

Clinical evaluation of a desktop robotic assistant

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Abstract—A desktop vocational assistant robotic workstation was evaluated by 24 high-level quadriplegics from the Palo Alto Veterans Affairs Spinal Cord Injury Center. The system is capable of performing daily living and vocational activities for individuals with high-level quadriplegia via voice control. Subjects were asked to use the robot to perform a repertoire of daily living activities, including preparing a meal and feeding themselves, washing their face, shaving, and brushing teeth. Pre- and post-test questionnaires, interviews, and observer assessments were conducted to determine the quality of the robot performance and the reaction of the disabled users toward this technology. Results of the evaluations were generally positive and demonstrated the usefulness of this technology in assisting high-level quadriplegics to perform daily activities and to gain a modicum of independence and privacy in their lives.

Key words: *activities of daily living, computer technology, occupational therapy, quadriplegia, robotics, spinal cord injury, voice control, vocational activities.*

INTRODUCTION

There are over 67,500 quadriplegics in the United States today, with an estimated 2,400 to 4,000 new injuries resulting in quadriplegia occurring each year (16). Spinal cord injuries occur most frequently among young males between the ages of

16 and 30. Due to advances in medical treatment, these individuals are now expected to live a relatively normal lifespan (16). It is estimated that caring for a quadriplegic veteran, including standard medical treatment, equipment maintenance, and attendant care, costs about \$47,000 per year. This translates to approximately \$1.6 million over a lifetime (6). The net direct cost to the Department of Veterans Affairs will be approximately \$5 billion for its current quadriplegic population. Is it worth investing in research and development that might yield improvements in the quality of life and productivity of these individuals? Young, *et al.*, estimated that every dollar spent for rehabilitation research and development returns \$11 in cost benefits to society (20).

A high-level quadriplegic is completely dependent on attendants to perform the majority of personal and vocational activities of life. Today's rapidly evolving automation and tele-robotics technology is on the verge of making home and work environments accessible to severely limited individuals. They can thus expect to achieve an important measure of personal independence and control of their lives.

BACKGROUND

The evolution of robotic assistants for persons with severe disabilities dates to the early 1960's (14). Leifer (10,11) summarized the work done in the intervening years and suggested that "interactive

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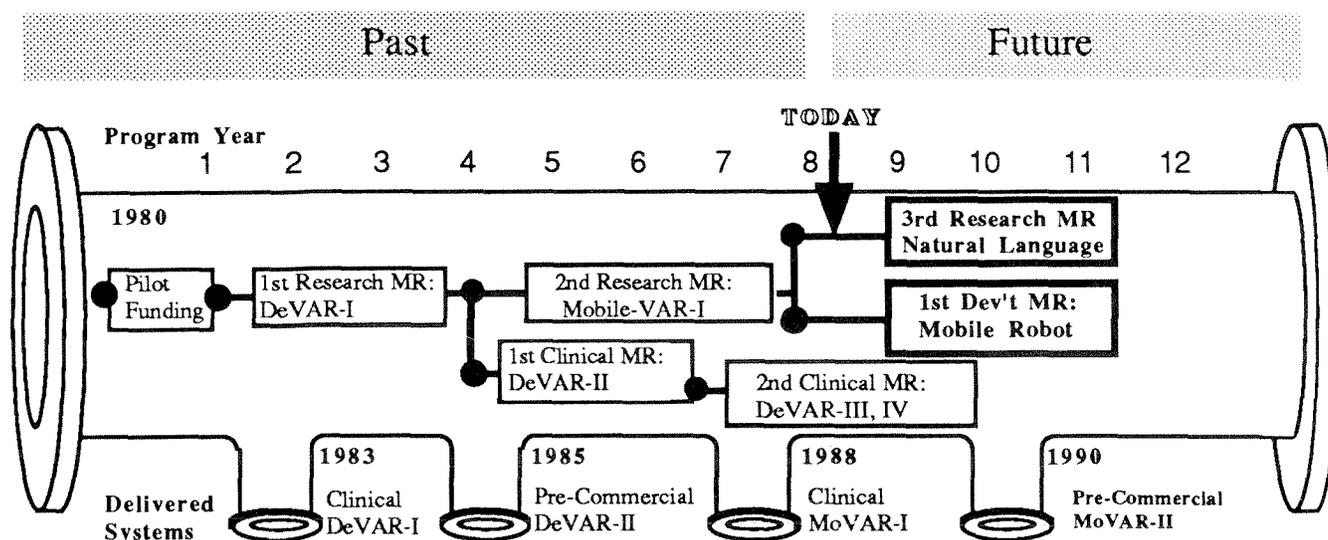


Figure 1.

Evolution of the Palo Alto Veterans Affairs desktop vocational robotic workstation (DeVAR). This collaborative effort with the Stanford University Department of Mechanical Engineering has resulted in four generations of desktop assistant robots and a first generation mobile assistant robot. The desktop units have been configured for activities of daily living (ADL), above, and for modular office furniture environments (**Figure 8**).

robots," or "tele-robots," represented an important new way for people to accomplish useful work. Thring (17) documented technical progress for industrial, space, and undersea applications. Most recently, the state of the art was summarized in the proceedings of the "First International Workshop on Robotic Applications in Medical and Health Care" (13,18). Very few archival clinical reports are available. Among the most notable are Corker, Lyman, and Sheredos (2), and Seamone and Schmeisser (15). Several other projects involved in rehabilitation robotics over the past ten years are summarized below. While not an exhaustive list, it highlights the more established research efforts to date.

- The Johns Hopkins University/Applied Physics Laboratory (JHU/APL) project (15) concentrated on the implementation of a workbench-mounted robot for activities of daily living (ADL) tasks. The design was derived from prosthetic arm technology. User input was by head-motion joystick and menu-selection via a sip-and-puff controller.
- The Tufts-New England Medical Center robotics project (4) concentrated on the software design of a universal robot programming language, CALVIN. Using CALVIN, they set up a va-

riety of small robots in clinics in rehabilitation settings.

- The Boeing Company developed a voice-controlled workstation using UMI's RTX robot arm. Based on this development effort, Prab Command, Inc. (3) began marketing a system in 1988 for vocational applications.
- Outside the United States, the Canadian Neil Squire Foundation has been involved in the development of a low-cost manipulator for desktop applications (1). They also have recently begun marketing their system.
- At the Institute for Rehabilitation Research in the Netherlands, Hok Kwee, one of the main contributors to the French SPARTACUS Project in the 1970's (7), has been developing a wheelchair-mounted joystick-controlled manipulator, MANUS (8).

