ENGINEERING AND CLINICAL EVALUATION OF THE VA-PAMAID ROBOTIC WALKER

by

Andrew John Rentschler

BS, Carnegie Mellon University, 1995

MS, University of Pittsburgh, 2002

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This dissertation was presented

by

Andrew John Rentschler

It was defended on

March 17, 2004

and approved by

Michael L. Boninger, MD, Associate Professor, Dept. of Physical Medicine and Rehabilitation

Bruce Blasch, PhD, Research Health Scientist, Atlanta VA Rehabilitation Research &
Development Center

Richard Simpson, PhD, Associate Professor, Dept. of Rehabilitation Sciences & Technology

Rory A. Cooper, Phd, Professor and Chairman, Dept. of Rehabilitation Sciences & Technology
Dissertation Director

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Andrew John Rentschler, PhD

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The Veterans Affairs Personal Adaptive Mobility Aid (VA-PAMAID) is a robotic walker that is designed to provide physical support, obstacle avoidance, and navigational assistance to frail visually impaired individuals. The goal of this study was to develop and implement testing protocols to determine the performance and safety capabilities of the device and use the results to redesign the walker to make it more reliable and effective.

Engineering tests were performed to determine factors such as stability, range, speed, and fatigue strength. Additional tests to characterize the reliability and accuracy of the sensors and avoidance/navigation algorithms were also conducted. The walker traveled 10.9 kilometers on a full charge, and was able to avoid obstacles while traveling at a speed of up to 1.2 m/s. There were no failures during static stability, climatic, or static, impact, and fatigue testing. Several significant differences were found with respect to the detection distance of the device when varying the obstacle height, material, approach angle, and lighting source. The walker also failed to detect 40-50% of the doorways during the hallway test.

Clinical trials were conducted to compare the VA-PAMAID to a low-tech mobility aid (AMD). Subjects were recruited and trained to use both devices efficiently. Each participant was then asked to traverse an obstacle course several times. The time to complete the course, number of wall and obstacle collisions, and number of reorientations were all recorded and averaged. There were no significant differences between the VA-PAMAID and the AMD with respect to collisions or reorientations. The AMD had a significantly lower completion time (p=0.017) than the VA-PAMAID on the obstacle course.

The results of the engineering and clinical tests were then used in a house of quality model to determine what factors of the walker needed to be revised. Specific modifications were recommended that would make the device safer, more reliable, and more marketable. Changing the wheel size, mass, component positions, detection algorithm, and other variables would make the VA-PAMAID easier to use and more effective for elderly visually impaired individuals.

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ACKNOWLEDGEMENTS

This project was truly a group effort. There were a number of dedicated and professional individuals involved that helped to make this multi-site study a success. I would like to specifically thank a few of the people that provided me with the guidance, encouragement, and wisdom that will undoubtedly follow me throughout the rest of my career. First and foremost, I would like to thank Dr. Rory Cooper, my doctoral advisor and mentor. Throughout the past eight years, he has been both a teacher and a friend. I owe much of my academic growth to the enthusiasm and dedication that he has endlessly expressed for the field of rehabilitation engineering. I would also like to thank Dr. Michael Boninger for his support and assistance. He and Dr. Cooper have created a unique and fantastic environment that enables students to learn and grow both personally and professionally. I consider myself lucky to have had the opportunity to share my work and life with them. I would also especially like to thank Paula Stankovic. She is the students' best friend and has been there since the beginning. I will miss her smiling face and our weekly conversations.

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1.0 INTRODUCTION

1.1 VISION AND AGING STATISTICS

The combination of frailty and visual impairment can have a devastating effect on the ability of the elderly to move around independently. Both mobility and navigation can present serious problems in moving around dynamic environments [1]. Psychological problems associated with a lack of motivation and lessened expectations can make mobility training challenging and difficult [2]. These fears can be compounded by memory loss, the need for support during walking, and the increased fear of falling. The population growth rate of older adults age 65 and above is double that of the general population [3]. Approximately 1/3 of the accidental deaths in this age group, around 10,000 per year, result from falls and complications. Marked increases in mortality and morbidity are associated with even minor slips and falls for adults 80 years and older [4].

Statistics show that as the number of elderly persons increases steadily, so to do the number of falls and accidents and the costs to treat them. It is predicted that by the year 2030 there will be 65 million people over the age of 65, and by 2050 there will be 15 million people above the age of 85 [5]. Every year, 33% of the community-dwelling elderly and 60% of nursing home residents fall [6]. The annual healthcare cost due to falls among the elderly was $20.2 billion in 1994 and could rise as high as $32.4 billion by the year 2020 [7]. In Europe, 25 percent of the population will be over the age of 65 by the year 2020, with the biggest increase in those ages 75 and above [8]. The number of blind and visually impaired elderly persons is also steadily increasing. There will be over 147,000 legally blind veterans and 880,000 veterans with a severe visual impairment by the year 2010 [9]. The American Foundation for the Blind reported that approximately 26 percent of all nursing home residents had some level of visual impairment [10]. In Europe, over 65 percent of all blind people are 70 years or older [11].

The elderly and frail blind are at a great disadvantage when it comes to the issue of mobility and navigational assistance. Traditional walkers offer support, but no assistance for navigation. Long canes and guide dogs can help people navigate their environment more safely, but offer no physical support. A walker that could provide both navigational assistance and support while reducing the need for supervision could increase the independence and well being of thousands of elderly individuals while reducing the cost of care. This is the goal of the Veterans Affairs Personal Adaptive Mobility Aid (VA-PAMAID). The VA-PAMAID is a robotic walker that is designed to provide physical support and obstacle avoidance and navigational assistance to frail visually impaired individuals.

1.2 SPECIFIC AIMS AND HYPOTHESES

The primary purpose of this study was to evaluate the performance and safety characteristics of the VA-PAMAID through the use of engineering tests and clinical trials. The results were then analyzed to determine what design changes could be made to the walker in order to make the device more reliable and functional for the intended population. The secondary goal was to begin to develop standardized tests that could be utilized to help evaluate and compare similar robotic assistive mobility devices that are currently being developed by other sources. Several hypotheses were formed in order to help evaluate the effectiveness of the VA-PAMAID. These hypotheses are listed below.

Hypothesis 1: The VA-PAMAID will function in a safe manner under both normal and adverse circumstances. The device will be statically stable, structurally sound, and unaffected by severe climatic conditions and power failures. The walker will perform in a safe and effective manner during the clinical testing.

Hypothesis 2: The performance of the VA-PAMAID will be adequate for the intended target population. The device will have adequate range, speed, and obstacle climbing ability. The walker will perform reliably during the clinical testing.

Hypothesis 3: The VA-PAMAID will create a safer mode of mobility than the adaptive mobility device. The walker will contact less walls and obstacles and require fewer reorientations than the AMD.

Hypothesis 4: The VA-PAMAID will decrease travel time when compared to the adaptive mobility device. The subjects will complete the test courses in less time with the walker than with the AMD.

Hypothesis 5: Revisions to the VA-PAMAID can be made, using the house of quality modeling concept, that will help make the device more user friendly, reliable, and marketable.

1.3 DISSERTATION ORGANIZATION

The Background section of this dissertation provides statistics on visual impairment and aging, as well as a brief history of the VA-PAMAID. The components and functions of the walker are described and the obstacle avoidance algorithm is explained. The Research Study subheading describes the four different phases of the study. The Conclusions section summarizes the information and findings discovered from the different study phases. The Future Research section describes the intended direction of research and possible changes in the use of the walker. The four different phases of the study are listed next. Each study includes an Introduction, Methods, Results, Discussion, and Conclusion section. Appendices A through E include the study questionnaires and device lesson plans.

2.0 BACKGROUND

Macular degeneration, cataracts, glaucoma, and diabetic retinopathy are the leading causes of visual impairments among older adults. The American Federation for the Blind has predicted that the number of individuals that are age 65 or above that have severe functional limitations in vision will increase 284% from the year 2000 to the year 2050. The use of electronic travel aids (ETAs) has been researched since the late 1940's as a form of assistance for visually impaired individuals. ETAs are devices that can help to transform environmental information that is normally relayed through vision into a form that can be transmitted through a different sensory modality [11]. Effective ETAs can help to provide environmental information not possible with long canes or guide dogs. ETAs can detect and locate objects, and provide information to allow the user to determine range, direction, and dimensions of the object. Many of the currently available devices pass information to the user through tones or vibrations. The user must then take the required corrective actions to avoid colliding with an object. Robotic ETAs reduce the amount of cognitive load placed on the user. The robot interprets the sensory information and allows for detailed descriptions of the environment to be passed to the user. Corrective actions can then be performed by the robot before any collisions occur.

Dr. Gerard Lacey started research on the idea of a smart walker for the frail visually impaired in 1994 at the Department of Computer Science, Trinity College, Dublin, Ireland [8]. Seven different versions of the smart walker were initially developed and evaluated in a residential care facility. A study to determine user requirements was performed with potential users and their caregivers in Ireland, Sweden, and the U.K. [12]. Interviews were conducted with 38 potential users and 14 caregivers and rehabilitation specialists who worked with frail and elderly visually impaired people. The results from these interviews helped guide the development of the first PAMAID and included ideas about switch and voice input and sound output. Figure 1 shows the early versions of the PAMAID.

Figure 1The PAMAID walker has been in development since 1994 and several different prototypes have been created.

The interaction between a human-machine system can be very complex and must be made reliable and intuitive in order to appeal to and ultimately benefit the frail elderly population. Both parts feed information into the system, which produces an output greater than any single part could provide. In the case of the robotic walker, the user will input the general direction that the device should move, and the machine will guide the user around any obstacles in that direction [13]. The VA-PAMAID needs to avoid obstacles in a smooth and predictable manner to guarantee the safety of the users, whose population consists of individuals with reduced mobility and visual impairment. This requirement complicates the development of an effective obstacle avoidance algorithm that disallows sharp and potentially hazardous turns [13]. Any actions taken by the VA-PAMAID to avoid obstacles must also be balanced with the user's need to feel in control of the device.

The most current design of the VA-PAMAID is shown below in figure 2. This version of the walker was used for the obstacle detection and avoidance capability tests, as well as the clinical trials in Atlanta, GA, Salisbury, NC, and Tucson, AZ.

Figure 2 The most current version of the VA-PAMAID.

The VA-PAMAID provides the physical support of a traditional walker frame coupled with obstacle avoidance and navigational assistance provided by the sensor and control systems, as well as auditory output. It is a passive device that must be propelled by the user. A laser and sonar sensors mounted on the front and sides of the device scan the environment to identify obstacles and landmark objects. Motors connected to the front two wheels can control the direction of the walker based on the navigational algorithm (Figure 3). The VA-PAMAID has three different control modes. Manual mode provides the user with complete control over the direction of the walker. The information gathered by the sensors is presented to the user through the auditory messages. Control of the walker is shared by both the user and the control system in automatic mode. The user can direct the walker unless an obstacle is encountered. The control system then takes over and the motors direct the walker around the obstacle. The controller will override any user input that would result in a collision. Park mode is the third option. In this mode, the front two wheels of the walker lock in an orientation that prevents the device from moving. This allows the user to transfer to and from the walker if necessary.

Figure 3 Motors connected to the front casters allow the device to control the direction of the walker.

The user can direct the walker with the spring-loaded handlebars that are equipped with sensors to determine the intended direction of travel. Turn buttons are located on the end of each handlebar (Figure 4). Depressing these buttons causes the front wheels to turn parallel to each other and thus allows the walker to rotate in a circle about its rear wheels. This feature was incorporated into the design because the obstacle avoidance algorithm does not account for reversing. The sensors are only actively scanning the environment in front of the device, not behind it. If the system detects a reversing motion, it can apply the brakes proportionally to reduce the speed [13]. Brake levers are also positioned on the handle grips (Figure 4). If the user squeezes the brakes, the front wheels will both turn inward to stop the walker. The control console contains a key slot to turn on the device, a volume knob for the auditory messages, and a switch for selecting the control mode. A voltmeter, fuse, and the recharging port are located on the back of the walker (Figure 5). The electronics and motors are run off of a 72-volt system that is powered by four 12-volt batteries that are located in the struts connecting the front and rear wheels.

Figure 4 The picture on the left shows the walker handgrip. The arrows are pointing to the red turn buttons and the white brake lever. The photo on the right shows the control console of the device.

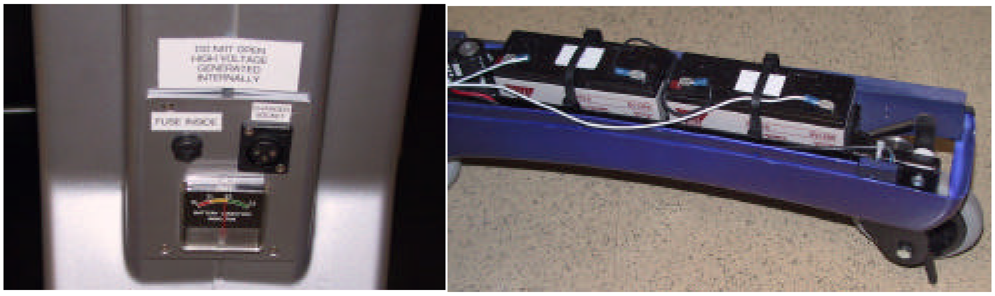


Figure 5 The photo on the left shows the rear of the walker, including the battery level indicator and the charging port. The photo on the right shows the position of the batteries along the right leg of the walker.

The first three walker prototypes had behavior based obstacle avoidance programs. The four different behaviors were: wall following, collision avoidance, unblock, and direct control. The main problem with this system was that the user was forced to switch between the modes in any given situation. This placed a large cognitive load on the user. The fourth active system used a shared controller that would automatically choose the level of user control versus robot control based on the calculated risk of collision. The fifth walker used the passive demonstrator idea developed by MacNamara et al [8].

The current VA-PAMAID utilizes what is known as the clean sweep algorithm [13]. This algorithm has two parts; the first is a generation of a map of the local environment and the second is the use of this map in the main obstacle avoidance method. The clean sweep system runs on an embedded PC running Linux. Task control architecture was used as a framework for the software design. Figure 6 shows a diagram of the software architecture. Figure 7 shows the data flow to and from the mapping/navigation. The mapping program receives information from the laser and sonar sensors, as well as the wheel encoders. The map that is generated is then sent to the navigation program, which takes into account the position of the walker and the intended direction of travel of the user. The clean sweep algorithm was designed to help the walker navigate through cluttered environments. The system is also intended to react quickly to the user input so that it will go in the direction intended by the user. Clean sweep is a geometry based obstacle avoidance method where the area in front of the walker is searched geometrically for clear paths [13].

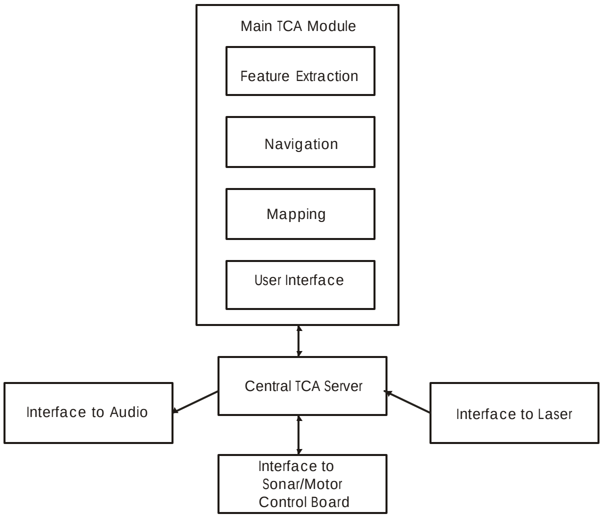


Figure 6 Software architecture for the VA-PAMAID [13].

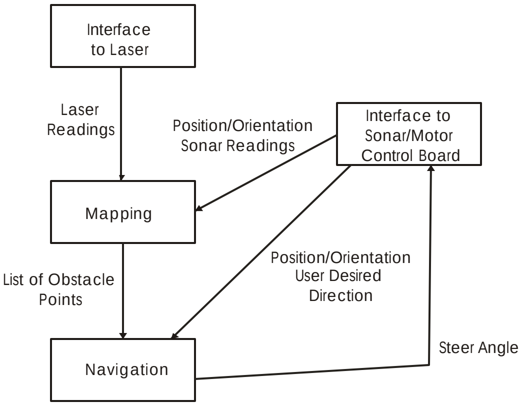


Figure 7 Mapping and navigation data flow for the VA-PAMAID [13].

The VA-PAMAID has four different types of sensors. The SICK LMS scanning laser (accurate ± 1 cm over 30m) is the main sensor used for obstacle and landmark detection. The laser gives an accurate 180° horizontal view of the environment in front of the walker. The laser scan returns a ray's length measurement for every degree, so there are 181 measurements in each scan. Since the laser produces only a 2-D plane view, nothing above or below the height of the plane is visible to the laser. Polaroid ultrasound sensors are positioned around the front and sides of the walker to help detect the objects out of view from the laser. They also detect glass and other transparent materials that the laser may not detect. Figure 8 shows the laser and sonar sensors on the walker. Two optical encoders are also positioned on the rear wheels of the walker. These encoders calculate the walker position and orientation in absolute values. The fourth sensor is a potentiometer on the steering wheel that receives user input. The signal is converted to an angle, -60° to 60°, from left to right and used to determine the direction of the front wheels.

