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Intelligent walkers for the elderly: Performance and safety testing of VA-PAMAID robotic walker

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Abstract—A walker that could help navigate and avoid collisions with obstacles could help reduce health costs and increase the quality of care and independence of thousands of people. This study evaluated the safety and performance of the Veterans Affairs Personal Adaptive Mobility Aid (VA-PAMAID). We performed engineering tests on the VA-PAMAID to determine safety factors, including stability, energy consumption, fatigue life, and sensor and control malfunctions. The VA-PAMAID traveled 10.9 km on a full charge and avoided obstacles while traveling at a speed of up to 1.2 m/s. No failures occurred during static stability, climatic, or fatigue testing. Some problems were encountered during obstacle climbing and sensor and control testing. The VA-PAMAID has good range, has adequate reaction time, and is structurally sound. Clinical trials are planned to compare the device to other low-technical adaptive mobility devices.

Key words: engineering test, navigational assistance, obstacle avoidance, robotic walker, visual impairment.

INTRODUCTION

A report by the U.S. Census Bureau on Americans with disabilities states that of the 267.7 million noninstitutionalized individuals surveyed, 7.6 million of them have some level of visual impairment [1]. A total of 1.7 million are unable to see and the other 5.9 million have difficulties seeing words and letters. Elderly individuals over the age of 65 accounted for over half of this group. The American Foundation for the Blind reported that approximately 26 percent of all nursing home residents had some level of visual impairment [2]. A study performed by Goodrich found that by the year 2010, over 147,000 veterans will be legally blind and 880,000 veterans will have severe visual impairments [3]. Studies have also shown that visual impairment increases the risk of falls and fractures and therefore also increases the likelihood that an older person will be admitted to a hospital or nursing home [4]. Current mobility devices for the elderly and visually impaired require certain levels of function and dexterity that many do not possess. These statistics underline the need for the research and development of new mobility devices that will reduce limitations and enhance the function of these individuals.

Abbreviations: ANSI/RESNA = American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America, GPS = global positioning system, ISO = International Standards Organization, PAMM = Personal Aid for Mobility and Monitoring, VA-PAMAID = Veterans Affairs Personal Adaptive Mobility Aid.

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The need for effective and interactive assistive mobility devices is becoming more prevalent every year. In the year 2030, 65 million people will be over the age of 65, and by 2050, 15 million people will be over 85 [5]. Fuller found that 33 percent of community-dwelling elderly persons and 60 percent of nursing home residents fall each year [6]. Such falls led to an annual cost of $20.2 billion in 1994 and are predicted to cost close to $32.4 billion by the year 2020 [7]. A walker that could provide both support and navigational assistance while reducing the need for supervision could reduce the cost of care and increase the independence and well-being of thousands of individuals.

Currently, several different computer-based assistive walker devices are being developed. The goal of these devices is to provide the basic support of a traditional walker coupled with the obstacle-avoiding capability of a computer algorithm. Ideally, these devices would function as a normal walker most of the time, but they would provide navigational and avoidance assistance whenever necessary.

The Veterans Affairs Personal Adaptive Mobility Aid (VA-PAMAID) is designed to provide physical support and navigational assistance to visually impaired individuals. Dr. Gerard Lacey developed the prototype walker while at Trinity College in Dublin, Ireland, and is now a part of the company Haptica, which is refining and manufacturing the device [8]. The Department of Veterans Affairs (VA) is working with Haptica to investigate the potential for commercialization of the VA-PAMAID design and technology. The main commercialization efforts will be concentrated toward the end of the study when viable prototypes are available and clinical results can demonstrate its potential usefulness. The sale price for the device has yet to be determined. The VA-PAMAID is built on the design of a basic walker. A computer controls the motors that guide the front wheels of the walker. Laser and ultrasonic sensors are mounted on the front and sides of the walker. These sensors can help to identify obstacles and landmark features, such as junctions and corridors. The user controls the walker through a set of spring-loaded handlebars that are equipped with an encoder that senses the direction in which the user wants to travel. A second set of optical encoders is mounted to the rear wheels and measures the total distance traveled by the device. The walker is 770 mm long, 630 mm wide, and 895 mm in height. The mass of the device is currently 41 kg. **Figure 1** shows the front and side views of the walker.