Stanford University, in collaboration with the Palo Alto VA Rehabilitation Research and Development Center, has studied the application of automation and robot technology in rehabilitation for over ten years. The evolution of this body of work from first generation pilot studies through to the fourth generation Desktop Vocational Assistant Robot (DeVAR) is summarized in **Figure 1**.

Table 1.

Listing of feeding, personal hygiene, vocational, recreational and miscellaneous tasks that the four generations of the desktop robotic assistant (DeVAR-I, II, III, and IV) have performed for disabled individuals.

Robotic tasks		
Meal preparation/feeding	Vocational	Hygiene
prepare meal	write with pen/pencil	wash/dry face
open/close microwave and refrigerator doors	retrieve books/manuals	brush teeth
manipulate bowls/containers	set up books	shave face
set timer	retrieve mouthstick	comb/brush hair
pour liquids	turn on/off computer equipment	Recreational
beat eggs	type on keyboard	arrange flowers
toss salad	adjust keyboard	hand out flowers
cook/serve soup	operate private/speaker phone	dance
heat and serve casserole/dinner	turn pages	paint
serve pudding/fruit	insert floppy disks	play board games
bake cake	insert audio tapes	chess
use standard knives, forks, spoons	operate dictation machine	checkers
get drinks	open/close drawers	play video games
mix drinks	operate printer	Miscellaneous
feeding all above foods	manipulate computer printouts	light candles
	run standard voice-controlled software applications	light cigarette for guest
	lock cabinets	
	handle PC board for inspection	
	operate ECU for: TV, stereo, lights, doors, windows, computer, robotic workstation	

Description of the DeVAR Robot System

At the Palo Alto VA, a voice-controlled desktop robotic assistant workstation has been developed to perform daily living and vocational tasks. Four generations of desktop robotic workstations have been developed; the first three have been clinically evaluated to date (5,9). Whereas earlier assistant robot configurations have emphasized ADL, recreation, and personal clerical tasks, the most recent version, DeVAR-IV, has been configured for vocational applications. **Table 1** is a compendium of all tasks addressed by the four generations of Palo Alto VA desktop robotic workstations.

The third generation system, DeVAR-III, the system evaluated in this study, is pictured in **Figure 2**. DeVAR-III is an integral part of the user's environment. For the purposes of this evaluation, the configuration of DeVAR-III was standardized to focus on daily living applications.

The system uses a Unimation PUMA-260 industrial robotic arm, manufactured by Westinghouse, which is mounted to the center of a wheelchair-accessible 3' x 6' table. The DeVAR computer and robot controller are industrial-grade instruments. For example, straight-line motions are controlled directly by the robot controller in real-time; a

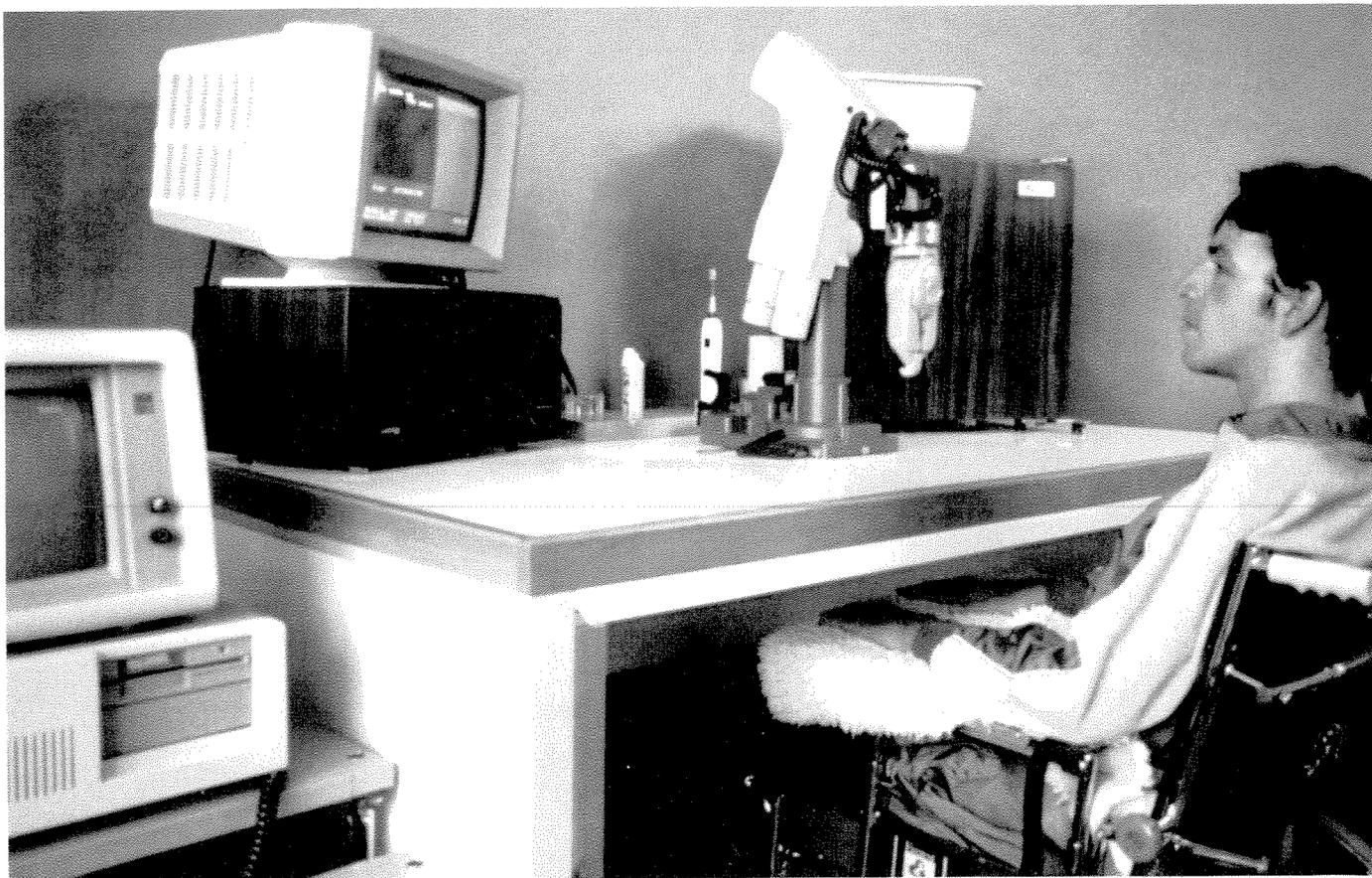


Figure 2.

This third generation Desktop Vocational Assistant Robot (DeVAR-III) is configured for activities of daily living (ADL). (Permission granted.)

complete and mature task programming environment, VAL-II, is included with the PUMA-260.