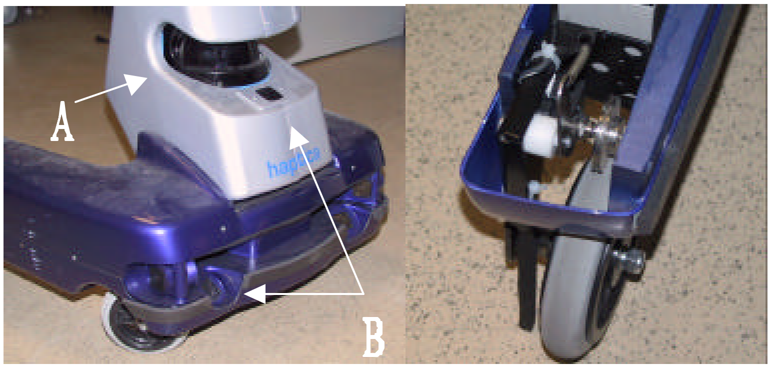


Figure 8 The photo on the left shows some of the different sensors on the walker. The laser scanner (A) is the main detection device, and the sonar sensors (B) provide coverage above and to the sides of the walker. The photo on the right shows one of the encoder

The map module keeps a local view of the environment (4m x 4m), but not a global map [13]. The map receives information from the laser sensor, the sonar sensors, and the wheel encoders. The map structure is a list of points stored as absolute coordinate points. There are two separate lists of points in the map, the current laser view and a history of points from the previous positions of the walker no longer visible to the laser. The system maintains a list of all of the walker positions and laser ranges for a number of iterations. The points that are in front of the current laser base line are placed into the current sensor points array. All of the points that are behind the laser base line are placed in the historical data points array. The resulting window of points is a 4m x 4m grid (1m behind walker, 2m to each side, and 3m in front of the walker.

The clean sweep program is a geometry based obstacle avoidance method where the space in front of the walker is searched in a geometric pattern for clear paths [13]. These paths checked by the system consist of circular paths corresponding to a given steering angle. A virtual wheel angle corresponds to a given turn radius of the device. Two separate circles are defined by the system that represents the sweep area that the outermost edges of the device would occupy for a specific turn radius. Figure 9 demonstrates how the device calculates the inner and outer paths for both a large and small turn radius. This method insures that the outermost edge of the device will not contact obstacles during turning.

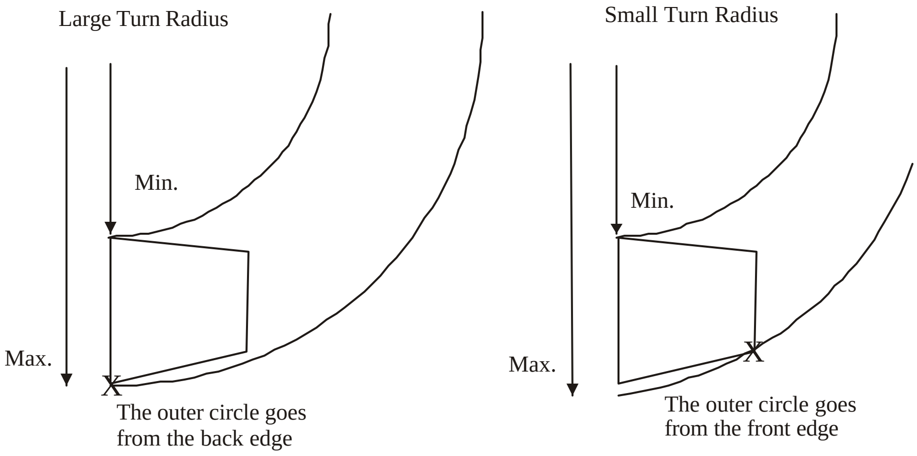


Figure 9 The walker calculates the inner and outer circle paths depending on the given turn radius.

The parameters for the area checked for a clear path are shown in Figure 10. They include: the search area circle, the left and right search limits, the baseline, and the maximum and minimum sweep edges.

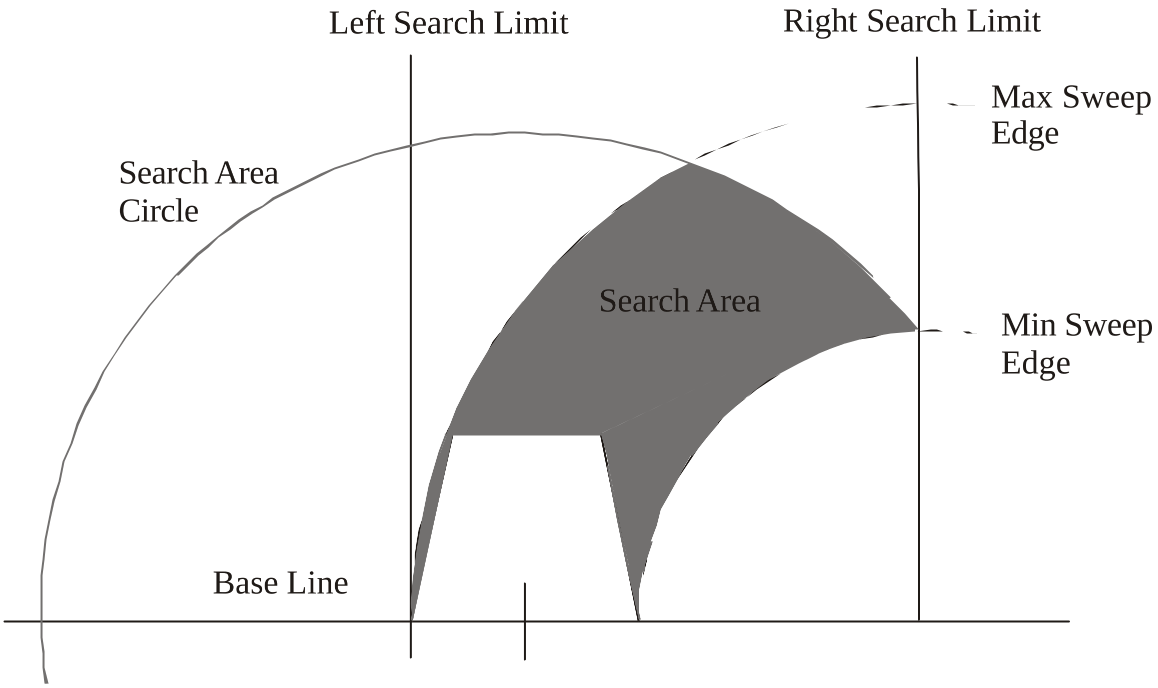


Figure 10 The walker performs a number of checks to insure that the given turn radius is free of obstacles.

The system first checks between the minimum and maximum sweep edges. The second check detects points in front of the baseline. The next check tests inside of the search area circle. The last check uses the left and right side limits.

There are several other navigational mobility aids currently in development in addition to the VA-PAMAID. Researchers at both the Massachusetts Institute of Technology and the Medical Automation Research Center at the University of Virginia are developing their own walkers with obstacle avoidance capabilities [14,15]. The Care-O-bot was designed by the Fraunhofer Institute of Manufacturing Engineering and Automation. It is a motorized robot that can perform autonomous obstacle avoidance and path following. Table 1 lists some of the other assistive mobility devices currently under development, as well as their main features and target populations.

Table 1 Mobility aids for navigation and obstacle avoidance

Device	PAMM	MARC	Care-O-bot	GuideCane
Investigative Center	Massachusetts Institute of Technology	Medical Automation Research Center, UVA	Fraunhofer Institute of Manufacturing Engineering and Automation	University of Michigan
Design	Motorized walker	3-wheel rollator	Motorized robot	Cane with wheeled sensor array
Target Population	Elderly, cognitive/physical impairments	Elderly, home environment	Elderly	Blind
Avoidance, Navigation	Obstacle avoidance, autonomous navigation	Obstacle avoidance, assisted navigation	Obstacle avoidance, path planning	Obstacle avoidance
Modes	4 modes: user control; controller path planning and obstacle avoidance; controller path planning, navigation, and localization; controller task planning and communication	User control; shared-control	Direct user control; target mode	Obstacle avoidance with active steering
Propulsion	Passive	Passive	Passive/Active	Passive
Human/System Interface	Handlebars	Handlebars	Walking aid handles	Mini joystick
Steering	Omni-directional drives	Motorized front wheel	Motorized wheels	Two wheels

2.1 RESEARCH STUDY

The objective of this project was to perform both engineering and clinical evaluations of the VA-PAMAID in order to determine if the walker could improve the safety, efficiency, and activity of elderly visually impaired individuals in a supervised care facility. The walker was first tested to insure that it would function safely and present no risk to the subjects. Yanco et al recommended that walkers for the elderly infirm with limited vision should be tested on sighted people first [16]. The move to the target user should be made only when safety and reliability of the system has been repeatedly demonstrated. The system performance should then be measured by conducting user tests that compare the performance of the walker against a non-robotic solution. Several tasks were outlined in the proposed grant for this multi-site study. These tasks are listed below in Table 2. Several different phases of this study were designed to accomplish these goals.

Table 2 Timeline for the different tasks in the VA-PAMAID project

Task	Year 1				Year 2			Year 3				
Design first VA-PAMAID (PGH)	■	■										
Design VA-PAMAID testing protocols (ATL)	■	■	■	■								
Integrate 1st VA-PAMAID (PGH)		■	■									
Test First VA-PAMAID (PGH)			■	■								
Assemble 3 field VA-PAMAIDs (PGH)				■	■	■						
Trial VA-PAMAID testing protocol				■	■	■	■					
Design VA-PAMAID training procedure (ATL)				■	■	■	■					
Initial VA-PAMAID testing (ATL)							■	■	■	■		
Continue to refine VA-PAMAID (PGH)							■	■	■	■	■	■
Complete VA-PAMAID testing (ATL)										■	■	
Analyze data (ATL)											■	■
Tech Transfer (PGH)											■	■

The first phase of this project involved conducting safety and performance testing on the device. Customized tests were designed drawing from both the ISO standards for walkers [17] and the ANSI/RESNA wheelchair standards [18]. The VA-PAMAID was run through a battery of tests to insure that it performed in a safe and effective manner under various circumstances and conditions. Testing included sections on static stability, maximum range, maximum effective speed, obstacle climbing ability, climatic conditioning, power and control systems, and static, impact, and fatigue strength.

The next two phases of the project were performed concurrently. Approval was obtained from the Veterans Health Administration Institutional Review Board to perform clinical trials with human subjects. Subjects were recruited from Atlanta, Georgia, Tucson, Arizona, and Salisbury, North Carolina, to participate in the study. All of the participants were trained to use both the VA-PAMAID and the assistive mobility device (AMD) in random order. The subjects then negotiated an obstacle course multiple times with the VA-PAMAID, the AMD, and their own device or a sighted guide. Elapsed time, wall and obstacle collisions, and reorientations were all recorded. Elapsed time was defined as the time it took the subject to traverse the obstacle course from start to finish. Wall and obstacle collisions refer to the number of times each subject contacted a wall or obstacle with their device or body. Reorientations was defined as the number of times that the subject had to be reoriented in order to finish the course. The resulting data was then analyzed for statistical differences. Each of the subjects also completed numerous surveys that included demographic information, sight and mobility levels, and questions about the VA-PAMAID and AMD (see appendix).

Once the clinical trials were started, the investigators and subjects began to identify certain drawbacks and performance issues concerning the VA-PAMAID. It was then decided to conduct additional engineering tests to target the detection and obstacle avoidance capabilities of the device. These tests included a hallway-opening test, overhead obstacle detection test, a material and lighting detection test, and a varying obstacle angle test. These tests helped to determine the effectiveness of the sensors and clean sweep algorithm, as well as identify differences between the manual and automatic modes.

The last phase of this study involved developing a house of quality model for the VA-PAMAID. The results from the engineering and clinical studies were analyzed and used to determine possible changes that could improve the use and appeal of the walker. These design changes were then analyzed and the feasibility and advantages of implementing them were determined. The overall goal of this study was to determine if the VA-PAMAID was a safe and effective means of mobility for frail elderly visually impaired individuals, as well as to determine what design changes could be made to the device to make it even safer, perform better, and more marketable to the target population.

3.0 CONCLUSIONS

The hypotheses developed for this study are reviewed and analyzed below according to the results obtained from the engineering testing, clinical trials, and house of quality modeling.

Hypothesis 1: The VA-PAMAID will function in a safe manner under both normal and adverse circumstances. The device will be statically stable, structurally sound, and unaffected by severe climatic conditions and power failures. The walker will perform in a safe and effective manner during the clinical testing. This hypothesis was rejected. The results from the first study demonstrate that the VA-PAMAID functions safely under normal and adverse circumstances. The device was stable, rugged, and performed in a safe and predictable manner during all of the engineering tests. However, the device did not perform reliably during the clinical trials or the obstacle sensor testing.

Hypothesis 2: The performance of the VA-PAMAID will be adequate for the intended target population. The device will have adequate range, speed, and obstacle climbing ability. The walker will perform reliably during the clinical testing. . This hypothesis was also rejected. The first study has shown that the walker appears to have sufficient range and speed for its intended population. The obstacle climbing ability of the walker, however, is far from adequate. The engineering tests and clinical trials have shown that the user will have difficulty negotiating even small obstacles, as well as propelling the device on thick carpets. The performance of the device during clinical trials was very erratic. The walker failed to detect doorways and openings. The detection distance in manual mode was also very short.

Hypothesis 3: The VA-PAMAID will create a safer mode of mobility than the adaptive mobility device. The walker will contact less walls and obstacles and require fewer reorientations than the AMD. This hypothesis was rejected. There were no significant differences between any of the devices when comparing wall and obstacle contacts and reorientation.

Hypothesis 4: The VA-PAMAID will decrease travel time when compared to the adaptive mobility device. The subjects will complete the test courses in less time with the walker than with the AMD. This hypothesis was rejected. The walker did not decrease the travel time of the subjects during any of the trials. The AMD had the lowest average travel times of all the devices.

Hypothesis 5: Revisions to the VA-PAMAID can be made, using the house of quality modeling concept, that will help make the device more user friendly, reliable, and marketable. This hypothesis was retained. The house of quality model presented in Study 4 provided a list of engineering factors that could improve the performance and effectiveness of the VA-PAMAID. Many of the design and performance issues that were highlighted during the engineering and clinical studies can be modified without spending excessive time and money. Component placement, control systems, and ease of propulsion were the major issues that both the investigators and subjects felt needed consideration. If implemented properly, the next generation VA-PAMAID should perform more reliably and be easier to use, thus increasing its marketability and usefulness for the intended population.

This study helped to identify both the advantages and shortcomings of the VA-PAMAID. A stark difference is apparent between the engineering and clinical aspects of the study. The walker was shown to be safe with respect to benchmark testing, but not with respect to clinical performance. From an engineering standpoint, the VA-PAMAID is a structurally sound device that performs well in laboratory tests. The reliability of the walker, specifically its ability to detect doorways and other landmarks, and its detection distance in manual mode need to be improved. Clinically, the VA-PAMAID failed to outperform the AMD and other devices. Improvements need to be made concerning the placement of certain components, its ease of use, and its ability to assist individuals with travel.

The use of navigational and obstacle avoidance software for assistive robotic mobility devices is becoming more prominent. Several different Universities and companies are developing walkers and other devices, such as the VA-PAMAID, that will be able to provide cognitive assistance to individuals. This study was one of the first to design and implement a program to evaluate such technology. The results of this study can be used to not only refine and improve the VA-PAMAID, but as a template to develop new tests and standards for a very important and rapidly developing field.

4.0 FUTURE RESEARCH

Future tests for the VA-PAMAID should incorporate long-term clinical studies instead of test runs on shorter courses. The main objectives of the VA-PAMAID are to increase the safety, efficiency and activity of elderly visually impaired individuals. These goals may not manifest themselves through immediate improvement on relatively short obstacle courses. It may take considerable time for individuals to become comfortable with the walker and how it works. This would involve a long-term study that follows and tracks the activity of subjects for a number of months. A baseline of activity could be established by equipping the subjects with activity monitors before the study. After sufficient training, walkers could be left with the subjects to be used independently without any supervision. Subject activity would again be recorded and the results could be compared to pre-test levels. In order to conduct such a study, it would be mandatory that the walker work reliably and safely.

Implementation of a Wizard-of-Oz experiment could also provide valuable insight to the possible advantages of the VA-PAMAID. A Wizard-of-Oz experiment involves assigning a test subject a task to complete using a system device. The subject is unaware that the system is partly simulated by a human operator (the wizard). It is then possible to test hypotheses concerning systems, control algorithms, and other components. The results of this testing can then be incorporated into the actual device.

Investigators could modify the walker so that they have control over the front wheel motors. This way they could control the direction of the device in automatic mode. Comparing the results of the Wizard-of-Oz testing on the obstacle course to the results of the automatic mode on the same course would allow the researchers to determine if the navigational and obstacle avoidance algorithm is performing accurately and efficiently.

The use of focus groups could also prove to be a valuable design tool. The surveys and comments recorded during the clinical study provided very useful feedback concerning the placement of components and the effectiveness of the device. Scheduling meetings at independent living facilities and rehabilitation centers would provide an opportunity to gather information about what potential users like and dislike about the VA-PAMAID.

Investigators may also want to alter the direction of research for this technology altogether. The results of this study have made it apparent that there is not an immediate need for this product for a large population of users. Pursuing other avenues may provide the ability to use this technology for other groups. Obstacle avoidance and navigational technology will play a large role in future projects for visually impaired individuals. The algorithms developed for the VA-PAMAID may be of some use to the blind community. Coupling this technology with devices that a larger percentage of the blind community can use may prove beneficial.