The VA-PAMAID has three control modes: manual, automatic, and park. In manual mode, the user has control of the walker. Information detected by the sensors is issued as voice messages, describing landmarks and obstacles. The user and the computer share control of the walker in automatic mode. The computer uses motors connected to the front wheels to steer the device away from obstacles. The controller will override user input when attempting to negotiate obstacles. Voice messages are still given as well. In park mode, the front wheels are oriented to prevent movement of the device. This allows the user to transfer to and from a chair.

BACKGROUND

Researchers at the Massachusetts Institute of Technology have developed a prototype walking aid system to assist the elderly who are either living independently or in senior assisted-living facilities [9]. The walker-based PAMM (Personal Aid for Mobility and Monitoring) that has omnidirectional drives locates itself by reading sign posts, detects and avoids obstacles, and measures the forces and torques on the handle to estimate the user's intent **(Figure 2(a))**. The device uses both user input and obstacle detection to prevent collisions. However, the user has control over which obstacle free path he or she wishes to traverse. The PAMM control system is designed to allow admittance-based user interaction

Figure 1.
Front and side views of VA-PAMAID walker.

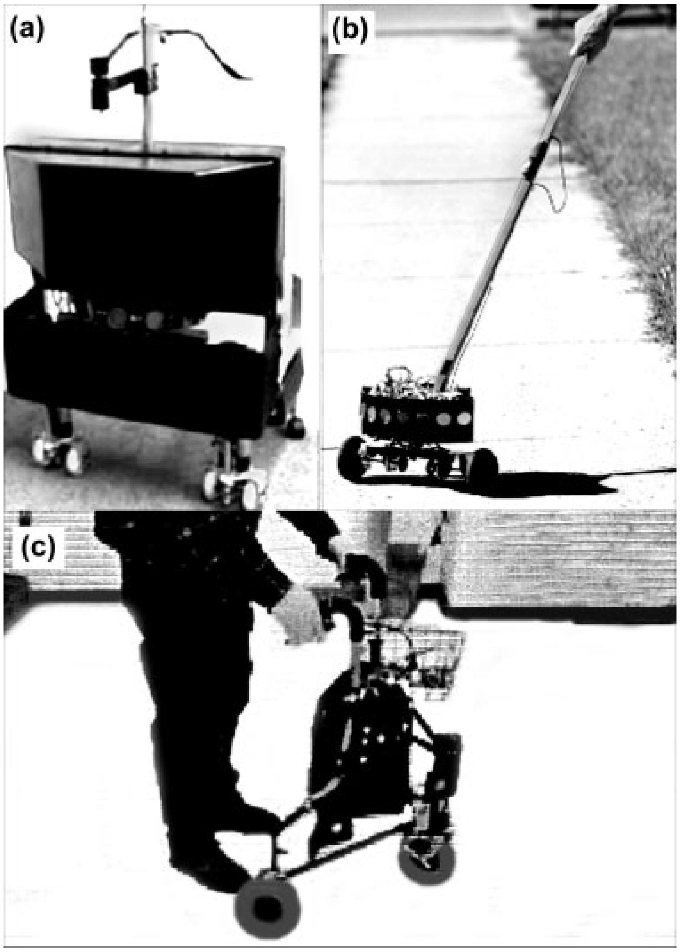

Figure 2.
(a) The PAMM smart-walker developed at MIT (© 2003 by MIT). **(b)** GuideCane invented at University of Michigan (© 2001 by Association for Computing Machinery). **(c)** Assistive robotic walker designed at University of Virginia Medical Center.

control. A dynamic model is created and the system is then made to behave like the dynamic system specified by the model. Information from force-torque sensors mounted on the handles to determine user intent is integrated with instruction from the schedule-based planner, facility map information, and signals from the obstacle avoidance sensors to control the system.

The device has four different control modes. The first mode gives full control of the walker to the user. The controller performs path planning and obstacle avoidance in mode two and the user responds to and directs the device. In mode three, the walker performs path planning, navigation, and localization. The user supplies the desired destination. Mode four involves task planning and communication by the walker. Currently, a cane-based system is being evaluated. The walker-based device is still in development. The goal of this research is to prevent individuals from having to move from assisted-living facilities, or their own homes, to skilled nursing facilities. The target population of the PAMM project is elderly individuals with cognitive and physical impairments. The VA-PAMAID targets frail visually impaired elderly people.