The end effector used with the PUMA-260 is an Otto Bock Greifer prosthetic hand capable of fingertip, cylindrical, and hook grasps. A VOTAN VPC-2100 voice unit recognizes voice commands from the disabled user. It produces digitized voice messages to confirm the user's intentions and provide warnings. A color monitor, placed in the user's line of sight, displays command prompts and the status of the robot throughout each task. The robot arm is surrounded by daily living equipment, including a microwave oven, a refrigerator, a tool holder for an electric shaver, a spoon, an electric toothbrush, pump toothpaste, adapted wash/dry cloths, and a mouthstick. Voice commands operate an X-10 environmental controller which supplies power to the robotic workstation, computers, lights, radio, and other appliances.

Safety is addressed at multiple levels within the robotic workstation. The controller has three levels of safety features: 1) careful and reliable mechanical design; 2) electrical signal fault diagnosis and fail-safe design; and, 3) software consistency checks. The PUMA's reliability (based on hundreds of man-years of industrial experience) has allowed the DeVAR system to maintain commercial standards of performance, robustness, and safety.

In addition to the above-named manipulator safety features, we have designed these additional safety features into the DeVAR system's software:

- The user can say STOP at any time to stop the motion of the robot.
- The user can press a stop switch mounted on the wheelchair to stop the robot at any time.
- The robot interprets any loud noise as a stop command.

- The robot stops moving and shuts itself off when it encounters a resistance of 5 pounds or more.
- The robot will only accept appropriate commands (e.g., it will listen only for the word STOP when the toothbrush is in the user's mouth).
- Before initiating a task, the robot checks to make sure that its hand is empty and the tabletop is clear.

Task set-up and programming are performed by the staff prior to the involvement of the user. A task is chosen for implementation based on user input and relevance to the clinical evaluation effort. The staff assesses the feasibility and practicality of the task. Task set-up includes choice of implements and appliances, possible modifications (handles, etc.), and choice of the voice command sequence the user will employ. The programming of the task consists of two parts. The first phase involves adding commands to the user-interface program, written in TurboPascal (9), by adding entries in a data table. These inform the program what to put on the screen, what to say to the user at various phases of the task, and what specific commands to send to the robot controller. The second programming phase is the implementation of the actual robot motions themselves. These are written in VAL-II, the PUMA's language.

Tasks are broken down into parts, like taking a cup out of the cooler (DRINK.OUT), and putting it back (DRINK.BACK). Motion programming involves writing VAL programs and teaching the robot its exact positions and trajectories by using a manual controller, or "Teach Box." While the first phase is quite short, the motion programming phase can take several hours by experienced robot programmers, often working in pairs, and most often involves several iterations. The new task is first tried out by all the staff members to test the screen prompts, the voice commands, and the quality of the motion programming itself. Users are then taught the sequence, and the words for the new task are added to their voice data files through voice-training.

PURPOSE

The DeVAR-III system has recently undergone formal clinical evaluation. The evaluation method

Table 2.
Distribution of subjects by level of spinal cord injury.

Level of injury	Number of subjects
C1	1
C2	3
C3	5
C4	12
C5	1
C6	1
Other	1 (Guillian-Barré)
TOTAL: 24	

was pilot-tested by 20 Spinal Cord Injury Service staff members and students, and subsequently tested by 24 severely physically disabled individuals. The objective of this study was to further assess the robot's utility, and to evaluate the quality of its performance. The primary question to be answered by the study was whether the desktop robotic assistant workstation would be a viable tool for use by severely disabled persons in both home and work settings. Issues addressed included: user training methodology, task specification, design attributes, control interface, safety considerations, and psychosocial factors regarding the use of this technology by disabled individuals.

METHODS

Subjects

Twenty-four quadriplegic inpatients and outpatients of the Spinal Cord Injury Center at the Palo Alto VA participated in the study. All subjects were concurrently participating in a full rehabilitation program. As a result, participation in this study was done on an "as available" basis.

The subjects had sustained injuries at neurologic levels C1 to C5 (motor complete). **Table 2** shows the distribution of injury levels. Individuals had little or no functional upper extremity movement, and were completely dependent on one or more attendants to perform daily activities for them. Twenty of the 24 subjects were injured more than one year before the study; the remaining four were