The environment that the walker can function in was the other limiting factor for this study. Constraining the device to an indoor supervised care facility with no steps or levels greatly reduces its possible effectiveness. Individuals who reside in such centers usually still travel outdoors. If the intention of the VA-PAMAID is to assist elderly, visually impaired individuals, then it should be able to function out in the community, not just indoors. This would require redesigning the device to function reliably and make it as easy as possible to use. The

VA-PAMAID would have to be simplified and the dimensions and mass of the device reduced. The MARC device being developed at the University of Virginia is a good example of minimizing the change made to a traditional walker. The device is built on the frame of a three wheeled rolling walker. The front wheel is motorized and a laser scanner is used to detect obstacles. The overall dimensions of the walker were not drastically changed, and only the necessary components were added to provide obstacle avoidance. This would allow individuals to safely and confidently use the device both indoors and outdoors. A much larger population could be targeted than with the current version and restrictions of the current VA-PAMAID.

5.0 PHASE I STUDY

The following article, titled ‘Intelligent Walkers for the Elderly: Performance and Safety Testing of the VA-PAMAID Robotic Walker’, was published in the Journal of Rehabilitation Research and Development (Vol. 40, No. 5, Sept/Oct. 2003).

5.1 INTRODUCTION

A report by the U.S. Census Bureau on Americans with disabilities states that of the 267.7 million non-institutionalized individuals surveyed, 7.6 million of them have some sort of visual impairment [19]. 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% of all nursing home residents had some level of visual impairment [20]. A study performed by Goodrich found that by the year 2010 there would be over 147,000 legally blind veterans and 880,000 veterans with severe visual impairments [21]. 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 [22]. Current mobility devices for the elderly and visually impaired require certain levels of function and dexterity that many of the users do not possess. These statistics underline the need for the research and development of new assistive mobility devices that will reduce limitations and enhance the function of these individuals.

The need for effective and interactive assistive mobility devices is becoming more prevalent every year. There will be 65 million people over the age of 65 in the year 2030, and 15 million people over the age of 85 by 2050 [5]. Fuller found that one third 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.

There are several different computer-based assistive walker devices currently 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 like a normal walker most of the time, but 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 Veteran's Affairs is working with Haptica to investigate the potential for commercialization of the VA-PAMAID design and technology. The main commercialization efforts will be concentrated towards 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 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 770mm long, 630mm wide, and 895mm in height. The mass of the device is currently 41kg. Figure 11 shows the front and side views of the walker.

Figure 11 The front and side views of the VA-PAMAID 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. In automatic mode, the user and the computer share control of the walker. 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.

5.2 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 [14]. The walker based PAMM (Personal Aid for Mobility and Monitoring) that has omni-directional 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 12). The device utilizes 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 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 in order 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.

Figure 12 Clockwise from the top left: The PAMM smart-walker developed at MIT; The GuideCane invented at the University of Michigan; The assistive robotic walker designed at the University of Virginia Medical Center.

The Medical Automation Research Center at the University of Virginia has also developed a pedestrian mobility aid for the elderly [15,23]. 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 (Figure12). 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 [24]. The device performs autonomous obstacle avoidance and path planning. In direct user control mode, the user pushes the robot, and 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 there is a problem, 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 [25]. The device is equipped with ten ultrasonic sensors and is controlled by a central computer and servomotors on both wheels (Figure 12). The GuideCane scans the environment and then determines the momentary optimal direction of travel. The computer first builds a local map of the surroundings. This is accomplished through a two-dimensional array based on certainty grids. The size of the map is 18m x 18m, with cell sizes of 10cm x 10cm. The local obstacle avoidance algorithm then determines the most appropriate instantaneous directional motion. The GuideCane is semi-autonomous 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 like the other walkers.

The VA-PAMAID differs from the other devices described above 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 always maintains 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-tech 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.

5.3 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, there is not a specific set of standards that 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 [17]. Test procedures were also employed from the ANSI/RESNA wheelchair standards [18]. Relevant sections were taken 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 rolling walker 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. The sliding angle of the walker was also recorded in each direction. This was defined as the angle at which the walker would begin to slide downhill when not restrained.

The maximum range of the walker was determined by propelling the walker around a hospital until the battery indicator reached the recharge position. The walker was initially fully charged for eight 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 is still able to avoid colliding with obstacles in automatic mode. A trailing wheel that can calculate speed and acceleration was attached to the back of the walker [26]. The VA-PAMAID was then propelled towards a wall at increasing speeds until the device was no longer able to avoid colliding with the wall.

The obstacle climbing ability of the VA-PAMAID was determined 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-meter run-up. The height of the platform was then increased by increments of 10mm.

Environmental testing was conducted to insure that the VA-PAMAID can operate 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 below in Table 3.

Table 3 Climatic conditioning

Climatic Test	Temperature (ºC)	Time (hours)
Hot Operating	50	3
Cold Operating	-25	3
Warm Storage	65	5
Cold Storage	-40	5

These values are based on Section 9 of the ANSI/RESNA Wheelchair Standards.

A functionality check was then performed on the walker five minutes after the operating tests and one hour after the storage tests. The device was pushed along a hallway and all of 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 insure that the electronics and batteries operate in a safe manner under all types of circumstances. Since electric powered wheelchairs are self-propelled and the VA-PAMAID is user-propelled, certain sections of the standard had to be adapted to effectively evaluate the walker. There should be a minimal danger of shock or electrocution to the user. Therefore, the placement and response of the fuse was checked and all electrically conducting parts of the walker were measured with a current probe. Any currents detected must not exceed five milliamps. The user depends on the VA-PAMAID to not only detect and announce obstacles and landmarks, but also to take evasive actions while in automatic mode. If the laser or ultrasonic sensors malfunction, it is imperative that the user 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 it 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. Additional tests were performed to check if the battery charged correctly and how the walker behaved on depleted batteries. Tests were also conducted to determine if any of the wires or components could be snagged on furniture or other items. In order to prevent injury to the user or those around the device, a probe was used to check if it was possible to touch any of the gears, pulleys, or drive belts.

Static, impact, and fatigue strength testing was performed according to both the ISO and ANSI/RESNA standards. A 1200 N downward and upward force was applied to the center of the handlebars. A 1000 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 25kg pendulum swung at an angle of 22^{o} from the vertical. The passing criteria for static and impact strength testing mandates 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 [18].

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 1m/s. An 800 N cyclic load was applied to the midpoint of the handlebars at a rate of 0.15 Hz [18]. The walker was then run through the functionality test and visually inspected for cracks or damage. Figure 13 shows the VA-PAMAID during fatigue strength testing.

Figure 13 The VA-PAMAID on the two-drum tester. A cyclic load was applied to the handlebars and the walker completed 200,000 cycles at 1 m/s.

5.4 RESULTS

The results for static stability testing are shown below in Table 4.

Table 4 Static stability tipping angles

Test	Mode	Roll/Slide/Tip Angle	Tip Angle
Uphill Stability	Park	10° slide	34°
	Automatic	1.0° roll	34.5°
	Manual	1.0° roll	34.3°
Downhill Stability	Park	22° slide	21°
	Automatic	1.0° roll	23°
	Manual	1.0° roll	24°
Sideways Stability (Facing Right)	Park	13.04° roll	21.3°
	Automatic	15.3° roll/slide	21°
	Manual	14.6° roll/slide	20.6°
Sideways Stability (Facing Left)	Park	9.95° roll	20.8°
	Automatic	15.0° roll/slide	22°
	Manual	15.4° roll/slide	21.5°

These tipping angles were calculated according to the ISO standards for walking aids manipulated with both arms.

The VA-PAMAID traveled a total distance of 10.9 kilometers in automatic mode during the maximum range testing. The elapsed time for this test was six hours and seventeen minutes. The maximum effective speed of the walker was determined to be approximately 1.2m/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 10mm or higher. The front wheels were not able to overcome this height even with a 0.5m run-up. The walker passed all of the climatic conditioning tests without any failures. The results for the power and control systems testing are shown in Table 5.

Table 5 Power and control systems

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 5mA?	No
Can any non-insulated electrical parts be touched?	No
Does the circuit protection device work?	Yes, it's a 10-amp fuse.
Create a short in the laser sensor system and observe walker response.	The walker detects the error and attempts to reboot the system.
Create a short in the ultrasonic sensor system and observe walker response.	The walker did not detect any errors.
Create an open circuit between the battery pack and the controller.	The power disconnects and all systems shut down.
Operate the walker with the batteries at 30% of their rated capacity.	The front wheels repeatedly attempt to reorient themselves.
Determine the force needed to push the walker.	10.2N
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.	26.7N
Determine the force needed to switch modes.	20.5N
Determine the force needed to push rotate buttons.	4.4N

These tests were based on Section 14 of the ANSI/RESNA Wheelchair Standards.

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. The device functioned properly after all testing was completed.

5.5 DISCUSSION

Requirements in the ISO static stability section mandate minimum tipping angles for rolling walkers. A walker must be stable to at least fifteen degrees in the downhill direction, seven degrees in the uphill direction, and 3.5° in the sideways direction [14]. The VA-PAMAID surpassed all of these requirements. The tipping angles for automatic and manual mode differed by only one degree at the most. The downhill angle was found to be 23º and the uphill angle was 34º. 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 2678 men, ages 71 to 93, found that on average, the distance walked per day was 1.9 kilometers [27]. Only thirty percent of the subjects walked more than 2.4 kilometers per day. Statistics released in 1995 by the National Institute on Aging found that in elderly people above the age of 75, forty percent could not walk two blocks, thirty two percent could not climb ten steps, and seven percent could not walk across a small room [28]. 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 eight hour 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 3671 senior pedestrians was 1.25m/s [29]. The maximum effective speed of the walker was found to be 1.2m/s. Since the average speed of the walker's target population will be even slower, the effective speed of 1.2m/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 ability 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. Considerations should be made for protecting the electronics in the next generation device by waterproofing the exposed components.

The VA-PAMAID was unable to negotiate a 12mm high obstacle. The lack of climbing ability of the device is due to a combination of its small front wheels (125x32mm), overall mass (41kg), and a high center of gravity. Since the device is designed for frail visually impaired individuals, it is important to provide the ability 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 of the strength testing and therefore development of a new design using lighter materials without sacrificing strength is already in progress. 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 of the control systems and the front wheels will be locked in position. While a failure with 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, it would still be advisable to give an auditory warning to the user that one or more of these sensors are malfunctioning. 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 operating 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 ability of the device to detect different surfaces under different conditions will also be examined. Individuals who use the walker in manual mode will depend on the voice messages to alert them to obstacles and other surroundings. Testing will be conducted 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 of 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 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.

5.6 CONCLUSION

The results for the testing on the prototype VA-PAMAID are encouraging. The walker has good range, adequate reaction time, and is structurally sound. The electronics are rugged and present minimal hazards due to failure. Revisions do need to be made with respect to wheel size and material selection. The next generation walker will take these considerations into account and should be even lighter and more maneuverable. Software upgrades are also being developed for the VA-PAMAID. Additional navigation systems utilizing dead reckoning and global positioning systems (gps) 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 it was in the cafeteria or the recreation room. Global positioning systems work 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 in order to compare the VA-PAMAID to a low-tech adaptive mobility device used by individuals with a visual impairment. Subject screening and activity data is 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. The VA-PAMAID will be compared to a low-tech mobility device.

The results of both the engineering and clinical testing will then be analyzed in order to determine what revisions should be made to the walker to make the device more reliable and effective. This will be accomplished through the use of a House of Quality model.

6.0 PHASE II STUDY

6.1 INTRODUCTION

Recent studies have shown that people are living longer [30]. As the generation of baby boomers from the 1940's and 1950's become older, the number of people 65 and over will be higher than ever before [31]. The number of persons ages 65 and older who lived in nursing homes in 1997 was approximately 1.5 million [32]. It has been predicted that this number could rise to 3 million by 2030 [33]. Residents of nursing homes are generally frailer than seniors living in the community. They also tend to be older, have more cognitive impairments, and experience more serious falls [34]. Rubenstein found that as many as 75% of nursing home residents fall annually [35]. A study in 1997 discovered that almost 30% of all nursing home residents had difficulty seeing even with glasses, and almost 10% were severely limited or completely blind [33]. There are approximately 25 million veterans in the U.S. of which 75% have served in a major conflict [36]. The Disabled American Veterans currently has 1.2 million members, who are veterans disabled as a result of their wartime military service [37]. The Veterans Administration Personal Adaptive Mobility Aid (VA-PAMAID) is an indoor walker that has been designed to provide navigational and mobility assistance to frail elderly individuals who are visually impaired.

The VA-PAMAID is equipped with a laser and sonic sensors that can map the environment and identify obstacles and landmarks (Figure 14). Feedback is provided to the user in the form of audio warnings. The front two wheels of the walker are coupled to motors that allow the device to control the direction of travel and avoid collisions. The VA-PAMAID has 3 different modes. In manual mode, the user has complete control of the walker. Information detected by the sensors is issued as voice messages describing landmarks and obstacles. In automatic mode, the user and the computer share control of the walker. 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 (Figure 15).

Figure 14 Front view of the VA-PAMAID robotic walker.

Figure 15 View of the front wheels in park mode.

The AMD is a cane-based assistive mobility device (figure 16). It was designed to be lightweight and equipped with wheels on the end to allow for easy maneuverability by elderly individuals. It has no autonomous navigational or obstacle avoidance capabilities. It requires very little training to master and can be used almost anywhere. This device was chosen to be compared to the VA-PAMAID because it is a low-technology device. Any possible advantages provided by the navigation and obstacle avoidance algorithm of the VA-PAMAID should be clearly evident when compared to the AMD.

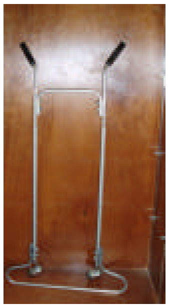


Figure 16 The AMD.

The purpose of this study was to determine if the VA-PAMAID could improve the safety, efficiency, and activity of elderly visually impaired individuals in a supervised care facility. Subjects were tested on a 36.6 meter obstacle course using the VA-PAMAID, the assistive mobility device (AMD), and their own device, if they used one. Differences in time, obstacle and wall contacts, and reorientation were analyzed. This work represents the second phase of the VA-PAMAID study. Initial engineering tests were performed to characterize the safety and performance of the walker [38].

6.2 METHODS

A total of 17 subjects were recruited for this study through the Veterans Administration HealthCare centers in Atlanta, GA, Salisbury, NC, and Tucson, AZ. An additional 8 individuals were recruited for the study, but dropped out before the testing had been completed. All of the subjects resided in a supportive living facility or rehabilitation center, and were ambulatory with limited assistance to the extent that they could walk at least 20 minutes over a 90 minute period. Demographic data collected from the subjects includes age, level of schooling, and information about visual impairment (Table 6).

The subjects were given an activity monitor before the testing began and after the testing was completed. The monitoring device was a FitSense speedometer capable of recording the number of steps taken and the corresponding time. Each subject was equipped with the monitor for three days before and after testing.

Baseline data collection was conducted after each subject was screened and signed the relevant informed consent forms. Subjects were first given a pretest independent mobility questionnaire (Table 6). This survey was intended to determine how the subjects rated themselves on mobility and how comfortable they were with their current mobility situation. Investigators will be able to determine specific areas of mobility that a given subject may benefit from by utilizing the walker. A mobility evaluation was then performed in order to determine the preferred walking speed (PWS) of each subject. The subjects were first asked to walk at their normal walking speed over a distance of 36.6 meters while accompanied by a human guide. The time was recorded and the PWS was calculated (PWS = Time (seconds)/36.6 meters).

Six different objects common to the living environment (such as chairs, wastebaskets, and wheelchairs) were then randomly placed along the 36.6-meter path. Each individual traversed the course with their own device and the time, number of obstacle contacts, number of wall contacts, and number of reorientations were all recorded. The subjects repeated this course three times with an appropriate rest between trials. The obstacles were randomly relocated before each trial. The subjects own devices included: 4 walkers, 7 long canes, and a sighted companion.

The testing order for the VA-PAMAID and AMD was randomly assigned for each subject. The pre-test subjective mobility questionnaire (Table 7) was then completed and the lesson plans (see appendix) were administered for the first device. The subjective mobility survey was intended to find out how the subjects initially felt about the devices without actually having used them. Once the subjects mastered the lesson plans, the post-test mobility evaluation for device 1 was conducted. The PWS was determined by having the subjects walk the 36.6-meter obstacle free path using the device. Each subject then used the device to traverse the 36.6-meter obstacle course three different times. The time, number of obstacle contacts, number of wall contacts, and number of reorientations were once again recorded. Finally, the post-test subjective mobility questionnaire was administered. The results of this survey were compared to the original survey to determine if the opinions of the subjects changed by the end of the study.

The subjects then completed the same tests and questionnaires for device 2. When all of the testing was completed for both devices, the post-test independent mobility questionnaire was then administered. The purpose of the pre and post-test questionnaires was to determine if the subjects' level of mobility had changed during the study. The progression of visual or mobility conditions could be identified, helping to highlight the need for an assistive device such as the VA-PAMAID. Figure 17 shows a flowchart listing the different sections of the clinical study.