The Medical Automation Research Center at the University of Virginia has also developed a pedestrian mobility aid for the elderly [10,11]. The device consists of a commercially available three-wheeled walker frame, sonar and infrared sensors, a front-wheel motor, and force sensors in the handles **(Figure 2(c))**. The walker can detect and avoid obstacles and varies its goals and level of activity based on an estimation of its user’s intentions. The device senses user steering input through the sensors imbedded in the handles. The control agent infers what the user’s intended path is by considering sensory data, user input, history, and position and orientation. Weighted paths are determined according to the orientation of the device, the length of the path, and the history of the user’s steering input. The project is investigating what can be accomplished with passive devices in home environments. It is intended to assist the elderly population and takes a less active role in guiding the user than does the VA-PAMAID.

The Fraunhofer Institute of Manufacturing Engineering and Automation has developed an intelligent walking aid system based on the Care-O-bot [12]. The device performs autonomous obstacle avoidance and path planning. With the device in direct-user control mode, the user pushes the robot, and with the device in target mode, the user follows the robot to a specified goal along a preplanned path. The device uses a reactive obstacle avoidance algorithm known as PolarBug. A visibility graph is created for finding the shortest collision-free path for the device. The path is evaluated, and if a problem is found, the next shortest path is selected. This process continues until an adequate reference path is determined. Robot configurations are then placed along the selected path so that the device can move from one configuration to the next while avoiding all obstacles on the map.

The GuideCane has been designed to help blind and visually impaired users navigate among obstacles and hazards [13]. The device is equipped with 10 ultrasonic sensors and is controlled by a central computer and servomotors on both wheels **(Figure 2(b))**. The GuideCane scans the environment and then determines the momentary optimal direction of travel. The computer first builds a local map of the surroundings. It accomplishes this task through a two-dimensional array based on certainty grids. The size of the map is 18 m × 18 m, with cell sizes of 10 cm × 10 cm. The local obstacle avoidance algorithm then determines the most appropriate instantaneous directional motion. The GuideCane is a semiautonomous device. It provides full autonomy for obstacle avoidance but requires user input for path planning and localization. This device is intended solely for navigation and does not provide mobility support as the other walkers do.

The VA-PAMAID differs from the other devices just described in several ways. One of the most significant advantages of the VA-PAMAID is its variable range of assistance. The device can be used like a traditional walker providing only support. The auditory feedback can also be used to help provide information about the surroundings. In automatic mode, the obstacle avoidance algorithms will assist the user only when needed. The user can adjust the level of assistance provided by the walker and can always maintain some control in every mode. The VA-PAMAID was designed to be able to provide assistance to anyone needing the use of a walker.

The objective of this study was to conduct an engineering evaluation of the safety of the VA-PAMAID and to determine the performance characteristics of the device and possible ways to improve them. The walker was subjected to a series of tests similar to those developed for testing electric-powered wheelchairs. Testing of the walker will continue throughout the project. Results will be analyzed and the information will be used to modify and refine future versions. The ultimate goal of this project is to compare the VA-PAMAID to a low-technical device used by visually impaired individuals. The testing will also help determine if the VA-PAMAID is a safe and effective device that elderly visually impaired individuals can use to aid with mobility in an indoor environment.

METHODS

A test plan was developed for the VA-PAMAID using a combination of two different standards. Since the VA-PAMAID combines the stability of a regular walker with the technology of obstacle avoidance software, no specific set of standards adequately defines the safety and performance requirements for this device. The International Standards Organization (ISO) for walking aids was used as the primary source for test information [14]. Test procedures were also employed from the American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) wheelchair standards [15]. We took relevant sections from both references to develop a comprehensive test plan for the walker. For this study, only the tests that were deemed critical to safety and performance were addressed. These sections include static stability; maximum range; maximum effective speed; obstacle climbing ability; climatic conditioning; power and control systems; and static, impact, and fatigue strength.

The test methods used to determine static stability were derived from the ISO sections. The walker was tested in the uphill, downhill, and sideways directions. The device was secured so that it could not roll downhill. A 250 N vertical load was applied to the midpoint of the handlebars at all times to simulate the force exerted by the user. The test platform was then inclined until the uphill wheels of the walker lost contact with the test surface. This value was then recorded as the tipping angle.

We determined the maximum range of the walker by propelling the walker around a hospital until the battery indicator reached the recharge position. The walker was initially fully charged for 8 hours. A Bell-four function digital speedometer was attached to a trailing wheel that was connected to the walker. The speedometer recorded both elapsed time and distance traveled.

