Cooper, R. A., & Wolf, E. (2002). Effectiveness of rear suspension in reducing shock exposure to manual wheelchair users during curb descents. *Proceedings of the RESNA 2002 Annual Conference,* 365–367.

Lawn, M., Sakai, T., Kuroiwa, M., & Ishimatsu, T. (2001). Development and practical application of a stair-climbing wheelchair in Nagasaki. *International Journal of Human-Friendly Welfare Robotic Systems, 2* (2), 33–39.

Levine, S., Bell, D., Jaros, L., Simpson, R., Koren, Y., & Borenstein, J. (1999). The NavChair assistive wheelchair navigation system. *IEEE Transaction on Rehabilitation Engineering, 7*(4), 443–451.

Manton, K. G. (1989). Epidemiological, demographic, and social correlates of disability among the elderly. *Milbank Quarterly, 67*(Suppl. 2, Part 1), 13–58.

Mills, T., Holm, M. B., Trefler, E., Schmeler, M., Fitzgerald, S., & Boninger, M. (2002). Development and consumer validation of the Functional Evaluation in a Wheelchair (FEW) instrument. *Disability and Rehabilitation, 24*(1–3), 38–46.

New Freedom Initiative Act. (n.d.). Accessed March 3, 2008, from http://www.whitehouse.gov/news/freedominitiative/freedominitiative.html

Nishiyama, K., Taoda K. & Kitahara T. (1998). A decade of improvement in whole-body vibration and low back pain fro freight container tractor drivers. *Journal of Sound and Vibration, 215,* 635–642.

Noseworthy, J. H., Lucchinetti, C., Rodriguez, M., & Weinshenker, B. G. (2000). Multiple sclerosis. *New England Journal of Medicine, 343*(13), 938–952.

Paluska, S. A. (2002). The role of physical activity in obesity management. *Clinics in Family Practice, 4*(2).

Pawlson, L, Goodwin, M., & Keith, K. (1986). Wheelchair use by ambulatory nursing home residents. *American Geriatrics Society, 34*(12), 860–864.

Public Law 106-117. n.d. Millennium Act. Available at http://www.doi.gov/budget/2001/data pdf/p1106 377.pdf

Rados, C. (2003). FDA works to reduce preventable medical device injuries. *FDA Consumer, July–August,* 29–33.

Regnier, V., Gordon, S., & Murakami, E. (1980). How neighborhood characteristics affect travel patterns. Washington, DC: U.S. Department of Transportation.

Rehab Specialties/Wheelchair Documentation. (1998). Continuing Education Workshop. Health Care Financing Administration. Fall.

Render, M. L., Taylor, P., Plunkett, J., & Nudent, G. N. (2003). Methods to estimate and compare VA expenditures for assistive devices to Medicare payments. *Medical Care, 41*(6), 70–79.

Russell, J. N., Hendershot, G. E., LeClere, F., & Howie, L. J. (1997). Trends and differential use of assistive technology devices: United States, 1994. *Advance Data 1997, 292* (Nov.), 1–9.

Schunkewitz, J., Sprigle, S., & Chung, K. C. (1989). The effect of postural stress on lower limb blood flow in SCI persons. *Proceedings of the RESNA 1989 Annual Conference,* 77–78.

Seidell, J. C, Bakx, J. C., De Boer, E., Deurenberg, P., & Hautvast, J. G. A. J. (1985). Fat distribution of overweight person in relation to morbidity and subjective health. *International Journal of Obesity, 9,* 363–374.

Seidel, H., & Heide, R. (1986). Long term effects of whole-body vibration: A critical review of the literature. *International Archives of Occupational Environmental Health, 58,* 1–26.

Shalala, D. E., Vladeck, B. C., Wolf, L. F., et al. (1996). *Health care financing review: Statistical supplement,* Table 57, 320–1.

Simpson, R. C., Poirot, D., & Baxter, F. (2002). The Hephaetstus smart wheelchair system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 10*(2), 118–122.

Sprigle, S., & Sposato, B. (1997). Physiologic effects and design considerations of tilt and recline wheelchairs. *Orthopedic Physical Therapy Clinics of North America, 6*(1), 99–122.

Sung, R. Y. T., Yu, C. W., Chang, S. K. Y., Mo, S. W., Woo, K. S., & Lam, C. W. K. (2002). Effects of dietary intervention and strength training on blood lipid level in obese children. *Archives of Disease in Childhood, 86*(6), 407–410.

U.S. Census Bureau. (2002). Available at: http://www.census.gov.hhes/www/disability/disability.html

U.S. Department of Commerce. (1994). Americans with Disabilities, Bureau of the Census Statistical Brief, SB/94-1, January. Washington, DC: U.S. Department of Commerce.

U.S. Department of Veterans Affairs. (2002a). Capital asset realignment for enhanced services. VSO Planning Initiatives Briefing, November 21. Washington, DC: Government Printing Office.

U.S. Department of Veteran Affairs. (2002b). Facts about the Department of Veterans Affairs. Retrieved March 2002, from http://www1.va.gov/opa/fact/vafacts.asp

Van Sickle, D., Cooper, R. A., & Boninger, M. L. (2000). Road loads acting on manual wheelchairs. *IEEE Transactions, 8*(3), 371–384.

Van Sickle, D., Cooper, R. A. & Boninger, M. L. (2001). Analysis of vibrations induced during wheelchair propulsion. *Journal of Rehabilitation Research and Development,* 38, 409–421.

Vitek, M. J., Cooper, R. A., Duncan, J. P., Ammer, W. A., Algood, D., Fitzgerald, S. G., et al. (2002). Durability and value of powered wheelchairs. *Proceedings of the RESNA 2002 Annual Conference,* 321–323.

Weil, E., Wachterman, M. M., McCarthy, E. P., Davis, R. B., O'Day, B., Iezzoni, L. I., et al. (2002). Obesity among adults with disabling conditions. *Journal of the American Medical Association, 208*(10), 1265–1268.

Wellman, P., Krovi, W., Kuma, V., & Harwin, W. (1995). Design of a wheelchair with legs for people with motor disabilities. *IEEE Transaction on Rehabilitation Engineering, 3,* 343–353.

Wolf, E., Cooper, R. A., Dobson, A., Fitzgerald, S. G., & Ammer, W. A. (2003). Assessment of vibrations during manual wheelchair propulsion over selected sidewalk surfaces. *Proceedings of the RESNA 2003 Annual Conference.*

Wolf, E., Cooper, R. A., & Kwarciak, A. (2002). Analysis of whole body vibrations of suspension manual wheelchairs: utilization of the absorbed power method. *Proceedings of the RESNA 2002 Annual Conference,* 303–305.

Yoder, J. D., Baumgartner, E. T., & Skaar, S. B. (1996). Initial results in the development of a guidance system for a powered wheelchair. *IEEE Trans. Rehabilitation Engineering, 4*(3), 143–151.

Zimmer, Z., & Chappell, N. L. (1994). Mobility restriction and the use of devices among seniors. *Journal of Aging and Health, 6*(2), 185–208.