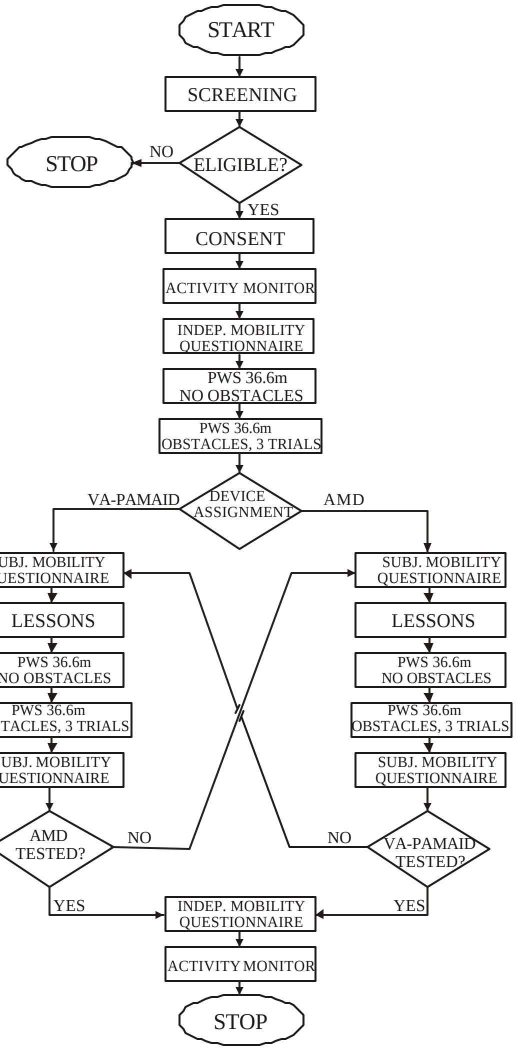


Figure 17 Clinical study flowchart.

6.3 STATISTICAL ANALYSES

All statistical analyses were completed using SPSS. Means and standard deviations were calculated for each of the independent factors. A paired T-test ($p< 0.05$) was used to compare the means of the pre and post testing activity data.

The Friedman Test for related samples ($p < 0.05$) was used to determine differences in time on the 36.6-meter path with no obstacles and the 36.6-meter path with 6 obstacles. The VA-PAMAID, the AMD, and the subject were the three levels of the independent variable. The Sign Test ($p < 0.05$) was then used to determine pairwise differences between the three levels if any significant differences were found.

Differences in the number of obstacle contacts, wall contacts, and reorientations on the 36.6-meter obstacle course were also determined by using the Friedman Test for related samples ($p < 0.05$). The results of the three trials were averaged for each device.

Each subject traversed the obstacle course using the VA-PAMAID during three separate trials. The first two trials were performed using the device in manual and automatic mode. The third trial was completed using the mode chosen by the subject. Differences were tested for between the selected mode and the non-selected mode. For instance, if the subject chose automatic mode for the third trial, then the results were compared to the first or second trial using manual mode. The Wilcoxon signed rank sum test ($p < 0.05$) was used to determine differences in time, obstacle/wall contacts and reorientations.

The intention of this study was to determine if the VA-PAMAID could provide mobility and navigational assistance to elderly visually impaired individuals. It is possible that certain subjects were able to effectively navigate the test path without the assistance of the VA-PAMAID. There would then be little difference between the results of the different conditions.

This may not necessarily mean that the VA-PAMAID was ineffective, rather that those subjects may not benefit from assistance. In order to account for such subjects, the distribution of the subjects' times to complete the test path without the use of either device was examined. The subjects with the longest times (> 60 seconds), implying that they had the most difficulty with ambulation, were identified. Additional Friedman Tests ($p < 0.05$) were then run to determine differences in time, obstacle/wall contacts, and reorientation. The models were identical to those run for the entire subject pool.

6.4 RESULTS

Subject characteristics are summarized below in Table 6.

Table 6 Subject Characteristics

Age	85.3 (7.0)
Initial Cause of Visual Impairment	13-age-related macular degeneration, 1-cataract, 2-other
Secondary Cause of Visual Impairment	4-other, 2-glaucoma, 1-cataract
Onset of Visual Impairment	1983 (13.0 years)
Amount of Schooling	1-8th grade diploma, 3-high school diploma, 2-tech. diploma, 5-some college, 2-4-year college degree, 2-additional college

The activity monitor data and paired t-test results are listed in Table 7.

Table 7 Activity Monitor Data

Activity Monitor Condition	Average steps/day (stand. Deviation)
Pre-Test	1361 (798)
Post-Test	1241 (768)
	Significance Level (p value)
Paired T-Test	.408

The results for the pre and post test independent mobility questionnaire are shown below in Table 8.

Table 8 Pre and Post Test Independent Mobility Questionnaire

	Pre-Test	Post Test	Difference
Problems walking around due to vision?	8/17	7/17	-1
Problems walking around due to other health issues?	9/17	4/17	-5
Feel safe walking by yourself?	14/17	8/17	-6
Each situation below was rated on a scale of 1-5, 1 signifies no difficulty and 5 signifies extreme difficulty.			
Walking in familiar areas	1.18	1.25	+0.07
Walking in unfamiliar areas	3.13	2.73	-0.4
Moving about in crowded situations	2.69	2.69	0
Walking through doorways	1.47	1.56	+0.34
Walking in high-glare areas	3.18	2.94	-0.24
Walking in dimly lit indoor areas	2.41	2.2	-0.21
Being aware of another person's presence	1.5	2.29	+0.79
Avoiding bumping into:			
People	1.76	1.56	-0.2
Walls	1.41	1.63	+0.22
Head-height objects	1.67	1.58	-0.09
Shoulder-height objects	1.19	1.36	+0.17
Waist-height objects	1.24	1.31	+0.07
Knee-height objects	1.94	1.81	-0.13
Low-lying objects	2.75	2.43	-0.32
Avoiding tripping over uneven travel surfaces	2.8	2.25	-0.55
Moving around in social gatherings	1.44	1.62	+0.18
Have you fallen in the last year?	6/17	5/17	+1
If yes, how many times?	8	9	+1
How often does someone accompany you?			
Are you satisfied with your present level of travel?	12/17	13/17	+1
Have you had mobility training?	7/17	4/17	-3
Do you use a mobility aid?	12/17	9/17	-3

Tables 9 and 10 list the results for the pre and post test subjective mobility survey for the VA-PAMAID and AMD, respectively.

Table 9 Pre and Post Test VA-PAMAID Subjective Mobility Questionnaire

Questions (Answered on a scale of 1-5, good to poor).	VAP-PRETEST	VAP-POST-TEST	Difference
How attractive do you find this device?	2.0	2.41	+0.41
How easy did you think it would be to use this device?	2.29	2.41	+0.12
How useful do you think it will be to move about in this living environment with this device?	2.65	2.47	-0.18
How comfortable do you think you will feel when using this device in front of other people?	1.94	1.71	-0.23

Table 10 Pre and Post Test AMD Subjective Mobility Questionnaire

Questions (Answered on a scale of 1-5, good to poor).	AMD-PRETEST	AMD-POST-TEST	Difference
How attractive do you find this device?	2.38	2.23	-0.15
How easy did you think it would be to use this device?	2.31	1.69	-0.62
How useful do you think it will be to move about in this living environment with this device?	3.15	2.92	-0.23
How comfortable do you think you will feel when using this device in front of other people?	1.54	1.62	+0.08

The average scores for the subjects on the 36.6-meter obstacle course are listed below in Table 11. Table 12 show the average scores for the subset of subjects with the longest times (>60 seconds).

Table 11 Average Scores for 36.6-meter Obstacle Course (All subjects)

	Own Device	VA-PAMAID	AMD
Time (sec)	86.1 (69.3)	98.5 (65.2)	76.3 (61.1)
Obstacles	.81 (3.1)	.73 (1.47)	1.0 (2.1)
Walls	.44 (2.27)	.31 (1.45)	2.26 (.39)
Reorientations	.27 (.63)	.3 (.74)	.18 (.39)

Note-standard deviations are in parentheses.

Table 12 Average Scores for 36.6-meter Obstacle Course (Subset of subjects, time >60s)

	Own Device	VA-PAMAID	AMD
Time (sec)	136 (85.1)	120.6 (83.2)	120.7 (80.7)
Obstacles	2.1 (4.9)	0.6 (1.5)	2.2 (3.0)
Walls	1.2 (3.9)	0.14 (.48)	5.7 (8.35)
Reorientations	.33 (.66)	.52 (1.03)	.2 (.41)

Note-standard deviations are in parentheses.

Tables 13 and 14 show the statistical results for all of the subjects and the subset of subset of subjects, respectively.

Table 13 Statistical Results (n=12)

	Significance Level*
36.6m Obstacle Course	
Time	0.017†
Obstacles	0.197
Walls	0.717
Reorientations	0.405
120’ Course- No Obstacles	
Time	0.368
Sign Test for Time on Obstacle Course	
Own device vs.VA-PAMAID	0.092
VA-PAMAID vs. AMD	0.039
Own device vs. AMD	0.98

* p-value

† Significant difference

Table 14 Statistical Results (Subset of subjects, time >60s, n=5)

	Significance Level*
36.6m Obstacle Course	
Time	0.819
Obstacles	0.584
Walls	0.368
Reorientations	0.99

* p-value

Table 15 shows the results for the paired t-tests for manual versus automatic mode for the VA-PAMAID.

Table 15 Statistical Results for Wilcoxon sign ranked sum test (Manual vs. Automatic mode, n=15)

Variable	Significance Level (p-value)
Time	0.442
Obstacles	0.671
Walls	0.276
Reorientations	0.269

6.5 DISCUSSION

There was no significant difference between the amounts of activity from the subjects before and after testing. In fact, the average number of steps per day was slightly more for the pre-testing period (1361 to 1241). Concerns with the reliability of the activity monitors were raised during the testing. The devices sometimes failed to register data for short periods of time. Allowing the subjects to use the VA-PAMAID, unsupervised, after testing had been completed, would provide a comparison to determine if the walker would increase the activity level of the users. However, due to constraints on equipment and personnel, as well as IRB restrictions, this was not a feasible option. One of the anticipated advantages of the walker is that it will encourage the user to be more active and move around the nursing home or rehab center more frequently. The best way to determine if this is actually happening is to train individuals on the walker and then let them use it independently. If an individual has unlimited access to the device then he or she may use it more often during their regular daily routine. The activity monitors used in this study recorded the number of steps each subject took before and after the testing. If the subjects were allowed to use the VA-PAMAID unsupervised for three days, then the result of such testing might produce the anticipated significant differences in activity.

A longer data activity collection time would have accounted for abnormal variations in subject routines. For instance, if a subject was feeling ill, or had an event planned that involved low activity, the results from that one-day could significantly skew the three-day activity total. If data were collected over a two-week period then the mean step count would be a better indication of daily activity. Therefore, future testing that involved collecting longer unsupervised activity data may prove to be more informative than the current results.

The practical amount of increase in the activity level that is possible with frail, elderly, visually impaired individuals should also be considered. The VA-PAMAID is intended as an indoor device that should be used in a supervised care facility. For the most part, these individuals have set schedules and are restricted to specific buildings or grounds. Given an effective mobility aid, the likely increase in activity level by these subjects would still be minimum. People who utilize guide dogs or long canes for visual assistance can usually travel anywhere in the community. These assistive technology devices provide the users with the tools necessary to navigate through their environments and their activity levels are therefore much higher than those who reside in supervised care facilities [39]. Therefore, an increase in activity level due to the VA-PAMAID would most likely be less evident than with another population [40]. This raises the question of whether the device should be modified to assist a larger population, or even simplified to produce more reliable behavior, since the mobility advantages provided by the current system appear to be minimum, and the investigators had difficulty recruiting enough subjects for the study.

The results of the pre and post-test independent mobility questionnaires demonstrate that there was little change in the perceived mobility levels of the subjects. Once again, the development of a long-term evaluation that has the subjects extensively using the VA-PAMAID would provide for an informative comparison. The results of the questionnaires show that many of the subjects were satisfied with their present level of travel, but had the most difficulty with crowded situations, high-glare areas, being aware of a person's presence, and avoiding low-lying objects and uneven surfaces. The current version of the VA-PAMAID does not detect drop-offs or very low obstacles. This may be a design change that should be considered in order to make the walker more effective. The opinions of the subjects did not change greatly for the pre and post-test subjective mobility questionnaires either. Their views on the performance of the device did not change during the testing and this seems to signify that the subjects were not overly impressed with the ability of the walker during the obstacle trials.

There were also no significant differences among the times taken to complete the test course with no obstacles. The AMD had a significantly lower completion time than the VA-PAMAID on the obstacle course. The AMD had the lowest average times on both courses for all of the conditions. The VA-PAMAID had lower average times than the subjects' own devices on the obstacle free course and on the obstacle course involving a subset of slower subjects.

On average, the VA-PAMAID contacted less walls and obstacles than the AMD and the subjects' devices, but the differences were not significant. The subjects had to reorient themselves fewer numbers of times with the AMD, but again, the difference was not significant. There were also no significant differences between the automatic and manual modes with the VA-PAMAID for any of the test variables.

The VA-PAMAID failed to outperform the other devices during the obstacle testing. It did not significantly reduce the travel time, obstacle/wall contacts, or reorientations. Based on the results of this study, the walker provides no significant advantages over the AMD with respect to travel time and safety. However, there are certain advantages provided by the walker that were not highlighted by this study. Mobility support is one of the main factors that the VA-PAMAID addresses. The other devices in the study provide no physical support for the users. The walker is also capable of providing information about the surrounding environment. It can recognize open doorways and t-junctions. Almost all of the subjects in this study also had some limited vision. They had to depend less on the ability of the walker to detect and avoid obstacles because they could identify them without assistance.

Although there were no significant differences for collisions with walls and obstacles, on average the subjects collided with less than 1 object per trial using the walker. Additional testing that incorporates factors that can measure the level of support and awareness of the surroundings may identify advantages that the VA-PAMAID provides that were not evident in this study. Testing subjects with severe visual impairments may also produce different results. However, the investigators had difficulty recruiting severely visually impaired elderly individuals for this study. The requirement that the subjects reside in an independent or assisted living center hampered recruitment. A majority of blind individuals reside in private residences until dementia limits their abilities to perform daily tasks. The walker is not capable of being used in homes and therefore cannot effectively reach its target population. The number of severely visually impaired individuals with the need for mobility assistance in supervised care facilities is low. Patients in nursing homes are not good candidates, either, because of low activity levels and dementia. Investigators may want to consider different subject requirements for future research. For instance, visually impaired subjects with no mobility problems would be easier to recruit. Useful information could be gathered involving the effectiveness of the navigational and avoidance software, and the overall performance of the device.

The results of this study also raise the question concerning how much time an individual should be exposed to a new technology prior to testing. The answer depends on several variables, including the complexity of the technology, how fast it can be mastered, how comfortable the users are with it, and the age of the users. Although the VA-PAMAID is not a difficult device to learn how to use, it does take some time to become accustomed to. The users must learn to trust the device and understand how to react during specific situations. The target population also complicates learning. Frail and elderly, visually impaired individuals will most likely have more reluctance to embrace the device than younger people. A robotic walker that can react autonomously could be intimidating. The clinical trials involved short-term sessions. A long-term analysis of subject use and reaction to the device may prove insightful.

The results of the clinical studies failed to detect any significant differences between the VA-PAMAID and the other devices for the test group as a whole, except for completion time on the obstacle course, where the AMD had a significantly lower time. Analysis of the individual cases showed that very few of the subjects even benefited from the walker with respect to the test variables. Using the VA-PAMAID, only three subjects had reduced travel times when compared to the subjects' own devices, and two subjects had lower travel times than when using the AMD. When comparing wall and obstacle contacts, and reorientations, three subjects benefited from the use of the VA-PAMAID over the AMD, and two subjects had less contacts than when using their own devices. The small number of subjects that showed increased performance by using the VA-PAMAID highlights the need to reevaluate the need for the device and the performance and function that it provides.

6.6 CONCLUSION

Overall, the results of the clinical testing showed that the VA-PAMAID performed at a similar level to the AMD and the subjects' own devices. Possible advantages in navigation and obstacle avoidance were not evident when compared to the other devices. Activity levels did not increase and travel time, wall/obstacle contacts, and reorientations did not significantly decrease. Additional testing including more obstacles, a longer course, and limited to severely visually impaired individuals may produce different results.

It appears to be unnecessary and of little value to continue research on the VA-PAMAID in its current condition. There are several reasons for this decision. First, the investigators had extreme difficulty recruiting subjects for this study. Only 17 subjects were tested at three different VA Healthcare sites. This resulted in an extremely low power for statistical analysis. The trouble with recruitment also identified a possible problem with the intended user population. The need for the VA-PAMAID, particularly for the stated population, appears to be lacking. It would be of little value to continue research before reanalyzing the need and intended users for the device. The results of the engineering and clinical tests have also demonstrated that the walker does not function reliably. The device fails to consistently detect doorways and t-junctions. The performance of the VA-PAMAID must be improved before additional testing should be considered.

7.0 PHASE III STUDY

7.1 INTRODUCTION

The Veterans Administration Personal Adaptive Mobility Aid (VA-PAMAID) is a walker that has been designed to provide navigational and mobility assistance to frail elderly individuals who are visually impaired [1,41]. The VA-PAMAID is built on the design of a traditional walker. The device is equipped with laser and sonar sensors that can map the environment and distinguish obstacles and landmarks such as doorways and junctions. Information is relayed to the user through a speaker on the control console. Motors are attached to the spindles on the front casters. When the device is in automatic mode, the computer will guide the direction of the walker away from walls and other obstacles. In manual mode, the user has full control over the device and is warned of objects and openings by the speaker. The VA-PAMAID is currently undergoing clinical trials to determine if it will improve the safety, efficiency, and activity of elderly visually impaired individuals in a supervised care facility. Figure 18 shows both the first generation and current edition of the VA-PAMAID.

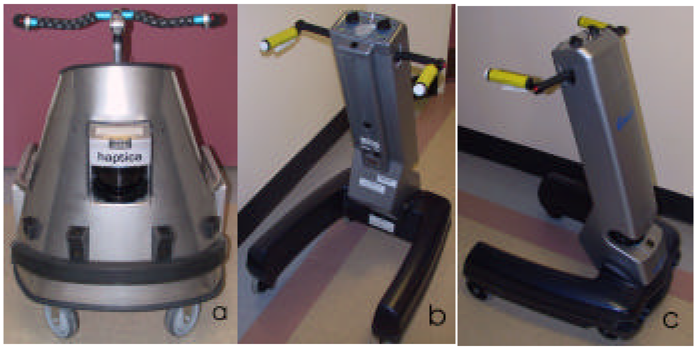


Figure 18 (a) Front view of the 1st generation VA-PAMAID. (b) (c) Back and side view of the current VA-PAMAID.