The maximum effective speed of the walker is defined as the maximum speed that the walker can be pushed and still avoid colliding with obstacles in automatic mode. A trailing wheel that calculated speed and acceleration was attached to the back of the walker [16]. The VA-PAMAID was then propelled toward a wall at increasing speeds until the device was no longer able to avoid colliding with the wall.

We determined the obstacle climbing capability of the VA-PAMAID by propelling the device onto an adjustable height-test platform. The walker was first placed directly in front of the platform, and then the user attempted to push the walker onto the platform. The user was a 29-year-old unimpaired male. The testing was repeated giving the walker a 0.5 m run-up. The height of the platform was then increased by increments of 10 mm.

We conducted environmental testing to ensure that the VA-PAMAID operated under extreme conditions. Although the device has been developed for indoor use only, it can still experience severe conditions during transport. Climatic conditioning was performed according to the ANSI/RESNA wheelchair standards. The walker was placed in an environmental chamber at the temperatures and times listed in **Table 1**.

A functionality check was then performed on the walker 5 min after the operating tests and 1 hr after the storage tests. The device was pushed along a hallway and all the modes and switches were examined. Any erratic or uninitiated behavior was classified as a failure.

The power and control system testing was derived from the ANSI/RESNA wheelchair standards. The main intention of this section is to ensure that electronics and batteries operate safely under all types of circumstances. Since electric-powered wheelchairs are self-propelled and the VA-PAMAID is user-propelled, we had to adapt certain sections of the standard to effectively evaluate the walker. There should be minimal danger of shock or electrocution to the user. Therefore, the placement and response of the fuses were checked and all electrically conducting parts of the walker were measured with a current probe. Any currents detected could not exceed 5 mA. The user depends on the VA-PAMAID not only to detect and announce obstacles and landmarks but also to take evasive actions while in automatic mode. If the laser or ultrasonic sensors malfunction, the user must be informed. Therefore, open circuits were created at the wires that connect the laser and ultrasonic sensors to the controller. The reaction of the walker was then observed. The ability of the user to push the walker and actuate the controls is another relevant issue. Since the target population for the VA-PAMAID is frail visually impaired elderly persons, they must possess the strength to operate the walker correctly. A force gauge was used to determine the forces needed to push the walker forward, turn the handlebars, switch modes, and push the rotate buttons. We performed additional tests to check if the battery charged correctly and how the walker functioned on depleted batteries. We also conducted tests to determine if any of the wires or components could be snagged on furniture or other items. To prevent injury to the user or those around the device, we used a probe to determine if touching any of the gears, pulleys, or drive belts was possible.

Table 1.
Climatic conditioning. Values are based on Section 9 of ANSI/RESNA wheelchair standards.

Climatic Test	Temperature (°C)	Time (hr)
Hot Operating	50	3
Cold Operating	–25	3
Warm Storage	65	5
Cold Storage	–40	5

Static, impact, and fatigue strength testing was performed according to both the ISO and ANSI/RESNA standards. A 1,200 N downward and upward force was applied to the center of the handlebars. A 1,000 N downward force was also applied to both the left and right wheel frames. The rear caster, battery cases, and the front and side of the walker were all impacted with a 25 kg pendulum swung at an angle of 22° from the vertical. The passing criteria for static and impact strength testing mandate that no components shall be cracked or fractured; all power-operated systems shall operate normally; and no components shall exhibit deformation, free play, or loss of adjustment [15].

The walker was then run on a two-drum test machine with 27.3 cm diameter drums and no slats for 200,000 cycles at a speed of 1 m/s. An 800 N cyclic load was applied to the midpoint of the handlebars at a rate of 0.15 Hz [15]. The walker was then run through the functionality test and visually inspected for cracks or damage. **Figure 3** shows the VA-PAMAID during fatigue strength testing.

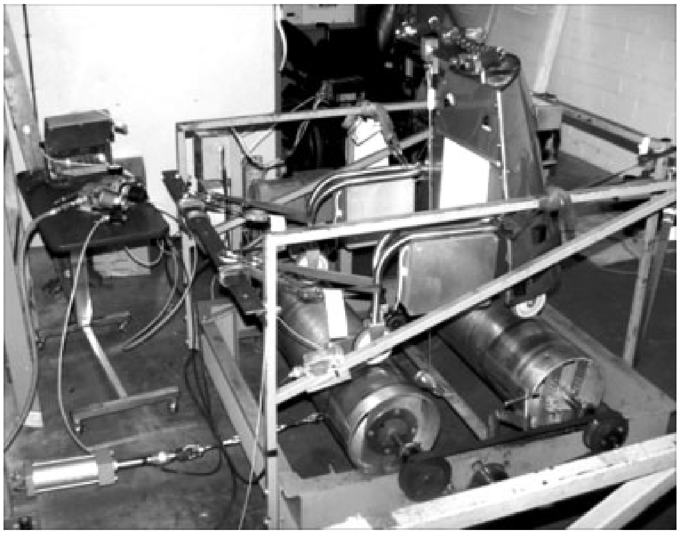

Figure 3.
VA-PAMAID on two-drum tester. A cyclic load was applied to handlebars, and the walker completed 200,000 cycles at 1 m/s.