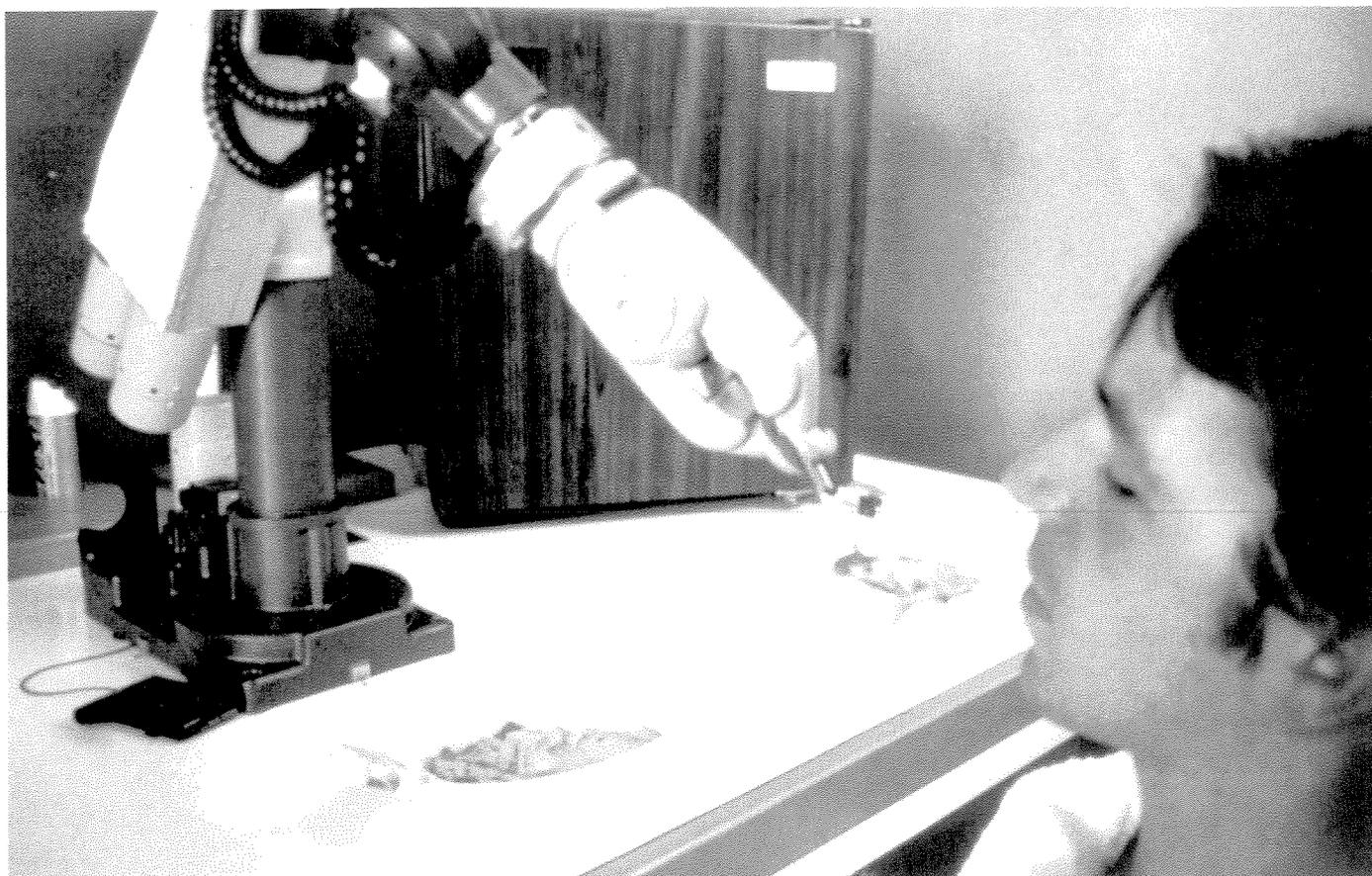


Figure 3.

A disabled individual uses DeVAR-III to prepare a bowl of soup and feed himself. (Permission granted.)

new injuries (less than one year post-injury). All subjects were males ranging in age from 20 to 73 years.

Of the 24 subjects, 14 had a high school degree or less; 6 had less than two years of post-high school work; 4 had college degrees. Of these subjects, 2 had previous experience in computer programming. None had prior experience with robots.

Before using the robot, subjects were screened by the occupational therapist to determine their mental and physical status. This information was gathered from medical charts and therapy evaluations from the Spinal Cord Injury Center. To use the robot safely, individuals needed at least 45 degrees of neck movement right, left, and backward, in order to use utensils and to activate an emergency stop switch located on the back of the wheelchair. Individuals also needed a consistent speaking voice to control the robot, good vision to see the monitor and gauge the robot's movements, intact judgment skills and normal reaction times. Individuals with moderate or severe head injuries

were not considered appropriate for this study, due to cognitive impairment. All individuals who met the above criteria (more than 80 percent of the rehabilitation patients admitted during the 18-month course of study), were invited to participate in the study as their rehabilitation program allowed. No prospective subjects declined to participate.

Training

Each user was given a standard training session by the occupational therapist and systems engineer. First, each subject was voice-trained for the 60 words in the robot's command vocabulary, a process involving responding to screen prompts. Users' voice sets were stored in separate data files. (VOTAN suggests repeating each word twice to ensure acceptable recognition.) A recognition test was then performed by having the user repeat key words used during task sequences to test the efficacy of the training session. This training procedure took approximately ten minutes to complete.

Subsequently, a voice-operated, computer-administered, pre-test questionnaire was given (refer to **Appendix A**). This was followed by a standard, verbal explanation of the design and operation of the robot, including its safety features. Subjects were then trained to command the robot through a selected repertoire of five tasks by instructing them to invoke the task and follow monitor prompts to complete it (**Figure 3**). Subjects were asked to guide the robot in getting them a drink of water to determine that they were able to follow prompts and execute a standard task. After all tasks were completed, a voice-operated post-test questionnaire was administered. This concluded a typical training session, which lasted approximately 2 to 4 hours.

The tasks users were asked to complete, including the voice commands used to invoke each task, are listed in **Table 3**.

As discussed in “Description,” all tasks were preprogrammed in advance by the staff. On the average, seven to eight spoken commands were required by the user to complete an entire task. **Table 4** is a transcript of a complete “SOUP” sequence.

In addition to executing preprogrammed movements, users were asked to “pilot” the robot, using simple direction commands (right, left, forward, backward, up and down) to bring objects, such as a spoon or a mouthstick, within their reach. The robot then remembered the last point the object was directed to, and returned to it each time. This capability is very important, since the robot cannot be programmed in advance to know the location of everything. In particular, this “real-time” programming was used to locate the user’s mouth in the feeding sequence.

Table 3.
Representative robot tasks performed in study.

Task	Command
1. Prepare a bowl of soup	“SOUP”
2. Eat the soup using a standard spoon	“SPOON”
3. Brush teeth with an electric toothbrush	“TOOTHBRUSH”
4. Wash and dry the face using adapted washcloths	“WASH”
5. Shave the face with an electric shaver	“SHAVE”

Table 4.

Sample command listing used to guide robot to prepare soup and feed.

Prepare a meal and feed	
Command	Action
“SOUP”	Robot takes soup out of refrigerator, puts in microwave, closes door, sets timer, and heats soup.
“SOUP”	Robot brings soup from microwave to table.
“SPOON”	Robot gets spoon from tool holder and brings to neutral point in front of user. User says direction commands to bring spoon near mouth (right, left, forward, backward, up, down). Robot remembers this point and returns to it each time.
“USE”	Robot scoops a spoonful of soup and brings to user’s mouth. User says USE for each mouthful until finished eating.
“BACK” or “CLEAN”	Robot returns soup to refrigerator to finish later (“back”) or puts bowl in dirty dish container to be cleaned (“clean”).

When time permitted, users were also asked to use the robotic workstation to retrieve a mouthstick for typing and turning pages, to play a computer video game via voice control, and to operate an electronic environmental control unit to listen to music and turn on a light. These tasks were judged representative of the collection of over 50 tasks that this and previous DeVAR systems were programmed to perform (see **Table 3**).

Measurement

1. *Pre-test questionnaire*: This computerized questionnaire asked disabled users their opinion of robots, in the form of multiple-choice questions, before they had an opportunity to actually work with the robot (see **Appendix A**).

Multiple choice questions were shown on the monitor screen. Using the voice commands “UP” and “DOWN,” subjects moved the highlight to the appropriate answer. The command “PROCEED” recorded the answer and moved to the next question. A sample question was used to train users on this procedure.

2. *Post-test questionnaire (Appendix A)*: This form included the same questions as on the pre-test.