The first generation VA-PAMAID was tested to determine its safety and performance characteristics [38]. Testing included sections pertaining to static stability; maximum range; maximum effective speed; obstacle climbing ability; climatic conditioning; power and control systems; and static, impact, and fatigue strength. The results of that study demonstrated that the walker had sufficient range, adequate reaction time, and was statically and structurally stable. Concerns with the wheel size and material selection were noted but the device performed safely and was cleared for use in clinical trials.

Specific issues concerning sensor accuracy and reliability arose during the clinical studies. The VA-PAMAID was not consistently detecting all landmarks and obstacles. The device would sometimes fail to detect doorways and obstacles, especially when approaching at different angles. Differences were also noted between the manual and automatic modes. The walker would announce obstacles much sooner in automatic mode. Sometimes, in manual mode, the device would approach to within inches of, or collide with, an obstacle before providing a warning.

The purpose of this study was to determine the range and reliability of the sensors and the obstacle/landmark algorithm. The importance of the ability of the walker to accurately and reliably detect and identify obstacles and landmarks should not be understated. If a visually impaired individual is to entrust his or her safety to the VA-PAMAID, then the device must function properly without fail. The testing performed for this study was intended to address specific issues identified during user trials.

7.2 BACKGROUND

The VA-PAMAID has two types of sensors that are used to scan and map the environment (Figure 19). A SICK LMS scanning laser is the primary sensor. It provides a 180° 2-dimensional horizontal view of the environment. Polaroid ultrasound sensors are situated around the base of the walker (figure 2). The function of the sonar sensors is to act as a backup to the laser sensor and help detect any objects that the laser may miss [13]. Three of the sonar sensors point upwards to check if there are any objects in front of the walker but above the plane of the laser scan. If an object is detected by one of these sensors, then the computer will compare the results with the laser scan. If no points were detected by the laser, then a “head height” point is added to the navigation map and the walker will announce, “obstacle above”. Each sonar sensor creates a fan shaped beam approximately 28° wide.

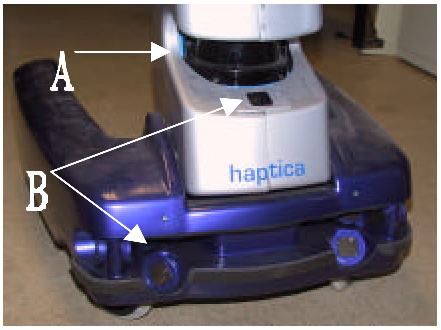


Figure 19 The VA-PAMAID consists of two different scanning sensors. The laser (A) is the main sensor and the ultrasound sensors (B) provide back-up and scan the area above.

The VA-PAMAID begins to search for a clear path in the direction specified by the user. If no clear path is found, then the system begins to alternate between the left and right sides of the user input angle until a clear path is located. If the user steers the device through a gap or past an obstacle, the walker will try to maintain a safe distance from the walls or obstacle [13]. The clean sweep algorithm first attempts to find a gap or clear space in the user specified direction and then attempts to find the safest path through the gap or space.

The safest path is defined as the extra distance of the extreme circles radii. The walker sets the safety distance to a maximum and determines whether or not a path can be found within that gap. If not, the distance is reduced in intervals until a safe path is found. This method insures that the walker will take the safest path through a gap or past an obstacle. For instance, if the walker is directed through a doorway, it will go through the center, and if the device is directed towards a wall, it will travel parallel to the wall at the maximum safe distance.

The laser and ultrasound sensors operate by measuring the time of flight of laser light pulses and ultrasound impulses, respectively. The range of the sensors depends greatly on the reflectivity of the target. Table 16 below lists the reflectivity values for some common materials

[42]. The light that is reflected off of the target surface can be split into two different components: diffuse and specular reflections (Figure 20). Specular reflections occur with mirrored or glossy objects. The angle of incidence of the light is equal to the angle of reflection. Diffuse reflections occur with materials with rough surfaces. Both the laser and sonar sensors are vulnerable to specular reflections. The placements of the sensors have been carefully selected to help create the maximum coverage for the walker.

Table 16 Reflectivity value of common materials

Material	Reflectivity
Cardboard, matt black	10%
Cardboard, grey	20%
Wood (raw pine, dirty)	40%
PVC, grey	50%
Paper, matt white	80%
Aluminum, anodized, black	110…150%
Steel, rust-free shiny	120…150%
Steel, very shiny	140…200%
Reflectors	>2000%

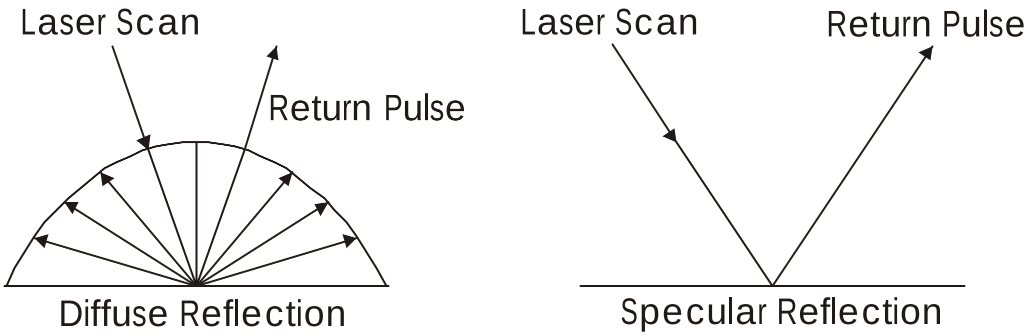


Figure 20 The diagram on the left shows the effects of diffuse reflection. The diagram on the right shows specular reflection.

7.3 METHODS

The VA-PAMAID has been programmed to detect doorways and other openings to the left and right. It informs the user of these landmarks by emitting an audio message that says, “opening right” or “opening left”. However, preliminary testing had shown that the device did not always detect or announce openings. Therefore, a hallway test was designed to measure the accuracy and reliability of the walker. The VA-PAMAID was pushed down the hallway shown in Figure 21. The number of openings detected and the distance that the walker was from each opening were recorded. The number of missed openings was also recorded. The VA-PAMAID was propelled at speeds of 0.5 m/s and 1.0 m/s. Testing was performed in both manual and automatic modes.

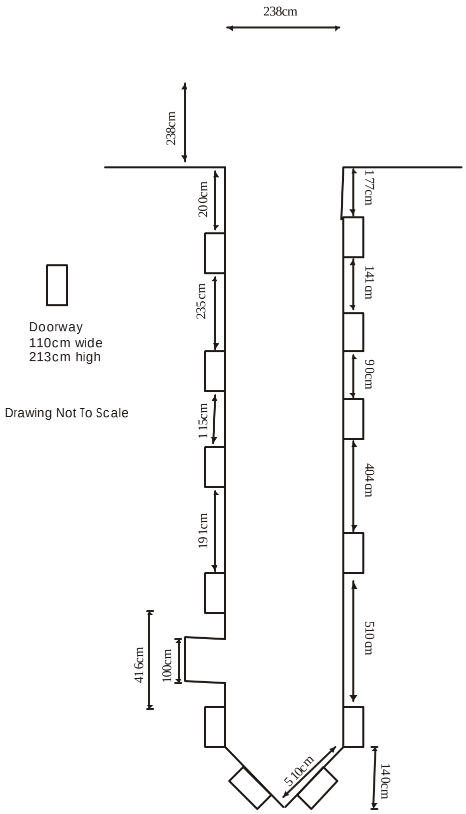


Figure 21 Layout of the hallway used for testing.

The VA-PAMAID is also designed to detect obstacles above the device, such as desks, cabinets, or doorways. An adjustable height obstacle (61cm wide x 30cm high x 35cm deep) was suspended from the ceiling and the walker was pushed under it to determine how well it actually detects overhead obstructions. The obstacle was suspended from an initial height of 30cm above the ground and then raised by an increment of 30cm until it was 180cm high. Two different obstacles were used for this test. One was constructed from wood and the other was built from sheet metal. Figure 22 shows a photograph of the sheet metal obstacle suspended 180cm above the ground. The reaction of the walker, including detection distance and response, was recorded during each trial. The device was tested in both manual and automatic modes at a speed of 0.5 m/s.

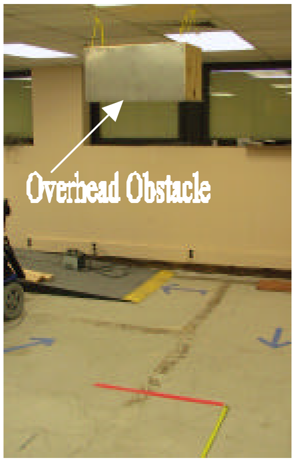


Figure 22 Obstacle and set-up for the overhead obstacle test.

The ability of the VA-PAMAID to detect and announce obstacles and landmarks is what will benefit the target population the most. The reliability of the device is therefore paramount to its success. A SICK LMS laser is used as the primary means of detection. Several ultrasonic sensors also provide periphery detection. Both laser and ultrasonic distance detection devices can be affected by target material and ambient light source [42]. A material/lighting test was performed to identify conditions under which the VA-PAMAID had difficulty detecting obstacles. Multiple obstacles were created out of wood, aluminum, polycarbonate lexan, steel, and PVC plastic. Each obstacle was 75 cm high by 45 cm wide. The walker was pushed towards each obstacle at a rate of 0.5 m/s. The detection time and response of the device were recorded. Each obstacle was tested under four different lighting conditions: fluorescent, incandescent, natural, and complete darkness. The walker was tested in both manual and automatic modes. Figure 23, below, shows the aluminum obstacle under fluorescent lights.

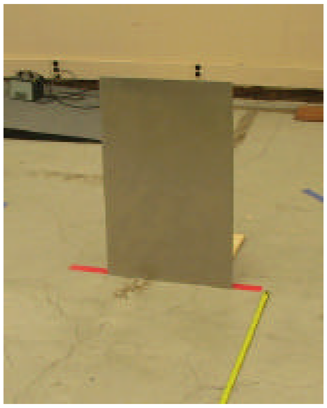


Figure 23 Obstacle and set-up for the material and lighting test.

The angle of detection is another important factor to consider when addressing the issue of device reliability. The VA-PAMAID must be able to reliably detect objects from various angles. The walker was pushed towards a 75 cm by 45 cm obstacle at a speed of 0.5 m/s. The angle of the obstacle was varied in both the sagittal and axial planes, as shown by Figure 24. The device was again tested in both the manual and automatic modes.

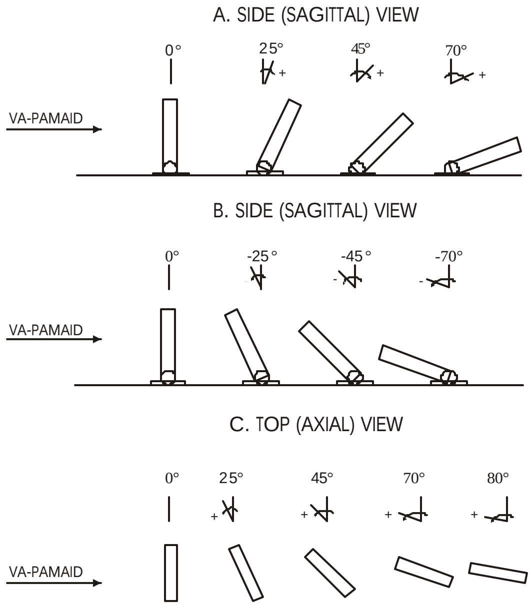


Figure 24 Set-up for the angle detection test.

7.4 STATISTICAL ANALYSES

All statistical analyses were performed using SPSS. A factorial analysis of variance (a = 0.05) was performed on the overhead obstacle test data. The obstacle height, material, and walker mode were used as the three factors. The manual and automatic mode trials were then separated and additional ANOVAs were performed for each set of data to determine significant differences in detection distance at the different obstacle heights for each mode. Post hoc analyses were performed using the Bonferroni method.

A factorial analysis of variance was also performed for the material/light test data, with obstacle material, light source, and walker mode as the three factors. Once again the manual and automatic mode trials were separated and two factor analyses using material and light source were performed for each mode. Post hoc analyses were performed using the Bonferroni method.

Two-factor ANOVAs were performed on both the axial and sagittal angle test data, with the obstacle angle and walker mode used as the factors. Single factor ANOVAs were also performed for each test after separating the manual and automatic mode data. Post hoc analyses were performed using the Bonferroni method.

7.5 RESULTS

The results for the hallway detection test are shown in Table 17.

Table 17 Hallway detection test

Condition*	Openings Detected		Avg. Detection Distance[†] (mm)	
	Left (out of 7)	Right (out of 8)	Left	Right
Middle/0.5/Manual	4	5	288 (229)	393 (233)
Middle/0.5/Auto	4	7	-142 (729)	-86 (728)
Left/0.5/Manual	6	5	-718 (875)	3 (612)
Left/0.5/Auto	4	5	-129 (719)	-30 (502)
Right/0.5/Manual	2	7	3 (4)	-215 (791)
Right/0.5/Auto	2	6	-374 (45)	-25 (278)
Middle/1.0/Manual	3	5	-273 (465)	-673 (645)
Middle/1.0/Auto	1	5	-380	-628 (633)
Left/1.0/Manual	4	5	-1095 (360)	-325 (722)
Left/1.0/Auto	4	4	-918 (646)	-600 (714)
Right/1.0/Manual	2	6	-1411 (284)	-664 (637)
Right/1.0/Auto	2	6	-806 (420)	-1221 (274)

*Condition- Position of VA-PAMAID/Speed (m/s)/Mode (manual or automatic)

[†] Average Detection Distances are averages of all openings detected on either the left or right side for that trial. Standard deviations are in parentheses.

The results of the overhead obstacle test are listed in Tables 18 and 19.

Table 18 Overhead obstacle detection test- Wood Obstacle

Height (cm)	Detection (yes/no)		Average Distance* (mm)	
	Manual	Automatic	Manual	Automatic
30	Yes	Yes	93 (21)	350 (87)
60	No	1/3[†]	-[‡]	50
90	Yes	Yes	175 (48)	164 (33)
120	Yes	Yes	213 (10)	218 (19)
150	Yes	Yes	229 (31)	244 (23)
180	Yes	Yes	264 (16)	278 (20)

*Average Distance is average of 3 trials for each height and mode. Standard deviations are in parentheses.

[†] Device detected obstacle only once during 3 trials.

[‡] Obstacle was not detected.

Table 19 Overhead obstacle detection test- Sheet Metal Obstacle

Height (cm)	Detection (yes/no)		Average Distance* (mm)	
	Manual	Automatic	Manual	Automatic
30	Yes	Yes	108 (4)	241 (27)
60	Yes	Yes	64 (14)	38 (15)
90	Yes	Yes	155 (26)	240 (53)
120	Yes	Yes	198 (8)	223 (11)
150	Yes	Yes	269 (24)	351 (27)
180	Yes	Yes	206 (5)	219 (4)

*Average Distance is average of 3 trials for each height and mode. Standard deviations are in parentheses.

The results for the material and lighting test are shown in Table 20.

Table 20 Material and lighting detection test

	Lighting Condition							
Material	Fluorescent		Incandescent		Natural		Darkness	
	Man*	Auto†	Man	Auto	Man	Auto	Man	Auto
Wood	39 (2)	374 (7)	41 (2)	282 (22)	32 (4)	368 (12)	24 (5)	381 (21)
Plastic	29 (2)	380 (25)	39 (5)	328 (22)	36 (5)	372 (27)	31 (4)	363 (17)
Alum.	27 (4)	395 (8)	24 (6)	319 (34)	29 (4)	373 (8)	21 (3)	397 (6)
Steel	26 (5)	380 (7)	26 (7)	372 (10)	29 (3)	381 (19)	24 (3)	386 (19)
Lexan	45 (5)	229 (16)	30 (4)	260 (19)	40 (2)	274 (11)	34 (5)	274 (18)
Glass	36 (4)	294 (12)	29 (4)	298 (24)	37 (5)	287 (19)	30 (4)	323 (21)

Note: Values in cells are the averages of the three trials for each condition. Values are detection distances in mm; standard deviations are in parentheses.

*Man- Manual mode

†Auto- Automatic mode

Table 21 lists the results for the object angle detection test.

Table 21 Object angle detection test

Obstacle Angle	Detection Distance* (mm)	
Sagittal Plane	Manual	Automatic
0°	46 (4)	298 (6)
25°	14 (5)	217 (17)
45°	7 (3)	163 (31)
70°	-[†]	-
-25°	-6 (6)	314 (12)
-45°	-14 (3)	302 (7)
-70°	-19 (3)	278 (3)
Axial Plane		
0°	48 (4)	299 (6)
25°	1 (2)	306 (5)
45°	0 (0)	215 (99)
70°	0 (0)	204 (4)
80°	0 (0)	196 (11)

*Detection Distance is average of three trials.

Standard deviations are in parentheses.

[†] Obstacle was not detected.

Significant differences (.000) were found between the manual and automatic modes for all of the tests. Significant differences in detection distance for varying obstacle heights, materials, angles, and light sources are listed below in Tables 22-26. There was no difference between the detection distances for the VA-PAMAID with a wood versus sheet metal obstacle for the overhead obstacle test.