RESULTS

The results for static stability testing are shown in **Table 2**. The VA-PAMAID traveled a total distance of 10.9 km in automatic mode during the maximum range testing. The elapsed time for this test was 6 hr and 17 min. The maximum effective speed of the walker was determined to be approximately 1.2 m/s. At speeds higher than this, the walker was not able to avoid colliding with the wall. The VA-PAMAID was unable to negotiate an obstacle height of 10 mm or higher. The front wheels were not able to overcome this height even with a 0.5 m run-up. The walker passed all the climatic conditioning tests without any failures. The results for the power and control systems testing are shown in **Table 3**.

The VA-PAMAID passed all of the static and impact strength tests. The walker also completed 200,000 cycles on the two-drum machine without any failures or problems.

DISCUSSION

Requirements in the ISO static stability section mandate minimum tipping angles for rolling walkers. A walker must be stable to at least 15° in the downhill direction, 7° in the uphill direction, and 3.5° in

Table 2.
Static stability tipping angles. Tipping angles were calculated according to ISO standards for walking aids manipulated with both arms.

Stability Test	Mode	Roll/Slide	Tip Angle (°)
Uphill	Park	10.0 slide	34.0
	Automatic	1.0 roll	34.5
	Manual	1.0 roll	34.3
Downhill	Park	22.0° slide	21.0
	Automatic	1.0 roll	23.0
	Manual	1.0 roll	24.0
Sideways (Facing Right)	Park	13.04 roll	21.3
	Automatic	15.3 roll/slide	21.0
	Manual	14.6 roll/slide	20.6
Sideways (Facing Left)	Park	9.95 roll	20.8
	Automatic	15.0 roll/slide	22.0
	Manual	15.4 roll/slide	21.5

Table 3.
Power and control systems. Tests were based on Section 14 of ANSI/RESNA wheelchair standards.

Power and Control Systems Tests	Results
Can live leads be touched when changing fuses?	No
Can any wires be snagged by furniture or moving parts?	No
Do any electrically conductive parts of the walker draw more than 5 mA?	No
Can any noninsulated electrical parts be touched?	No
Does the circuit protection device work?	Yes, it's a 10 A fuse.
Create a short in the laser sensor system and observe walker response.	Walker detects error and attempts to reboot system.
Create a short in the ultrasonic sensor system and observe walker response.	Walker did not detect any errors.
Create an open circuit between the battery pack and the controller.	Power disconnects and all systems shut down.
Operate the walker with the batteries at 30% of their rated capacity.	Front wheels repeatedly attempt to reorient themselves.
Determine the force needed to push the walker.	10.2 N
Can any gears, pulleys, or drive belts be touched?	No
Does the battery charger indicate when it is connected correctly?	Yes
Determine the force needed to turn the handlebars.	26.7 N
Determine the force needed to switch modes.	20.5 N
Determine the force needed to push rotate buttons.	4.4 N

the sideways direction [14]. The VA-PAMAID surpassed all of these requirements. The tipping angles for automatic and manual mode differed by only 1° at the most. The downhill angle was found to be 23° and the uphill angle was 34°. Since the VA-PAMAID is designed as an indoor mobility device, it is highly unlikely that slopes of these degrees will ever be encountered. Also, the device would most likely roll downhill instead of tip because the user would not have the strength to hold the walker at such a steep angle.

The VA-PAMAID was able to travel 10.9 km on fully charged batteries before needing to be recharged. This distance is a reasonable range considering the reported distances traveled in some elderly studies. A study of 2,678 men, ages 71 to 93, found that on average, the distance walked per day was 1.9 km [17]. Only 30 percent of the subjects walked more than 2.4 km a day. Statistics released in 1995 by the National Institute on Aging found that in elderly people above the age of 75, 40 percent could not walk two blocks, 32 percent could not climb 10 steps, and 7 percent could not walk across a small room [18]. The average daily walking distance of an elderly visually impaired subject will most likely be even less than these values. The walker can be charged overnight during an 8 hr period and be ready to go the next day.