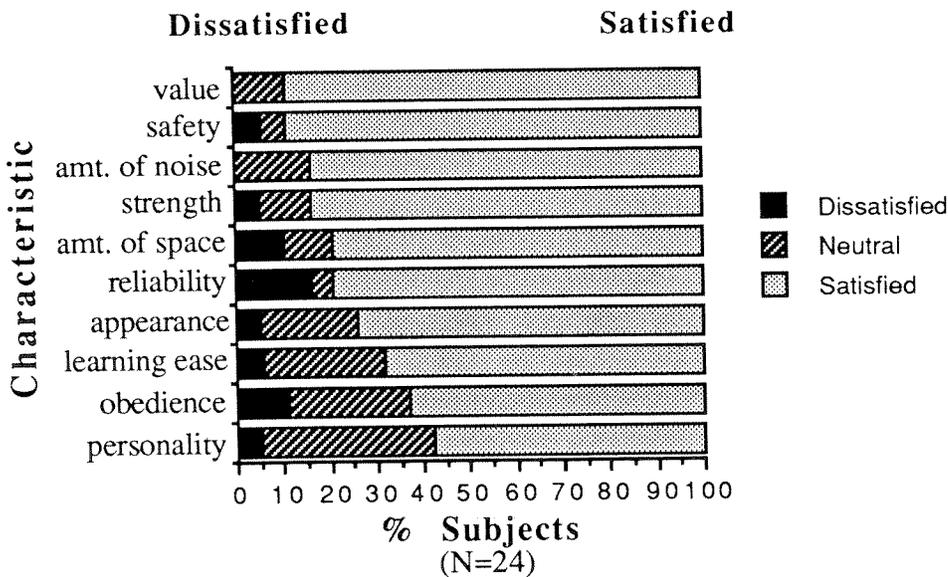


Figure 4.

Post-test results of the subjects' opinions regarding characteristics of the robotic workstation. Characteristics were condensed from a five-point to a three-point scale (1&2 = satisfied, 3 = neutral, 4&5 = dissatisfied).

Additionally, users were asked to comment objectively on the robot's performance, and subjectively on their response to the robotic aid after working with it.

3. *Interview form:* The interview was conducted by a member of the project staff after pre- and post-tests to clarify any responses marked "other," or requiring further explanation.

4. *Observer assessment:* The observer assessment is a standardized form filled out by a member of the project staff during the evaluation session. The observer was asked to evaluate the overall quality of the robot's performance during each task, as well as to note specific problems, the cause of the problems, and their resolution. The same observer supervised all training sessions in this study.

5. *Computerized history list:* This listing recorded the user's voice commands and robotic workstation's responses, the status of the robot throughout the training session, and the time required to complete each task.

RESULTS

Data were collected over 18 months, during which 24 disabled subjects participated in the study. Compilation of the observer assessment forms and computerized history listings showing the average completion time in minutes for each task are shown in **Table 5**.

The time to complete each component of each task was not formally recorded during sessions.

Table 5.

Task completion time data.

Task	Ranges*	Average time to complete*	Standard deviation
Prepare soup and feed self	7:00-13:00	9:24	1.89
Brush teeth and rinse	1:54-9:00	5:25	2.33
Shave face	4:31-14:00	9:82	4.98
Wash and dry face	7:00-10:00	8:00	1.73

*Time is presented in minutes and seconds.

Subjects were asked in both the pre- and post-tests to give their opinions regarding characteristics of the robotic workstation. The post-test results are summarized in **Figure 4**.

Subjects were asked to use DeVAR to perform four tasks: 1) prepare a meal and feed themselves; 2) brush their teeth with an electric toothbrush; 3) wash and dry their face; and, 4) shave their face with an electric shaver. **Figure 5** shows the subjects' post-test opinions on satisfaction with these tasks.

Tasks were rated on a five-point scale (1=very satisfied, 2=satisfied, 3=neutral, 4=dissatisfied, 5=very dissatisfied), which was condensed to a three-point scale (1=satisfied, 2=neutral, 3=dissatisfied). A fifth task, retrieving a mouthstick, was only tested by two people; both were very satisfied with the robot's performance on this task.

When asked to indicate a preference for family/attendant versus robot assistance, the 24 high-quadruplegics preferred the robot (**Figure 6**).

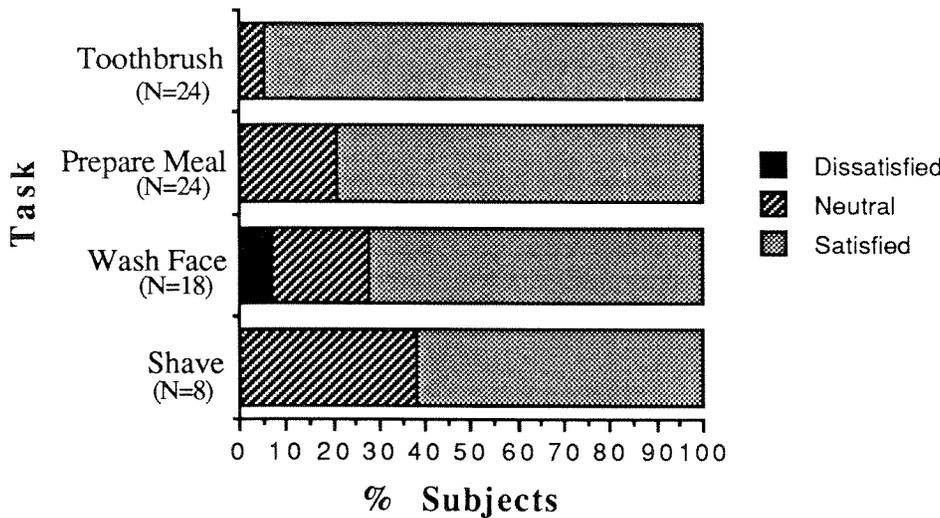


Figure 5. Post-test results of subjects' satisfaction with tasks performed by DeVAR-III.

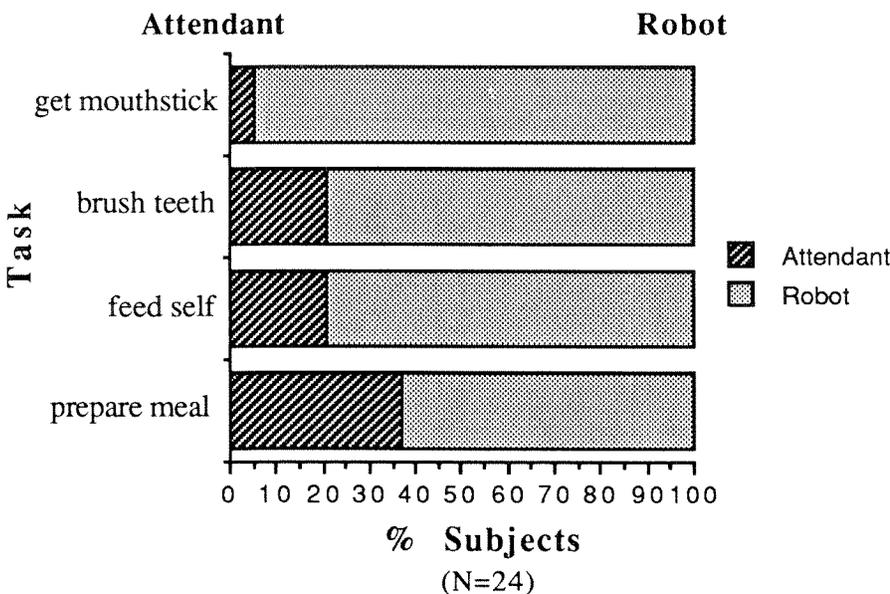


Figure 6. Subject preference of robot versus attendant/family assistance in performing daily tasks.