Table 22 Statistical results for overhead obstacle test

Obstacle Height	Obstacle heights with significantly longer detection distances for VA-PAMAID
Manual Mode	
30cm	90cm (.001), 120cm (.000), 150cm (.000), 180cm (.000)
60cm	90cm (.000), 120cm (.000), 150cm (.000), 180cm (.000)
90cm	150cm (.000), 180cm (.000)
120cm	150cm (.003)
Automatic Mode	
30cm*	60cm (.000), 90cm (.003), 120cm (.025)
60cm	90cm (.000), 120cm (.000), 150cm (.000), 180cm (.000)
90cm	150cm (.002)
120cm	150cm (.020)

* Statistical results for height of 30cm represent obstacle heights with shorter detection distances.

Table 23 Statistical results for material/light test

Obstacle Material	Obstacle materials with significantly shorter detection distances for VA-PAMAID
Manual Mode	
Wood	Aluminum (.000), Steel (.000)
Plastic	Aluminum (.000), Steel (.001)
Lexan	Aluminum (.000), Steel (.000)
Glass	Aluminum (.001), Steel (.004)
Automatic Mode	
Wood	Lexan (.000), Glass (.000)
Plastic	Lexan (.000), Glass (.000)
Aluminum	Lexan (.000), Glass (.000)
Steel	Lexan (.000), Glass (.000)

Table 24 Statistical results for material/light test

Light Source	Light source with significantly longer detection distances for VA-PAMAID
Manual Mode	
Natural	Fluorescent (.000), Incandescent (.021), Darkness (.000)
Automatic Mode	
Fluorescent	Natural (.004)
Incandescent	Natural (.005)

Table 25 Statistical results for axial angle test (manual mode)

Obstacle Angle	Obstacle angles with significantly shorter detection distances for VA-PAMAID
Manual Mode	
0°	25° (.000), 45° (.000), 70° (.000), 80° (.000)
Automatic Mode	
0°	45° (.043), 70° (.025), 80° (.017)
25°	45° (.032), 70° (.019), 80° (.013)

Table 26 Statistical results for sagittal angle test

Obstacle Angle	Obstacle angles with significantly longer detection distances for VA-PAMAID
Manual Mode	
-70°	-25° (.027), 0° (.000), 25° (.000), 45° (.000)
-45°	0° (.000), 25° (.000), 45° (.001)
-25°	0° (.000), 25° (.001), 45° (.040)
25°	0° (.000)
45°	0° (.000)
Automatic Mode	
25°	-70° (.007), -45° (.000), -25° (.000), 0° (.001)
45°	-70° (.000), -45° (.000), -25° (.000), 0° (.000), 25° (.018)

7.6 DISCUSSION

The VA-PAMAID detected 64% of the openings in manual mode at a speed of 0.5 m/s. The device detected 62% of the openings in automatic mode at the same speed. The rates of detection for manual versus automatic mode at 1 m/s were 56% versus 49%. These results demonstrate that the VA-PAMAID needs to be more accurate and reliable when locating and identifying doorways. The detection distance of the device also varied greatly. A majority of the time, the device recognized the doorway after it was even with it or had already passed it. The average detection distance ranged from 393mm to (–718mm) at 0.5 m/s, and (–273mm) to (–1411mm) for 1.0 m/s. The negative sign implies that the device had already passed the doorway and the distance recorded is the distance past the beginning of the doorway.

While the VA-PAMAID failed to detect all of the door openings, it also became evident that the device was not capable of detecting closed doors. This may present problems in supervised care and rehabilitation settings. The use of reflective tape or transmitters may be able to alleviate this problem. If doorways were lined with reflective tape that the device could recognize or if transmitters were placed near doorframes, then there would be less of a chance of the walker missing a doorway, whether it was open or closed.

The VA-PAMAID detected the obstacle at every height except for 60cm for the wood obstacle. The device also had difficulty detecting the sheet metal obstacle at this height. The detection distance was considerably shorter than at the other heights. This height appears to be a blind spot for the walker. As the height of the obstacle increased, the detection distance of the walker generally increased, as well (see Figure 25).

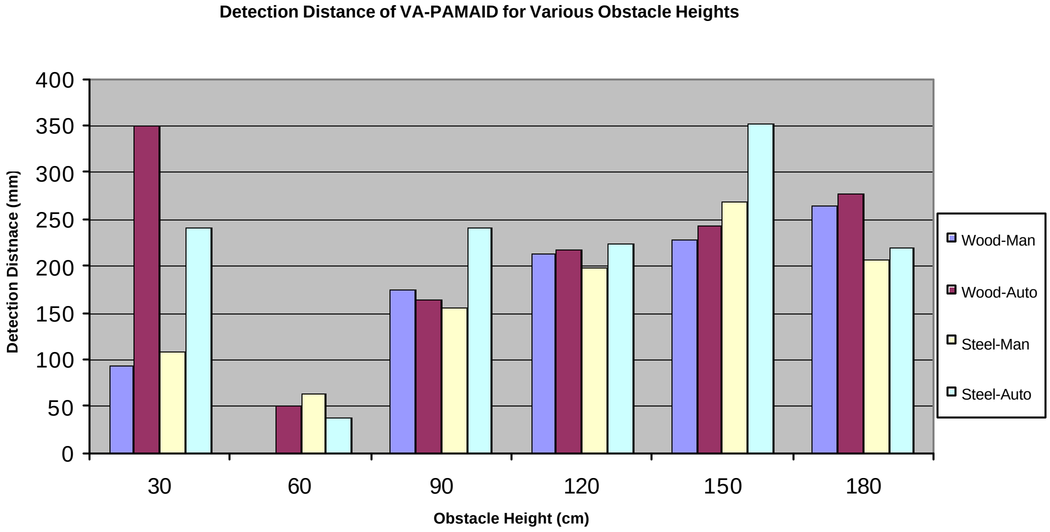


Figure 25 Graph showing the relationship between detection distance and obstacle height.

The ability of the walker to reliably detect overhead objects may actually cause more problems than it prevents. The detection of lights, signs, and other high placed objects can cause the walker to swerve in automatic mode, even if there is no danger of collision due to the height of the obstacle. Decreasing the range of the height sensors may prove to be advantageous. An evaluation of the specific site for which a given walker may be used would allow the staff to identify any head height or lower obstacles that could cause harm. The height sensor setting could then be adjusted to set the maximum range at said height.

The results for the material/light test show that in manual mode, the aluminum and steel obstacles are detected later than the other materials and that natural ambient sunlight produces the shortest detection distances. In automatic mode, lexan and glass are detected later and natural ambient sunlight allows for better detection than fluorescent and incandescent lights. Although there were significant differences between the detection distance of many of the different materials and light sources, the walker was able to detect all of the materials under every light. There were no apparent problems caused by specular reflection or transparent materials such as the glass and lexan. The most troubling result from this test was the average detection distance of the walker in manual mode under all conditions, 32mm. The maximum detection distance for any trial in manual mode was only 51mm (lexan/fluorescent). Theses detection distances simply do not allow enough time or distance to avoid a collision.

Luchies et al performed a study analyzing a voluntary step task in young adult (average age 20 years), young-old adult (average age 67 years), and old adult (average age 78 years) healthy females [43]. The subjects were asked to step as fast as possible in eight directions in response to a visual cue in a simple or choice reaction time condition. The effects of age, reaction condition, and step direction and their interactions on the outcome variables of response time, step liftoff, and step landing time were examined. The results showed that the reaction time of the old adults were 10 percent slower than the young-old adults, who were 23 percent slower than the young adults. The same trend held true for the other variables. The liftoff time of the old adults was 20 percent slower than the young-old adults, who were 24 percent slower than the young adults. The landing time of the old adults was 7 percent slower than the young-old adults, who were 19 percent slower than the young adults. This study demonstrates that the reaction time of an individual increases with age, particularly when a person is 65 or older. Since the target population of the VA-PAMAID is frail elderly visually impaired individuals, sufficient time and distance should be given to the user with the device in manual mode to avoid obstacles.

The VA-PAMAID had sufficient time to detect and avoid the different obstacles when in automatic mode. The obstacle detection algorithm for manual mode was written differently. Lacey determined through questioning prospective users that individuals who were most likely to use manual mode would have at least some vision [8]. Therefore, it was predicted that less of a warning distance would need to be given because the user would be able to see the obstacle. However, a detection distance of under 50mm provides very little room for error. At a speed of 0.5m/s, an individual would only have 1/10 of a second to respond at a distance of 50mm. Increasing this range to approximately 400mm would be safer. It would increase the reaction time to 8/10 of a second at a speed of 0.5m/s. Enabling the device to state distance along with the warning could also prove useful, particularly in automatic mode. The user could get a better sense of the location of the obstacle or landmark if given an exact distance.

Figure 26 shows the detection distance of the VA-PAMAID versus obstacle angle in the sagittal and axial planes. Similar to the other tests, the detection distances for automatic mode are significantly greater than those for manual mode. The maximum detection distance in manual mode was less than 50mm. The walker detected and avoided the obstacles without any problems in automatic mode. The only exception was with the obstacle at 70° in the sagittal plane. At this angle, the device failed to detect the obstacle in either automatic or manual mode. The angle of the obstacle affected the detection distance of the walker in both planes. The larger the angle of tilt of the obstacle the shorter the distance of detection. This was because of the amount of reflectance energy returned to the receiver. If an object is not perpendicular to the sensors, then a larger amount of the energy is reflected away from the sensors, making it difficult for the walker to detect the object [44].

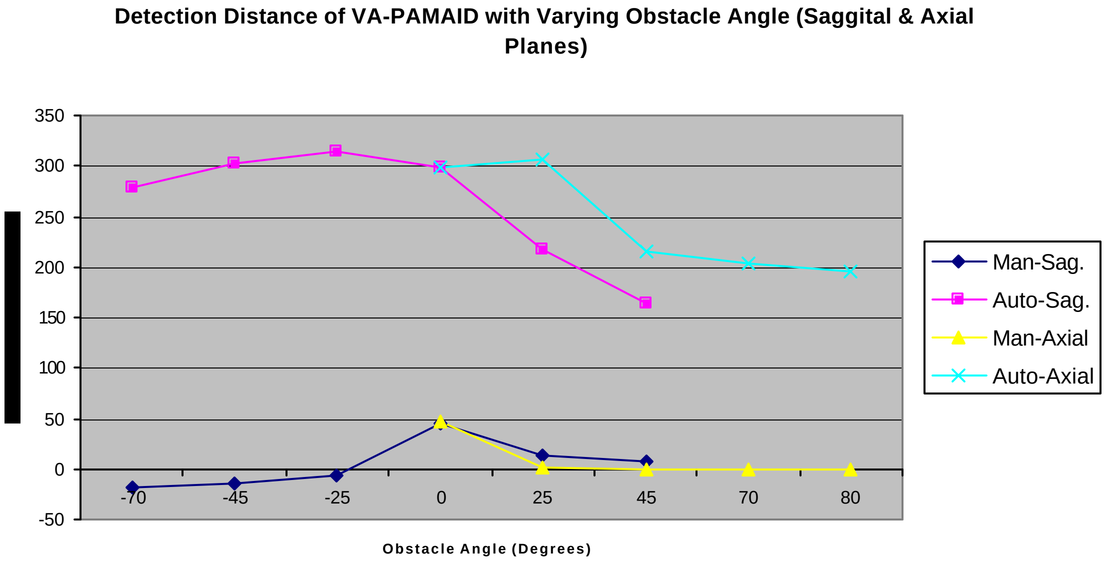


Figure 26 Graph showing detection distance in relationship to angle of the obstacle in both the sagittal and axial planes. Data points below 0 for detection distance mean that part of the obstacle had already passed the walker before it was detected.

The results of this testing mirrored the observations recorded during the clinical trials. The failure of the VA-PAMAID to consistently detect doorways was apparent in both studies. Subjects in the clinical trials found that the walker sometimes missed doorways or detected them too late. Investigators also observed that the walker was sometimes detecting overhead obstacles that posed no danger to the users. For instance, signs and some light fixtures were being identified as obstacles. These objects were located well above head height. The overhead obstacle testing in this study found that the walker was indeed capable of detecting objects up to the ceiling. Limiting the range of the overhead sensor may prevent unnecessary maneuvering by the device and reduce the confusion experienced by the user. The angle of approach by the VA-PAMAID also caused some detection problems. Clinical subjects that approached doorways and obstacles at an angle found that the walker sometimes failed to identify these objects. The obstacle angle test demonstrated that the greater the angle of an object deviated from the perpendicular, the more difficult it was for the walker to detect it. The walker sensors are most accurate when the device is directly facing a perpendicular target. The energy that is transmitted, either laser or sound, will bounce directly back to the receiver.

Researchers should investigate the use of simpler obstacle detection sensors. Results of clinical testing have shown that many of the subjects did not benefit from the advanced obstacle detection and navigation system of the walker. A simpler system that provides just basic information may provide enough assistance to help elderly visually impaired individuals. Such a system could be developed by using whisker sensors to detect obstacles and walls [45]. There are several different types of contact whiskers available, including binary and proportional, that when arranged in pairs can be used to detect obstacles and landmarks, as well as perform wall following and other navigational programs [46]. Investigators had difficulty recruiting totally blind subjects for this study. Most of the subjects had some level of vision and did not require mobility assistance. The use of a low cost whisker sensor system might provide the limited type of assistance that would aid these individuals, without providing too much extraneous information. Simplifying the device would make it more reliable and easier to use.

7.7 CONCLUSION

The results of the different tests in this study were consistent. Two main conclusions can be drawn from the data. First, the VA-PAMAID must be made more reliable and accurate when detecting landmarks such as doors and openings. An individual cannot rely on the device to give accurate information consistently. This could cause serious navigational problems and create confusion and helplessness. The second issue concerns the amount of time and distance given to the user in manual mode when confronted with an obstacle. The parameters of the manual mode detection program should be changed to those of the automatic mode. The users must be given enough time to react to the presence of an obstacle.

The VA-PAMAID is currently undergoing clinical evaluations. The results of this study have illustrated that certain issues with the software and avoidance algorithm must be addressed. Recommendations for changes to the device will be considered after all clinical and engineering tests have been completed and an overview of the advantages and disadvantages of the device has been analyzed. The device can then be retested using the same protocol in order to determine what effect the changes would have on the performance.

8.0 PHASE IV STUDY

8.1 INTRODUCTION

Specific design issues that could improve the safety and performance characteristics of the VA-PAMAID have been identified during the engineering test phase of the project [38]. The results of the clinical trials have also provided both quantitative and qualitative data that will highlight additional design changes that may make the device more user-friendly and ultimately more marketable. In order to evaluate these ideas and determine what effect they will have on the overall design of the device, a house of quality model was instituted. The house of quality is a basic design tool of the broader management approach known as quality function deployment [47]. The process adheres to the belief that products should be designed to reflect customer desire and taste. It integrates marketing, design engineering, and manufacturing so that the team can account for the effect that a specific change can have over the entire process.

8.2 METHODS

The house of quality model is essentially a matrix that can illustrate the relationship between customer attributes (CAs) and engineering characteristics (ECs). Customer attributes refer to phrases used by the customers to describe requirements for products and product characteristics. For instance, subjects from the clinical trial might list “easy to push over rugs and thresholds” and “easy to push up inclines” as customer attributes they desire for the VA-PAMAID. The CAs can also be grouped into bundles of attributes that represent an overall customer concern, such as “easy to push” or “easy to use”.

The ECs are listed by the design team along the top of the house of quality. The ECs that are listed are likely to affect one or more of the CAs. A positive sign by the EC means that engineers desire to increase the level of that EC and a negative sign means that they wish to decrease it. For instance, if “+ wheel size” is listed as an EC, then the design engineers wants to increase the size of the walker wheels. If a common EC affects none of the CAs, then it may be redundant to the list or it may mean that a CA has been missed.