A study funded by the Department of Transportation concluded that the average speed of a group of 3,671 senior pedestrians was 1.25 m/s [19]. The maximum effective speed of the walker was found to be 1.2 m/s. Since the average speed of the walker's target population will be even slower, the effective speed of 1.2 m/s should be sufficient. Advances in sensor technology and microprocessing speed will allow for even faster walkers in the future. The next phase of the investigation will evaluate the effective range of the sensors and their capability to detect various types of materials and geometric shapes.

The walker passed all of the climatic conditioning tests without any failures. The device is mechanically and electronically robust enough to withstand severe changes in temperature. The electronics, however, are susceptible to damage from water or other liquids. Protecting the electronics in the next generation device by waterproofing the exposed components should be considered.

The VA-PAMAID was unable to negotiate a 12 mm high obstacle. The lack of climbing capability of the device is due to a combination of its small front wheels (125 × 32 mm), overall mass (41 kg), and a high center of gravity. Since the device is designed for frail visually impaired individuals, it is important to provide the capability to overcome obstacles, such as rugs or power cords, with a minimal amount of effort. This should be corrected in the future version. The walker passed all the strength testing, and therefore, a new design using lighter materials without sacrificing strength is already being developed. Increasing the diameter of the front wheels would also have a dramatic affect on the ability of the device to overcome small obstacles.

The results of the power and control systems testing demonstrate that any electronic failure with the device should not present safety hazards to the user. A loss of power will shut down all the control systems and lock the front wheels in position. While a failure with the laser sensor sends an error signal to the controller, if an ultrasonic sensor fails, the device does not detect it. Although the ultrasonic sensors are used mainly for detecting objects on the periphery of the walker as well as glass, giving an auditory warning to the user that one or more of these sensors are malfunctioning would still be advisable. Since the device is user-propelled, any electronic failures will at worst leave the user immobile. This is not a significant problem because the device will be operated in nursing homes and hospitals where assistance is readily available.

Future work on the next generation model will involve more testing of the sensors and electronics. The maximum distance and angle of detection of the sensors will be established. The capability of the device to detect different surfaces under different conditions will also be examined. Individuals who use the walker in the manual mode will depend on the voice messages to alert them to obstacles and other surroundings. Investigators will conduct tests to determine exactly how and when the walker recognizes objects and relays that information to the user.

The structural strength of the walker satisfies all the criteria for the static, impact, and fatigue testing. Many of the forces applied to the walker far surpass any real-world forces that will be encountered. This finding creates the opportunity to redesign the walker with lighter materials. The prototype tested in this study was constructed of box section stainless steel and sheet aluminum. The next generation walker is already incorporating molded bodywork and a leaner frame. The intended indoor environment and low-speed use of the VA-PAMAID should also help keep the static and impact forces to a minimum.

CONCLUSIONS

The results for the testing on the prototype VA-PAMAID are encouraging. The walker has good range and adequate reaction time and is structurally sound. The electronics are rugged and present minimal hazards because of failure. Wheel size and material selection do need to be revised. The next generation walker will consider these revisions and should be even lighter and more maneuverable. Software upgrades are also being developed for the VA-PAMAID. Additional navigation systems using dead reckoning and global positioning systems (GPSs) are being researched. Downloading a map of a given hospital or area could enable the user to simply select a desired destination and then allow the walker to steer them. Transmitters could also be placed throughout an institution or hospital at specific locations. Signals could then be coded to represent different rooms so that the walker could identify whether the VA-PAMAID was in the cafeteria or the recreation room. A GPS works best outdoors where the signal is strongest. Future models that may be designed for outdoor or community use could benefit from GPS navigation.

While development continues on the chassis, sensors, and other electronics, the VA-PAMAID project will begin to move into the next phase of the study. Clinical trials will be conducted to compare the VA-PAMAID to a low-technical adaptive mobility device used by individuals with visual impairment. Subject screening and activity data are being conducted during the first part of the clinical trials. Testing will be performed using the next generation of the VA-PAMAID walker that has been developed in part on the information collected from this study. The next phase will attempt to determine if the VA-PAMAID will improve the safety, efficiency, and activity of elderly visually impaired individuals in a supervised care facility.

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