Table 6.
Robot performance tasks most commonly requested by subjects.

User requested robot tasks (N = 24)	
Task	Number of requests
• perform hygiene tasks (brush teeth, shave, wash)	9
• prepare a meal and feed	6
• get a drink of water	6
• fetch and carry objects	4
• operate environmental appliances (phone, TV, stereo)	4
• setup a splint for feeding/writing	2
• perform tasks at bedside	2
• turn book pages	1
• write letters	1
• light a cigarette	1

When asked, "How would your family/attendant react to the robot?," 79 percent (19 subjects) responded "positively." Three were "in-different," and two were "negative." When asked, "Would this reaction affect your use of the robot?" 88 percent responded "no effect." Of the two who said the reaction of the family would have an effect on their usage of the robot, one replied the family would react positively; one answered the family would react negatively.

Finally, each of the 24 high-quadruplegics was asked, "Would you want this robot in your home?" Responses, shown in **Figure 7**, show a large shift from "undecided" to "yes."

In the interview following the post-test, subjects were asked what they would like about using this robot in their homes. Twelve responded that they would like the independence it could give them; one responded that he would like the convenience of having the robot available to do tasks at all times. When asked what they would dislike about having the robot, three responded that they had concerns about reliability; three had concerns about the amount of space the workstation would take in their

homes; one worried about the possibility of other people such as children playing with the system; one was concerned about voice recognition problems.

In an open-ended question format, subjects (N=24) were asked: "What tasks would you most like to have the robot do for you?" The results, shown in **Table 6**, show the preponderance of interest in ADL tasks.

DISCUSSION

It should be noted that upgrades to the robotic workstation were constantly being made throughout this study in response to subjects' suggestions for improvement. It is for this reason that statistical analysis was not performed on the data. For example, since the subjects were encountering voice recognition errors when trying to command the robot while brushing their teeth with the toothpaste in their mouth, or while trying to talk with the shaver on, the robot program was rewritten to operate on a timed sequence. Before the task, users set up the individual positions inside their mouths, or on their faces, using piloting commands. The robot then completed the sequence using these positions, so that the user did not have to make any verbal commands until the task was finished. This upgrade, in conjunction with voice system software revisions, has significantly improved voice recognition performance. Observer forms also showed that voice recognition accuracy approached 100 percent (2 to 3 misrecognitions were noted per training session); therefore, an analysis is not presented here.

Due to these changes, it is difficult to generalize from the first users' reactions to the most recent users' reactions: however, a clear trend of improved ratings emerged from the first to last ratings. In comparing pre- versus post-test results, there was an improved rating post-test noted in all questions; therefore, these data were not generally reported, except for one example given in **Figure 7**.

The results of this study indicate that high-level quadriplegic users generally had positive responses to the robotic workstation. Notably, users' responses were uniformly more favorable on the post-test than they were on the pre-test. Contributing factors to the subjects' initial skepticism were their lack of knowledge of the capabilities of modern industrial robots, fear of and/or negative

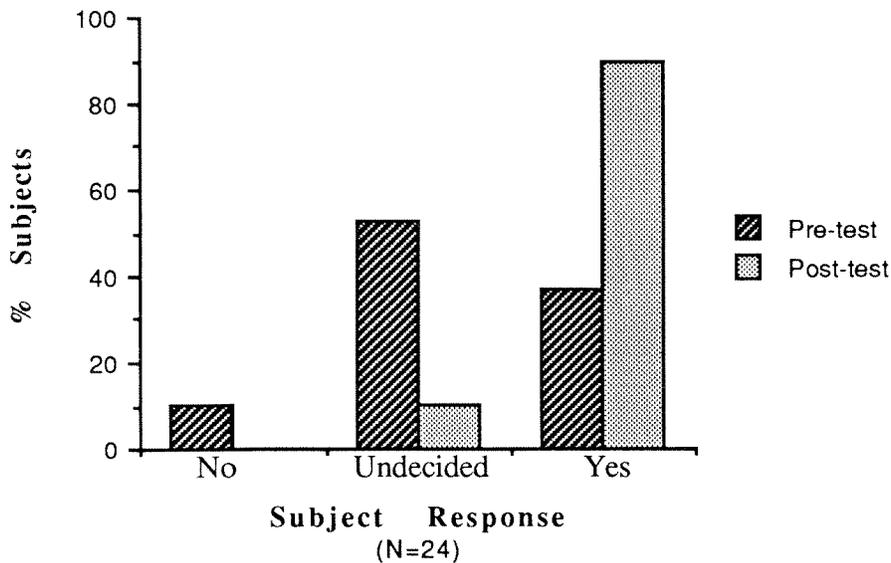


Figure 7.

Pre-test versus post-test results to the question: “Would you want this robot in your home?”

feelings toward computer technology, and the preconceived image of robots derived, for example, from popular science fiction.

On the post-test, subjects were largely satisfied with the robot’s safety, strength, reliability, ease of use, appearance, noise level, and space requirements. Overall, subjects were satisfied (88 percent) with the voice control interface to the workstation.

Subjects did not feel strongly about the personality of the robot, with 37 percent choosing “neutral” and 5 percent choosing “dissatisfied.” This could be expected since a machine, such as a robot, is not commonly thought to have a distinct personality. The staff consciously chose not to endow the robot with a name for this reason, and left the decision of associating a personality or name with the robot to the individual user.

A preliminary analysis of the operation history lists from the evaluation sessions indicates that the robot was slower than a human attendant at completing tasks. However, information from the post-tests and interviews showed users were satisfied with the time it took to complete tasks, particularly if the robot allowed them to complete that task independently (79 percent of users who tested the system were satisfied with the time required to complete the tasks). In fact, information from interviews with the subjects showed the primary reason users would want a robot is to gain control

and independence in their home and work environments, regardless of the time it takes to perform these tasks.

The subject sample size was different for each of the four tasks. This was due to time limitations on the part of patients participating, and appropriateness of the tasks for each user. Only eight subjects evaluated the shaving task, for example, since the majority of the users had a beard. Several mentioned that they preferred not to shave to avoid dependency on assistance from others. However, as we saw in **Figure 6**, subjects were satisfied with the performance of the robot in all tasks.