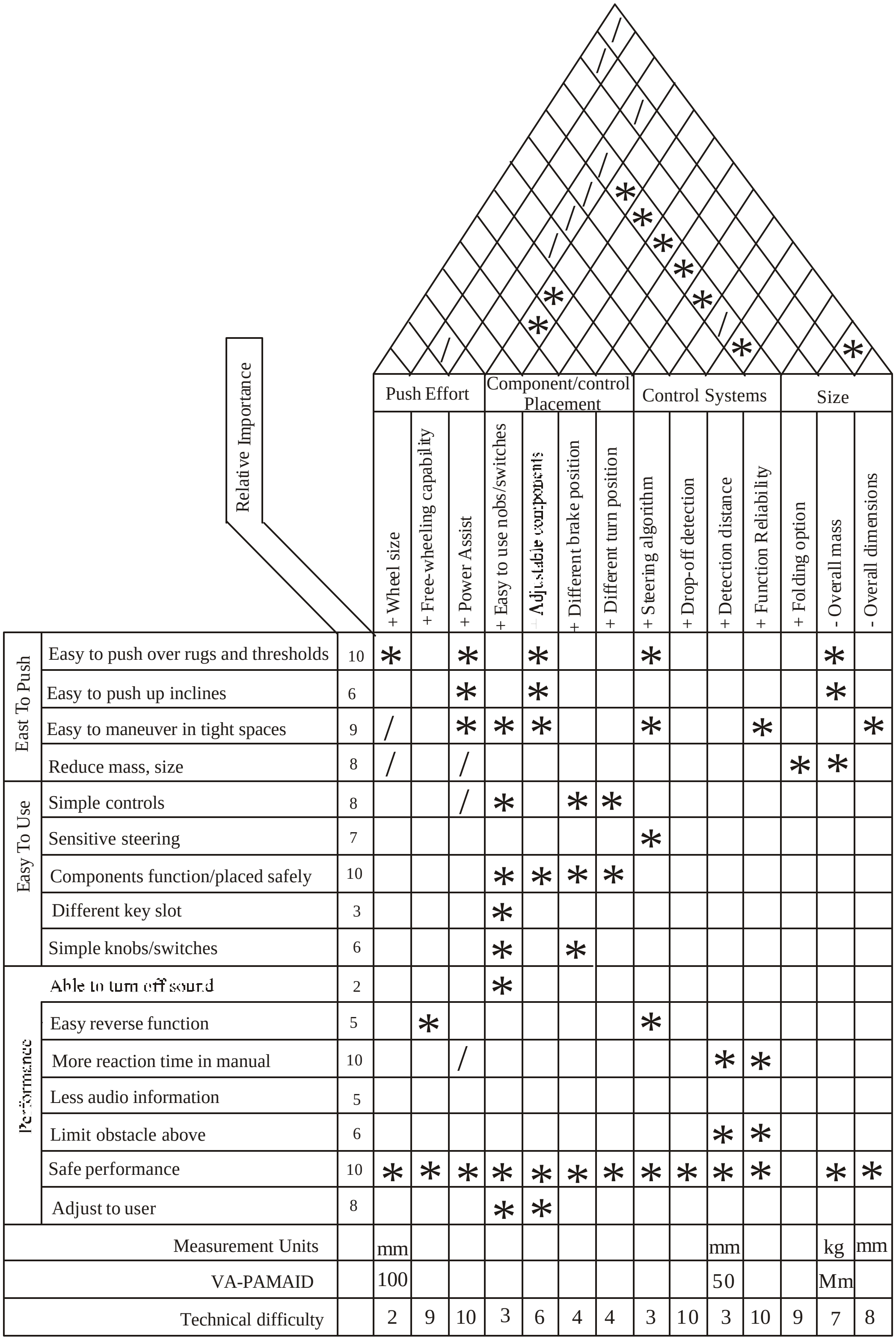
The CAs are listed on the left side and go from groups to specific attributes. The ECs are listed in a similar fashion along the top. Below the CAs are the objective measures as well as the technical difficulty. The objective measures list known values for specific ECs For example, the diameter of the wheels is 100mm. The technical difficulty row lists how difficult it will be to institute the change on a scale of 1-10 (10-hardest). The column right next to the CAs lists the relative importance of the attributes. For example, the ability to easily push the walker over rugs is of more importance to the customers than the ability to easily push the walker up an incline. These values were determined by the number of times the subjects logged a suggestion or complaint, as well as by what factors the engineers and test personnel felt would best increase the safety and performance of the device.

The interaction between each CA and EC is rated with a *, a /, or nothing. A * signifies a positive relationship between the factors and a / represents a negative relationship. A blank space means that there is little or no relationship between the variables. Take wheel diameter, for instance. Increasing the wheel diameter, as listed for the EC, will make it easier to push the device over rugs (*) but more difficult to maneuver in tight spaces (/). Analyzing the matrix will allow the engineers to determine how changing one EC can affect multiple CAs. However, changing an EC can also affect other ECs. The relationship between ECs is shown as the roof of the house. The same symbols are used to illustrate these relationships. For instance, increasing the wheel diameter will actually raise the COG (unless the body is lowered to account for the larger wheels).

The house of quality model will allow for an in-depth analysis of the possible changes that could be made to the VA-PAMAID. The effects of changing engineering characteristics can be balanced with the requirements of the subjects. The ECs were created from the results of the engineering and clinical testing as well as from the opinions and observations of the individuals involved in the testing of the walker. The CAs were developed from the subject surveys and comments.The individuals involved in both aspects of the testing will provide opinions and observations for ECs as well as CAs.

8.3 RESULTS

The house of quality model for the VA-PAMAID project is shown below in Figure 27. The customer attributes are located along the left side of the house and the engineering characteristics are located along the top of the house.



		Relative Importance	Push Effort			Component/control Placement				Control Systems				Size		
			+ Wheel size	+ Free-wheeling capability	+ Power Assist	+ Easy to use nobs/switches	+ Adjustable components	+ Different brake position	+ Different turn position	+ Steering algorithm	+ Drop-off detection	+ Detection distance	+ Function Reliability	+ Folding option	- Overall mass	- Overall dimensions
East To Push	Easy to push over rugs and thresholds	10	*		*		*			*					*	
	Easy to push up inclines	6			*		*								*	
	Easy to maneuver in tight spaces	9	/		*	*	*			*			*			*
	Reduce mass, size	8	/		/									*	*	
Easy To Use	Simple controls	8			/	*		*	*							
	Sensitive steering	7								*						
	Components function/placed safely	10				*	*	*	*							
	Different key slot	3				*										
	Simple knobs/switches	6				*		*								
Performance	Able to turn off sound	2				*										
	Easy reverse function	5		*						*						
	More reaction time in manual	10			/							*	*			
	Less audio information	5														
	Limit obstacle above	6										*	*			
	Safe performance	10	*	*	*	*	*	*	*	*	*	*	*		*	*
	Adjust to user	8				*	*									
Measurement Units			mm									mm			kg	mm
VA-PAMAID			100									50			Mm	
Technical difficulty			2	9	10	3	6	4	4	3	10	3	10	9	7	8

Figure 27 House of quality model for VA-PAMAID.

8.4 DISCUSSION

Listed below are explanations of the engineering characteristics listed in the model and their effects on the customer attributes.

Wheel size: Increasing the size of the wheels on the walker will make it easier to push the device over obstacles such as rugs and thresholds. Results from both the engineering tests and clinical evaluations have shown that it takes considerable strength and energy to propel the walker over even the smallest of obstacles [38]. However, increasing the wheel size will have some negative effects, as well. It will make it more difficult to maneuver in tight spaces and will increase both the overall size of the walker and the position of the center of gravity, unless the body is lowered. Increasing the wheel size will also have a slightly negative effect on the overall mass and dimensions of the walker.

Free-Wheeling: Adding a free-wheeling capability to the VA-PAMAID will add to the safety of the device and confidence of the user. Currently, if the walker locks up or shuts down, its front wheels are locked in place. Therefore, it is unusable and unmovable if an error occurs with the control system or electronics. Equipping the device with a free-wheel option would allow the user or an assistant to be able to bypass the control system if an error occurs. However, designing a free-wheel device that could be incorporated into the current walker set-up would be challenging and difficult. The motors would need to be able to spin freely and an alternate steering method would have to be utilized since the current design is based on a potentiometer that relays information to the controller.

Adjustable components: The target population for the VA-PAMAID is frail, elderly, visually impaired individuals. These users will have reduced strength and reaction times [43,48]. Providing a customized set-up will help the users to be more efficient and confident. The height and angle of the handlebars can be slightly adjusted (Figure 28). Increasing the amount of adjustability for the handlebars as well as being able to change the width and horizontal position would allow for users to create a more comfortable fit with the device and should help increase reliability.

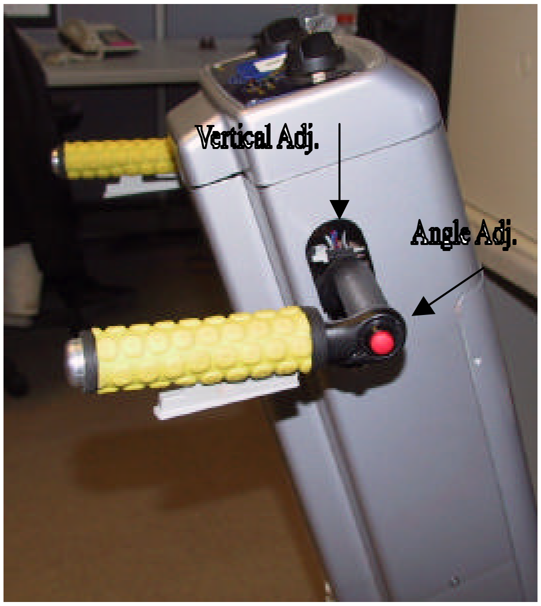


Figure 28 A side view of the VA-PAMAID handlebars. There is limited adjustment for the vertical position of the handlebars. The angle of the handgrips can also be adjusted.

Easy to use knobs and switches: It is important to make the controls of the walker as easy to use as possible. This includes making them readily accessible and intuitive to use. Subject surveys during the clinical testing showed that some of the subjects had difficulty operating the function knobs and even inserting the start-up key (Figure 29). Safety and reliability of the device will be improved if the users are comfortable with the controls.

Figure 29 Subjects had difficulty with the mode knob (A), sometimes clicking it too far so that no mode was selected. Some subjects also had problems inserting the power key (B).

Brake position: Many of the subjects were unknowingly squeezing the brake handles during the clinical tests.The fact that an individual needs the assistance of a walker signifies that they have some sort of strength and/or mobility issue. It is not possible for an individual to wrap his or her hands completely around the handgrip without actuating the brakes. Using a button to activate the brakes or changing the lever to a more traditional bicycle type lever would afford the users more stability by allowing them to fully grip the handles (Figure 30).

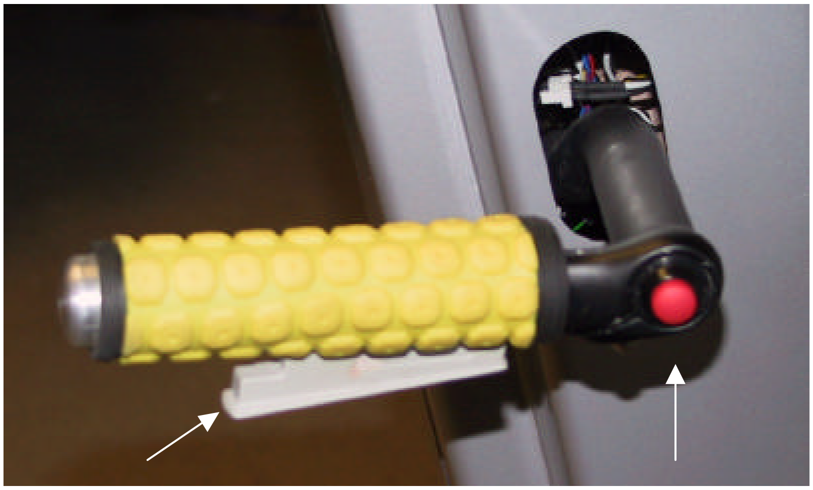


Figure 30 The brake lever is positioned directly under the handgrip and prevents the user from gripping properly. The turn button is also in somewhat of an awkward position and makes it difficult for the user to depress and hold it in order to turn the device.

Turn button position: Some of the subjects also reported that they had difficulty pushing the turn button because of its location (Figure 30). A button positioned on the handgrip near the thumb might allow for easier activation by the user without having to move their hand or release their grip. Currently, the subject must either use their index finger or supinate their hand and extend their thumb to push and hold the button.

Steering algorithm: The VA-PAMAID is equipped with a spring-loaded handlebar mounted with a potentiometer. When the user turns the handlebar, the potentiometer sends an angle reading to the control system, which then directs the front wheel motors to turn in that direction. However, the spring is extremely stiff and it requires some effort to turn the handlebars in order to initiate a turn. Making the steering algorithm more sensitive would reduce the force needed to turn the walker and improve the maneuverability and user driving skills. Another solution to the problem could be to install a lighter spring that would require less strength to extend.

Drop off detection: Currently, the VA-PAMAID is designed to function indoors at supervised care and assistive living centers. It has not been equipped to detect stairs or drop-offs and should not be used anywhere there is a change in levels. Developing a drop-off detection program would allow the device to be used in many more places. However, this is a low priority change. Improving the other functions and capabilities of the walker should be accomplished first since they have a significant effect on performance and safety.

Detection distance: The results from both the engineering and clinical tests have shown that the walker detects and announces obstacles in manual mode at a very short distance (< 50mm). The user has little time or space to successfully maneuver around the obstacle. Therefore, increasing the audio warning when the obstacle is detected would enable the user to react in a timelier and safer manner.

Function reliability: The VA-PAMAID has to function reliably on a consistent basis. Additional engineering tests found that it has troubles consistently detecting open doorways and often fails to detect closed doors. In confined space, the device can also lock up and prevent the user from maneuvering. The navigational and obstacle avoidance software must perform flawlessly in order for the user to trust the device. If the walker cannot accurately map its environment then it provides little advantage over a traditional non-robotic device.

Overall dimensions: Some of the subjects felt that the walker was too big and bulky. People are most likely more used to traditional type walkers that are smaller and lighter because they contain no electronics or motors. Certain steps could be taken to reduce the overall size of the device, though. Reducing the length of the struts that connect the rear wheels to the walker would decrease the footprint of the walker (Figure 31). This would allow for tighter maneuvering and make the device look less bulky. Additional testing would have to be performed to insure that stability is not grossly affected. However, few supervised care facilities have steep indoor inclines.

Figure 31 The length of the walker legs could be shortened in order to reduce the overall dimensions of the device.

Overall mass: Reducing the overall mass will make the walker easier to push on carpets, over thresholds, and up inclines. Currently, the mass of the walker is 32.8 kilograms. Many of the elderly subjects commented that the device was too bulky and difficult to push. A minimum amount of effort should be needed to propel the walker under normal operating conditions.

Folding option: Although not a priority, future versions of the walker should incorporate the ability to fold for transport in a vehicle. Currently, the device is bulky and fits only in a van or truck. Since the device is only intended for indoor use, transportability is not an immediate concern. However, it should be considered if future versions are intended for community use.

Power assist: One of the earlier versions of the PAMAID was an active robot that could drive itself [5]. It was decided due to safety and navigational concerns that the VA-PAMAID should be a passive device propelled by the user. However, most elderly patients residing in supervised care facilities and rehabilitation hospitals have decreased strength and stamina [49]. Adding the option of power assist for going over thick carpets or up inclines might make the walker easier to use and more attractive to potential candidates. The technical difficulty involved in this modification is extremely high. Safety issues must also be considered when considering an active walker. However, if the mass of the device cannot be significantly reduced in order to assist user propulsion, this may become a viable option.

The most important design changes identified by the house of quality model affect the safety and performance of the VA-PAMAID. These changes should include the wheel size, brake and turn button positions, detection distance, and function reliability. The detection distance and function reliability changes take priority above all other issues. The walker must be able to identify landmarks and obstacles both correctly and consistently. These are the most significant concerns that will ultimately impede or contribute to the success of the device.

The relative importance of the customer attributes is directly correlated with the priority engineering design changes. Ease of propulsion, maneuverability, component function, reaction time, and safety and performance are listed as the most important factors. All of the individuals involved in this study, from investigators to subjects, have focused on safety and performance as the most crucial aspects of the development of a successful robotic walker.

Several of the proposed design changes involve ergonomic issues. For example, the addition of adjustable components, and the placement of easy to use knobs and switches will provide greater physical comfort to the user and therefore result in better performance. Although these factors may not appear to be as vital to the immediate success of the device, they will certainly affect long-term evaluations for comfort and performance.

The power assist, drop-off detection, and folding capability options represent future changes that should be considered after the other design components have been addressed. These factors will not affect the immediate performance of the walker or its capabilities.

8.5 CONCLUSION

Initial tests conducted on the VA-PAMAID have shown that given the right circumstances and locations, the walker can provide a beneficial source of independent mobility. The testing has also identified specific design and performance criteria that need to be modified in order for the walker to perform in a safe, reliable, and effective manner. The house of quality model for the VA-PAMAID has helped to identify what factors should be changed. Once revisions have been implemented, additional tests should be run on the device to determine the effectiveness of the changes.

APPENDIX A

The Independent Mobility Questionnaire is shown below. It was administered to the subjects before testing began and again after testing was completed.

INDEPENDENT MOBILITY QUESTIONNAIRE-PRETEST

1. Do you have problems walking around because of your vision? ___Yes ___No
2. Do you have problems walking around because of other health problems? ___Yes ___No
If "Yes," please describe: ____
3. Do you feel safe when you walk by yourself? ___Yes ___No
4. List 3 things that cause you the most stress in your mobility situations (walking around):
   a.______ b.______ c.______

Directions: Read each mobility situation given below and circle the number that best expresses the level of difficulty you feel in the situation without any assistance (cane, companion, guide dog, etc.). **On a scale of 1 to 5, 1 represents no difficulty** and **5 represents extreme difficulty**. N/A represents not applicable. Use N/A also if you only perform an activity with assistance. If your selection is greater than 1 and the difficulty is due to some reason other than your vision loss, please place an "x" in the blank space.

		No Difficulty			Extreme Difficulty	
Walking in familiar areas………………………	N/A	1	2	3	4	5
Walking in unfamiliar areas……………………	N/A	1	2	3	4	5
Moving about in crowded situations…………	N/A	1	2	3	4	5
Walking through doorways…………………..	N/A	1	2	3	4	5
Walking in high-glare areas…………………	N/A	1	2	3	4	5
Walking in dimly lit indoor areas……………	N/A	1	2	3	4	5
Being aware of another person's presence…..	N/A	1	2	3	4	5
Avoiding bumping into:						
People………………………………	N/A	1	2	3	4	5
Walls………………………………	N/A	1	2	3	4	5
Head-height objects………………..	N/A	1	2	3	4	5
Shoulder-height objects……………	N/A	1	2	3	4	5
Waist-height objects………………	N/A	1	2	3	4	5
Knee-height objects………………..	N/A	1	2	3	4	5
Low-lying objects………………….	N/A	1	2	3	4	5
Avoiding tripping over uneven travel surfaces..	N/A	1	2	3	4	5
Moving around in social gatherings…………	N/A	1	2	3	4	5

Have you fallen in the last year? (By "fallen", I mean unintentionally come to rest on the ground or at some lower level) ___Yes ___No

If so, approximately how many times? ___

How often do you ask someone to accompany you when you leave your house?
___Always ___Usually ___Sometimes ___Never

Are you satisfied with your present level of travel? ___Yes ___No

Have you ever had any kind of training to help you move around better ("mobility training")? __Yes __No

Do you use a mobility aid such as a guide dog, cane, sighted companion, walker (if yes, circle appropriate device used)? ___Yes ___No

APPENDIX B

The Subjective Mobility Questionnaire is shown below. It was administered to the subjects before the lessons for each device (VA-PAMAID and AMD) and after testing was completed for each device.