Subjects did prefer the robot versus their attendant/family caregiver to feed them, brush their teeth, and get them a mouthstick. Many of the subjects agreed on an interesting point in regard to the ability to feed themselves. With an attendant, these users felt they had no control over the feeding process, and in fact, felt like babies being spoon-fed. However, with the robot, they felt they had complete control over when to take the next bite, or if they were not hungry, when to postpone the meal for a later time. Thus, the robot allowed them to eat according to an individual schedule, not the schedule of their attendants or family members.

Users were not as enthusiastic about having the robot prepare a meal as feed them (63 percent versus 79 percent). This could be due to the fact that the



Figure 8.

This fourth generation Desktop Vocational Assistant Robot (DeVAR-IV) is configured for vocational tasks typical of information office tasks like computer programming. The system is being evaluated by severely physically limited students attending "Disabled Programmers Incorporated" computer school. A combination of vocational and daily living activities are an important part of working independently.

menu was restricted to soup for purposes of the study. Possibly, users could not easily imagine the variety of foods that might be prepared by the robot.

The overall value of the system was rated very highly (88 percent rated the robot "valuable"), demonstrating users' acceptance of the technology as a valuable aid in their daily lives. Subjects predicted their families and attendants would also have a positive reaction to the robot (79 percent responded that family/attendants would react positively). Notably, 88 percent of the subjects responded that the reaction of the family/attendant to the robot, whether it be positive or negative, would have no effect on their use of the system. Perhaps the most significant demonstration of the disabled user acceptance of robotics technology is found in the responses to the question: "Would you want this robot in your home?" On the pre-test, thirteen of

the subjects responded "undecided" (54 percent); and two said "no." But on the post-test, 21 of the subjects responded "yes" (88 percent), three responded "undecided," and no one responded "no."

Interview results showed the most requested tasks for the robot to perform were in the areas of personal hygiene, meal preparation and feeding, environmental control, and environmental manipulation, such as picking up objects from the floor and fetching and carrying objects to the user. This last category demonstrates the need for a mobile robot capable of moving about the room to manipulate objects.

FUTURE PLANS

In the future, plans for the desktop robotic workstation include allowing the user to program

new tasks completely by voice, installing more sophisticated sensing capabilities in the robot hand, and implementing other control interfaces in addition to voice.

Based on the level of satisfaction with the third generation DeVAR, and given additional user requests, a fourth generation system has been developed for the combination of vocational and daily living tasks (**Figure 8**). In addition to doing daily living tasks, this robotic workstation is also capable of performing vocational tasks including: setting up a book/manual/file for review, retrieving a mouthstick for typing on a keyboard and turning pages, turning on/off office lights and a computer system, inserting floppy disks into a disk drive, or bringing the phone receiver to the user's face, thus allowing use of a private and/or speaker phone. This system is currently being evaluated by a C-3/4, respiratory-dependent, quadriplegic student at a school where physically limited students learn to become professional computer programmers. We also plan to evaluate DeVAR at other private industry worksites. It is hoped that DeVAR will allow disabled individuals to function independently for an entire work-day. Demonstrating this goal is the current focus of our DeVAR development and evaluation effort.

In addition, the development and evaluation of a sophisticated mobile robotic assistant, capable of moving from room to room to execute tasks, are scheduled to take place at the Palo Alto VA within the year (12,19).

CONCLUSION

The results of this study have demonstrated the usefulness of a robotic workstation in assisting high-level quadriplegics in gaining independence in the performance of daily living activities. A number of improvements have been made based on suggestions from disabled users. Users have noted and commented on improvements in voice recognition performance, number and type of added safety features, reliability and consistency in task performance, and overall aesthetics of the workstation.

Further research is needed in evaluating the robotic system with individuals who have other severe physical disabilities, such as multiple sclerosis, cerebral palsy, amyotrophic lateral sclerosis, and

the multitude of disabilities associated with aging. This type of research could determine the best user interface for each disability. In addition, the robotic workstation is now undergoing long-term evaluations in which one individual uses it in the same setting for extended periods of time (from 4 to 8 hours a day) over several months, to determine the reliability of the system over time.

In order for this robotics technology to become available on the market, many factors will have to be considered. One important factor is that of determining the cost benefit of implementing these workstations, both in the home and in the worksite. The robotic workstation itself would cost approximately \$50,000 for the entire workstation; \$38,000 of the total amount is the cost of the robotic arm alone. One strategy for addressing this initial investment calls for cost justification based on saving human attendant time and cost. If the robot could replace an attendant for a period of four continuous hours, the robotic workstation could pay for itself within a period of two to three years. Since the PUMA-260 robotic arm is of industrial caliber, it is projected the arm could perform reliably for over ten years. Evaluations to determine if the robotic workstation is capable of performing reliably for the four- to eight-hour period are currently being conducted at the Palo Alto VA. Based on the positive results of these long-term usage evaluations, insurance companies, workman's compensation agencies, and private corporations have stated an interest in purchasing this equipment for their severely physically disabled clients and employees in order to return them to the workforce.

Other factors that need to be considered in the acceptance of this technology involve gaining support from the health care community, including the doctors, nurses, and therapists who will be evaluating and prescribing these workstations, and support from private industry and third-party payers who will determine which potential users receive funding for this technology.

Robotics technology offers an opportunity for the severely disabled individual to return to productive employment. Most importantly, this technology has the psychological benefit of restoring to the severely disabled person a significant amount of control and independence in performing daily activities.

APPENDIX A: ROBOT STUDY PRE- AND POST-TEST* QUESTIONS

1. Which word most accurately reflects your personal opinion of this robot?
STURDY NEUTRAL FRAGILE
2. Which word most accurately reflects your personal opinion of this robot?
DANGEROUS NEUTRAL SAFE
3. Which most accurately reflects your personal opinion of this robot?
EASY TO USE NEUTRAL DIFFICULT TO USE
4. Which word most accurately reflects your personal opinion of this robot?
OBEDIENT NEUTRAL DISOBEDIENT
5. Which word most accurately reflects your personal opinion of this robot?
VALUABLE NEUTRAL NOT VALUABLE
6. Which word most accurately reflects your personal opinion of this robot?
UNRELIABLE NEUTRAL RELIABLE
7. How much do you think is a reasonable amount of money to spend on this robot?
\$40,000 to \$80,000
\$20,000 to \$40,000
\$10,000 to \$20,000
\$5,000 to \$10,000
\$1,000 to \$5,000
8. How much do you think is a reasonable amount of money to spend on a chin-controlled electric wheelchair?
\$10,000 to \$30,000
\$5,000 to \$10,000
\$1,000 to \$5,000
\$500 to \$1,000
\$100 to \$500
9. If you had this robot in your home, how would you feel about the following?
LIKE STRONGLY LIKE NEUTRAL
DISLIKE STRONGLY DISLIKE
 - a. The appearance of the robot
 - b. The robot does not move around
 - c. The personality of the robot
 - d. The amount of space the robot takes up
 - e. The amount of noise the robot makes
10. How do you think your family/attendant would react to this robot in your home?
POSITIVE INDIFFERENT NEGATIVE

*Denotes questions used on Post-test only.