SUBJECTIVE MOBILITY QUESTIONNAIRE- ROBOTIC WALKER PRE-TEST

	Good			Poor	
1. How attractive do you find this device?	1	2	3	4	5
2. How easy did you think it will be to use this device?	1	2	3	4	5
3. How useful do you think it will be to move about in this living environment with this device?	1	2	3	4	5
4. How comfortable do you think you will feel when using this device in front of other people?	1	2	3	4	5

APPENDIX C

The lesson plans for the AMD and VA-PAMAID are shown below. The lesson plans were conducted before any testing was performed with the devices.

AMD Lesson Plans

Lesson 1

Objective: Familiarization with the structure and function of the adapted cane.
Instruction: 1. Identify the parts of the adapted cane- grips, shifts, cross bars, bumper bar, and wheels.
2. Grasped with both hands, moves forward as the body moves forward, understands that the cane will not support any body weight.
Criteria for Success: Will name the parts of the adapted cane.

Parts	1st	2nd	3rd	4th	5th	6th
Grips						
Shifts						
Cross bars						
Bumper bar						
Wheels						
DATE						

Lesson 2

Objective: Able to walk forward using the adapted cane.
Instruction: Maintains cane on the ground, grasps with both hands, in front of the body while walking forward.
Criteria for Success: While maintaining normal up-right posture, participant will walk the full length of a 120-foot hallway using the adapted cane.

DATE ACHIEVED ____________________

Lesson 3

Objective: Participant will stop walking when the adapted cane contacts an obstacle and locate a clear area to either the right or left of the obstacle.

Instruction: Participant will walk forward and make cane contact with an obstacle placed in the line of travel. Participant will stop walking once the cane has made contact. With the cane, she/he will locate the clear area to the side of the obstacle.
Criteria for Success: Participant stops when the cane contacts an obstacle and locates the clear area to the side of the obstacle 8 out of 10 attempts.

DATE ACHIEVED ______________________

Lesson 4

Objective: Able to re-establish line of travel after contacting an obstacle.
Instruction: Participant will walk forward through a hallway that the instructor has placed 10 obstacles in the line of travel. When the adapted cane contacts the obstacle, the participant will walk around the obstacles and re-establish the correct line of travel.
Criteria for Success: Participant can contact an obstacle and re-establish line of travel in 8 out of 10 attempts.

DATE ACHIEVED______________________

Lesson 5

Objective: Able to use the adapted cane to trail a wall and locate opening.
Instruction: Participant will locate the wall with the bumper bar. While maintaining intermitting contact with the wall, she/he will walk parallel to the wall, identify hallway openings and cross over the opening while maintaining line of travel.
Criteria for Success: Can successfully identify and cross 3 out of 4 openings.

DATE ACHIEVED______________________

Lesson 6

Objective: Able to make accurate turns after locating hallway opening.
Instruction: Participant will walk down a hallway, locate hallway openings to the right and to the left either using sound location or by trailing with the adapted cane. Once the opening is located, she/he will make an accurate 90-degree turn into the opening.
Criteria for Success: Can successfully make a turn 3 out of 5 times with at least one turn being to the left.

DATE ACHIEVED______________________

Lesson 7

Objective: Able to travel a prescribed route with a starting and ending point that involves at least three turns.
Instruction: Participant will walk the prescribed route (ex: To complete the route, go out of one room and into a hallway by making a turn, travel down the hallway and turn into another hallway, then locate a room and turn into it). During the route, the participant must negotiate around three obstacles. These obstacles can be natural to the environment or positioned by the instructor.
Criteria for Success: Participant will be able to complete the route, reaching the destination, maintaining a line of travel after making cane contact with obstacles, and making the correct turns without any episodes of disorientation.

DATE ACHIEVED____________________

PAMAID Lesson Plans

Lesson 1- MANUAL MODE
Objective: Able to walk forward with PAMAID.
Instruction: Begin instruction in manual mode, volume off- walk comfortably, walk forward.
Criteria for Success: Can walk the full length of a 120-foot hallway.

Date:_____________________

Lesson 2- MANUAL MODE

Objectives: Respond to statement of “obstacle above”; pushing the red button to negotiate the wheels; turn the PAMAID until the “path clear” statement is heard.
Instruction: Instructor will hold a book at shoulder height directly above the student’s path. Once the student hears the statement “obstacle above”, the student stops.
Criteria for Success: Participant stops when the statement “obstacle above” is heard 3 out of 5 times.

Date:____________________

Lesson 3- MANUAL MODE
Objectives: Respond to statement of “obstruction”; pushing the red button to negotiate the wheels; turn the PAMAID until the “path clear” statement is heard.
Instruction: Instructor will serve as obstacle. Student hears statement “obstruction”. Student pushes button then moves the PAMAID to a very small degree to achieve the “path clear” statement.
Criteria for Success: Participant can approach an obstacle and be able to achieve the “path clear” statement in 8 out of 10 attempts.

Date:____________________

Lesson 4- MANUAL MODE
Objectives: Participant is able to negotiate around obstacle.
Instruction: Participant will walk forward through a hallway that the instructor has placed 10 obstacles in front of him/her. When the PAMAID states “obstruction”; recognize command, respond by moving around obstruction and toward the “path clear” command.
Criteria for Success: Participant can approach an obstacle and be able to achieve the “path clear” statement in 8 out of 10 attempts.

Date:_____________________

Lesson 5- MANUAL MODE
Objective: Able to stop when hearing the response “opening right” and “opening left”.
Instruction: Have participant walk down the hallway, listening for the statement “opening right” or “opening left”. When the statement is heard, stop and point toward the opening.
Criteria for Success: Can successfully stop and point to 8 out of 10 openings.

Date:______________________

Lesson 6- MANUAL MODE
Objective: Able to turn into an open hallway or doorway after hearing the response “opening right” or “opening left”.
Instruction: Have participant walk down the hallway, listening for the statement “opening right” or “opening left”. When the statement is heard, make the turn into the hallway/doorway.
Criteria for Success: Can successfully make 8 out of 10 turns.

Date:______________________

Lesson 7- MANUAL MODE

Objective: Able to stop when hearing the response “t-junction”.

Instruction: Have participant walk down the hallway, listening for the statement “t-junction”. When the statement is heard, participant will turn either right or left.

Criteria for Success: Can successfully make a turn 3 out of 5 times.

Date:________________________

Lesson 8- MANUAL MODE

Objective: Able to travel a prescribed route with a starting and ending point that involves at least three turns.

Instruction: Participant will walk the prescribed route (ex: To complete the route, go out of one room and into a hallway by making a turn, travel down the hallway and turn into another hallway, then locate a room and turn into it). During the route, the participant must negotiate around three obstacles. These obstacles can be natural to the environment or positioned by the instructor.

Criteria for Success: Participant will be able to complete the route, reaching the destination, avoiding all physical contact with obstacles, making the correct turns without any episodes of disorientation.

Date: ________________________

Lesson 9- BEGIN AUTOMATIC MODE

Objectives: Participant is able to negotiate around obstruction.

Instruction: Explain automatic mode to participant. Participant will walk forward through a hallway that the instructor has placed 10 obstacles in front of him/her. When the PAMAID states “obstruction”; recognize command, respond by moving around obstruction and toward the “path clear” command.

Criteria for Success: Participant can approach an obstacle and be able to achieve the “path clear” statement in 8 out of 10 attempts.

Date: ________________________

Lesson 10- AUTOMATIC MODE

Objective: Able to turn into an open hallway or doorway after hearing the response “opening right” or “opening left”.

Instruction: Have participant walk down the hallway, listening for the statement “opening right” or “opening left”. When the statement is heard, make the turn into the hallway/doorway.

Criteria for Success: Can successfully make 8 out of 10 turns.

Date: ___________________________

Lesson 11- AUTOMATIC MODE

Objective: Able to travel a prescribed route with a starting and ending point that involves at least three turns.

Instruction: Participant will walk the prescribed route (ex: To complete the route, go out of one room and into a hallway by making a turn, travel down the hallway and turn into another hallway, then locate a room and turn into it). During the route, the participant must negotiate around three obstacles. These obstacles can be natural to the environment or positioned by the instructor.

Criteria for Success: Participant will be able to complete the route, reaching the destination, avoiding all physical contact with obstacles, making the correct turns without any episodes of disorientation.

Date:___________________________

BIBLIOGRAPHY

1. Lacey G, Dawson-Howe KM. Personal adaptive mobility aid (PAM-AID) for the infirm and elderly blind. AAAI Fall Symposium, Developing Assistive Technology for Persons with Disabilities, Boston, November 1996.

2. Welsh, R.; Blasch, B. Foundations of Orientation and Mobility, Second Edition. American Foundation for the Blind, New York, NY, pp. 291-293, 1997.

3. Glover J, Holstius D, Manojlovich M, Montgomery K, Powers A, Wu J, Kiesler S, Matthews J, Thrun S. A robotically-augmented walker for older adults. Technical report CMU-CS-03-170, Carnegie Mellon University, Computer Science Department, Pittsburgh, PA, 2003.

4. Rubenstein L, Powers C, MacLean C. Quality indicators for the management and prevention of falls and mobility problems in vulnerable elders. Annals of Internal Medicine 2001; 135(8):686-693.

5. MacRitchie RF. Reducing the incidence of falls among elderly nursing home residents: an evaluation of an ameliorative pilot program. Southern Connecticut State University; 2001 May. p. 4.

6. Fuller GF. Falls in the elderly. Am Fam Physician 2000;61 (7):2159-68.

7. Englander F, Hodson T, Terregrossa R. Economic dimensions of slip and full injuries. Journal of Forensic Science 1996;41(5):733-46.

8. Lacey G, MacNamara S. User involvement in the design and evaluation of a smart mobility aid. Journal of Rehabilitation Research and Development 2000; 37(6):709-23.

9. Goodrich GL. Growth in a shrinking population: visual impairment in the veteran. Palo Alto Health Care System, Palo Alto (CA); 1997. p. 1995-2010.

10. Gabrel CS. Characteristics of elderly nursing home current residents and discharges: Data from the 1997 National Nursing Home Survey. Advance data from vital and health statistics; No. 312, Hyatsville, MD. National Center for Health Statistics; 2000. p. 4.

11. Blasch B, Long RG, Griffin, SN. Results of a national survey of electronic travel aid use. Journal of Visual Impairment and Blindness; November, 1989, 33(9): p. 449-453.

12. O'Neill AM, Petri H, Lacey G, Katevas N, Karlson MA, Engelbrektsson P, Gallagher B, Hunter H, Zoldan Domitilla. Establishing initial user requirements for PAM-AID: a mobility and support device to assist frail and elderly visually impaired persons. Proceedings of the Third TIDE Congress. Improving Quality of Life for the European Citizen: Technology for inclusive design and equality. editors I. Placencia Porrero and E. Billabio. IOS Press. 1998, pages 292-295.

13. Cassidy D. Improved obstacle avoidance for a human-machine system. University of Dublin, Trinity College; September 2002.

14. Dubowsky S, Genot F, Godding S, Kozono S, Skwersky A, Yu LS, Yu H. PAMM-a robotic aid to the elderly for mobility assistance and monitoring: a "helpful-hand" for the elderly. IEEE International Conference on Robotics and Automation; 2000 April; San Francisco, CA. Piscataway (NJ): IEEE Press; 2000. p. 570-76.

15. Wasson G, Gunderson J, Graves S, Felder R. An assistive robotic agent for pedestrian mobility. AGENTS '01. Proceedings of the ACM Conference on Autonomous Agents; 2001 May 28-June 1; Montreal, Canada. New York: ACM Press; 2001 June.

16. Yanco HA. Evaluating the performance of assistive robotic systems. Proceedings of the Workshop on Performance Metrics for Intelligent Systems, NIST; 2002 August; Gaithersburg, MD.

17. International Standard. Walking aids manipulated by both arms: Requirements and test methods, Part 2: Rollators. Geneva, Switzerland: International Organization for Standardization; 1999. p. 1-13.

18. ANSI/RESNA. Wheelchair standards, Sections 1,2. Arlington (VA): Rehabilitation Engineering and Assistive Technology Society of North America; 1998.

19. US Census Bureau. Americans with Disabilities- Household Economic Studies. 1997.

20. National Center for Health Statistics: National Nursing Home Survey, 1997.

21. Goodrich GL. Growth in a shrinking population: visual impairment in the veteran. 1995.

22. Ivers RQ, Cumming RG, Mitchell P, Attebo K. Visual impairment and falls in older adults: the Blue Mountain Eyes Study. J Am Geriatr Soc. 1998; 46:58-64.

23. Wasson G, Gunderson J, Graves S, Felder R. Effective shared control in cooperative mobility aids. Proc. Of the fourteenth inter. Florida artificial intelligence research society conf. May 2001. 509-518.

24. Graf B. Reactive navigation of an intelligent robotic walking aid. Proc. Of the IEEE Intl. Conf. On Robot and Human Int. Sept 2001; 353-358.

25. Ulrich I, Borenstein J. The guidecane- applying mobile robot technologies to assist the visually impaired. IEEE Transactions on Systems, Man and Cybernetics,-Part A: Systems and Humans. Vol. 31, No. 2, March 2001, 131-136.

26. Lawrence BM, Cooper RS, VanSickle DP, Gonzalez JP. An improved method for measuring wheelchair velocity and acceleration using a trailing wheel design. Proceedings of the RESNA '97 Annual Conf. 1997.

27. Hakim AA, Curb, JD, Petrovich H, et al. Effects of walking on coronary heart disease in elderly men. The Honolulu Heart Program. Circulation (7) 1999;100:6-13.

28. Council Close-Up. Today's elderly: physically unfit. April 7, 1995. Number 2.

29. Knoblauch RL, Pietrucha MT, Nitzburg M. Field studies of pedestrian walking speed and start-up time. Transportation Research Record 1538. Dec. 1996; 27-38.

30. Freid VM, Prager K, MacKay AP, Xia H. Chartbook on Trends in the Health of Americans. Health United States, 2003. Hyattsville, Maryland: National Center for Health Statistics. 2003.

31. Biomedical Innovations, Baby Boomers, and Aging. The Pfizer Journal. Impact Communications, INC. NY, NY. Vol. 3, No. 1, Spring 1999.

32. Kramarow E, Lentzner H, Rooks R, Weeks J, Saydah S. Health and Aging Chartbook. Health, United States, 1999. Hyattsville, Maryland: National Center for Health Statistics 1999.

33. Sayhoun NR, Pratt LA, Lentzner H, Dey A, Robinson KN. The changing profile of nursing home residents: 1985-1997. Aging Trends; No. 4. Hyattsville, Maryland: National Center for Health Statistics. 2001.

34. Bedsine RW, Rubenstein LZ, Snyder L, editors. Medical Care of the Nursing Home Resident. Philadelphia, PA. American College of Physicians;1996.

35. Rubenstein LZ, Josephson KR, Robbins AS. Falls in the nursing home. Annals of Internal Medicine 1994; 121:442-51.

36. Department of Veteran Affairs. Facts about the Department of Veteran Affairs. March 2002. Available at http://www.va.gov/opa/fact/docs/vafacts.htm.

37. Disabled American Veterans. Available at http://www.dav.org/about/index.html.

38. Rentschler AJ, Cooper RA, Blasch B, Boninger ML. Intelligent walkers for the elderly: performance and safety testing of the VA-PAMAID robotic walker. Journal of Rehabilitation Research and Development. September/October 2003, Vol. 40, No.5.

39. Baker M, Winyard S. Lost vision: older visually impaired people in the UK. Royal National Institute for the Blind. 1998.

40. Wahl HW, Schilling O, Oswald F, Heyl V. Psychosocial consequences of age-related visual impairment: comparison with mobility-impaired older adults and long-term outcome. J Gerontol B Psychol Sci Soc Sci. Sept 1999, 54(5): p. 304-16.

41. Lacey G. Adaptive Shared Control of a Robot Mobility Aid. Proc. Field and Service Robotics (FSR); CMU, August 1999: p. 25-30.

42. SICK AG. LMS2 laser measurement systems. Germany; 8008970/WU.FD/06-2000: p. 7.

43. Luchies CW, Schiffman J, Richards LG, Thompson MR, Bazuin D, DeYoung AJ. Effects of age, step direction, and reaction condition on the ability to step quickly. Journal of Gerontology: Medical Sciences 2002; 57A(4): p. M246-M249.

44. Modi S. Comparison of three obstacle avoidance methods for an autonomous guided vehicle. University of Cincinnati; 2002. p.27-29.

45. Russell, R.A., 'Object recognition by a 'smart' tactile sensor', Proceedings of the Australian Conference on Robotics and Automation, Melbourne, Aug 30- Sept 1, 2000, pp. 93-98.

46. Jung D, Zelinsky A. Whisker based mobile robot navigation. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), vol 2. November 1996. p. 497-505.

47. Hauser JR, Clausing D, The house of quality. Harvard Business Review. May-June 1988.

48. Porter M. The power of strength training for older adults. Research Update March 2002; (2): p. 1-6.

49. Karani R, McLaughlin MA, Cassel CK. Exercise in the healthy older adult. Am J Geriatric Cardiology; 2001 Sept/Oct; 10(5):269-73.