11. Would your (family/attendant) reaction to the robot affect your use of this robot?
 NO YES
12. Which would you prefer to do the following tasks: this robot, or a family member/attendant?
 THIS ROBOT FAMILY/ATTENDANT
- Brush teeth, wash face, shave, brush hair
 - Prepare your meal
 - Feed you, get you a drink
 - Get your mouthstick
13. Since you would rather have an attendant or a family member do some of the tasks, please indicate why.
 YES NO
- Because people are more reliable
 - Because people provide companionship
 - Because people perform tasks better
 - Because people provide physical contact
 - I prefer people for other reasons
- *14. Rate your satisfaction with the following:
 SATISFIED VERY SATISFIED NEUTRAL
 DISSATISFIED VERY DISSATISFIED
- Ease of learning to use robot
 - Voice recognition
- *15. Rate your satisfaction with the robot's OVERALL performance of the following tasks.
 SATISFIED VERY SATISFIED NEUTRAL
 DISSATISFIED VERY DISSATISFIED NOT APPLICABLE
- Brush your hair
 - Wash your face
 - Brush your teeth
 - Shave your face
 - Feed you salad
 - Feed you soup
 - Feed you pudding
- *16. Rate your OVERALL satisfaction with the TIME it takes for the robot to perform tasks.
 SATISFIED VERY SATISFIED NEUTRAL
 DISSATISFIED VERY DISSATISFIED
- *17. Rate your satisfaction with the robot's OVERALL SAFETY while performing the tasks.
 SATISFIED VERY SATISFIED NEUTRAL
 DISSATISFIED VERY DISSATISFIED
18. Given what you know about a robotic aid, would you want one in your home?
 YES UNDECIDED NO

ACKNOWLEDGMENTS

The authors would like to thank Karen Glass, OTR, for her initial work on the daily living study, and the staff and patients of the Spinal Cord Injury Center who participated in this study. This work was funded by the VA Rehabilitation Research and Development Service, and supported by the Center for Design Research at Stanford University.

REFERENCES

1. **Cameron W:** Manipulative appliance development in Canada. In *Interactive Robotic Aids—One Option for Independent Living: An International Perspective*, 24-28. New York: World Rehabilitation Fund, Inc., 1986.
2. **Corker K, Lyman J, Sheredos J:** A preliminary evaluation of remote medical manipulators. *Bull Prosthet Res BPR* 10(32):107-134, 1979.
3. **Fu C:** An independent vocational workstation for a quadriplegic. In *Proceedings of the 9th Annual RESNA Conference*, 182-184. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1986.
4. **Gilbert M, Foulds R:** Robotics at Tufts-New England Medical Center: A progress report. In *Proceedings of the 10th Annual RESNA Conference*, 778-780. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1987.
5. **Hammel J, Hall K, Van der Loos HFM, Leifer LJ, Perkash I:** Clinical evaluation of a desktop robotic aid for severely physically disabled individuals. In *Proceedings, ICAART '88, Montreal*, 448-449. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1988.
6. **Kalsbeek W, McLaurin R, Harris-III B, Miller D:** The national head and spinal cord injury survey: Major findings. *J Neurosurg* 53:S19-S31, 1980.
7. **Kwee HH:** Spartacus and Manus: Telethesis developments in France and in the Netherlands. In *Interactive Robotic Aids—One Option for Independent Living: An International Perspective*, 7-17, New York: World Rehabilitation Fund, Inc., 1986.
8. **Kwee HH, Duimel JJ, van Woerden JA, Smits JJ:** Development of the MANUS wheelchair-borne manipulator: A progress report. In *Proceedings of the 10th Annual RESNA Conference*, 781-783. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1987.
9. **Lees D, Crigler R, Van der Loos HFM, Leifer LJ:** A third generation desktop robotic assistant for the severely physically disabled. In *Proceedings, ICAART '88, Montreal*, 450-451. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1988.
10. **Leifer LJ:** Rehabilitative robotics. *Robotics Age* May/June:4-15, 1981.
11. **Leifer LJ:** Restoration of motor function: A robotics approach. In *Uses of Computers in Aiding the Disabled*, Amsterdam: North-Holland Co., 1982.
12. **Leifer LJ, Michalowski SJ, Van der Loos HFM:** Development of an advanced robotic aid: From feasibility to utility. In *Proceedings of the 9th Annual RESNA Conference*, 170-172. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1986.
13. *Proceedings of the First International Workshop on Robotic Applications in Medical and Health Care*. 30 papers, available from Editorial Office Rm-301, Division of Electrical Engineering, National Research Council of Canada, Ottawa, Canada, K1A 0R8, 1988.
14. **Reswick J, Mergler K:** *Medical Engineering and Progress Report on the Case Research Arm Aid*, Case Institute of Technology, Report No. EDC 4-64-63, 1962.
15. **Seamone W, Schmeisser G:** Early clinical evaluation of a robot arm/worktable system for spinal-cord injured-persons. *J Rehabil Res Dev* 22(1):38-57, 1985.
16. **Stover SL, Fine PR, et al.:** *Spinal Cord Injury: The Facts and Figures*. Tuscaloosa: University of Alabama, 1986.
17. **Thring MW:** *Robots and Telechairs*. West Sussex, England: Ellis Horwood Ltd., 1983.
18. **Van der Loos HFM, Michalowski SJ, Hammel J, Leifer J, Stassen HG:** Assessing the impact of robotic devices for the severely physically disabled. In *Proceedings of the First International Workshop on Robotic Applications in Medical and Health Care*, 1.1-1.6, Ottawa, Canada, 1988.
19. **Van der Loos HFM, Michalowski SJ, Leifer LJ:** Development of an omnidirectional mobile vocational assistant robot. In *Proceedings, ICAART '88, Montreal*, 468-469. Washington, DC: RESNA, Association for the Advancement of Rehabilitation Technology, 1988.
20. **Young J, Burns P, Bowen A, McCutchen R:** *Spinal Cord Injury Statistics*. Phoenix, AZ: Good Samaritan Medical Center, 1982.