A Review of Design Issues in Rehabilitation Robotics with Reference to North American Research
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Abstract—Since rehabilitation robotics is a small field, progress toward useful devices will be faster if research groups are cognizant of the successes and failures that have been made in the past. This paper reviews past and present work, focusing on projects in North America (a companion paper in this issue reviews work in Europe), and attempts to identify the key features that have led to the success or failure of devices. Of particular note is the reliance in the past on position controlled robots, as these were the available level of technology. Lack of exemplar products has made it difficult for researchers to identify the needs and expectations that a person with a physical disability might have of a rehabilitation robot. This situation is changing rapidly and the field can now benefit from "consumer in the loop" research and design methods.

I. INTRODUCTION

THE discipline of rehabilitation robotics is diverse, and although a liberal definition of both words is usual, the intersection of these two areas is still small. This situation is not likely to continue. Rapid developments in robotics and computing, together with an increasing need to develop tools for daily living tasks, especially to allow a greater independence for the elderly, are expanding the role of robotics in assistive technologies.

The perception of what constitutes a "robot" is often misleading; the noun form is often used to denote "hi-tech" rather than an integration of mechanical and electrical expertise. In this paper, we will review work that demonstrates the application of robotic technology in rehabilitation, thus encompassing purely mechanical systems and systems that seek applications other than simply replacing the mechanical function of a person's arms and legs. We will, however, omit applications that target a sensory disability, although Ralph [34] is an excellent demonstration of the potential in this direction. Likewise, therapeutic applications are not included as these are covered elsewhere in this issue. Finally, the more general area of applications of robotics in health care, such as robots to assist surgical procedures or perform fetch and carry duties in a hospital, is also excluded. The special issue of Robotica gives a good overview of these disciplines [37].

The unifying theme of all work in rehabilitation robotics is that of the human-machine interface. This interface is highly dependent on the available level of technology. Although speech recognition systems might be considered "state of the art," more important developments concern how the human, with mechanical assistance, can interact effectively with commonly encountered environments. The specification of the human-machine interface is closely tied to more general design issues such as proposed tasks, projected cost, aesthetics, and operator safety. Ideally, the compromises made at each stage of the design process need to be assessed by the consumers of the technology—the family, care givers, rehabilitation professionals, and third party payers, as well as the ultimate user. The human-machine interface extends beyond simply the exchange of information between the person and the machine and includes all aspects of its utilization in the targeted environment.

Currently, all commercial and most research rehabilitation robotic systems are based on position controlled servo mechanisms. This has resulted in mechanisms where the operator must rely on visual feedback as the primary source of information about the robot and must maintain a direct line of sight to the robot's gripper when attempting to grasp or place items. Further, since a position controlled robot has no sense of any contact it makes with the environment, users cannot determine the forces that it exerts. Most meaningful interactions require environmental contact and the ability to develop strategies to deal with unforeseen events. The total dependence on visual information has driven interface design toward defining a human-computer interface rather than an intuitive and direct interface to the robot itself.

Advances in mainstream robot technologies are now moving away from pure position control and toward mechanisms that either have an inherent ability to control contacts with the world or sufficient auxiliary sensing integrated into the low level control loops to control force. The challenge is to reflect this new ability in the interface to the users. This will require more than simply providing an alternate representation since the human visual-motor system has a response time measured in hundreds of milliseconds, which is usually sufficient for any mechanical system to saturate to the point where the maximum force is being exerted on the environment. The limitations of position-based control have tended to direct research on rehabilitation robots toward applications where contact with the world is minimized and highly contrived.

Some important lessons on the human-machine interface can be learned from prosthetics and telerobotics. This paper will identify key aspects that relate to rehabilitation robotics. This is not to denigrate the relevance of other disciplines such as planning, control, and sensing, but these literatures

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are generally more accessible and tend to have relevance to specific implementations. A history of rehabilitation robotics follows, along with a discussion on current research in North America. The current market for devices is considered together with longer term implications and critical comments on the research field.

II. HISTORICAL OVERVIEW OF PROSTHESES AND TEOLEPROSTHESIS

The fields of prosthetics and orthotics have goals similar to rehabilitation robotics—that of augmenting or replacing a person's abilities—and are therefore included in this overview. Interfaces to rehabilitation robots have some similarity to teleoperation where an operator interacts with a master robot and a slave robot interacts with the environment. Of particular note is how this field has used sensory feedback mechanisms other than vision to effect accurate control.

A. Prosthetics

The following discussion centers on upper limb prosthetics, where an effective mechanical replacement is provided to a person who has lost an arm.

The body-operated Bowden cable arm came into widespread use after World War II and still remains the prosthesis of choice for many amputees because of inherent kinesthetic feedback associated with cable control [15]. However, with the advent of new technologies such as the transistor and microprocessor, it became apparent that external power would play a significant role in prosthetics.

Diminished human strength was the main impetus for the use of external power. External power was accompanied by an increase in the control complexity. Two control philosophies have been leading since the early 1940's:

1) Activation of the prosthetic joints with the aid of myoelectric (EMG) signals from remaining musculature.
2) Control by displacement signals obtained from body movements (digital and analog).

The drawbacks of EMG control are well documented [29], [51]. EMG control is essentially open loop where position proprioception is absent. With EMG control, the individual with an amputation relies on vision and exteroceptive feedback to determine how well his/her intentions have been executed by the prosthesis. Soede notes that “Feedback based on visual and auditory cues is slower, less automated, and less programmed than the normal proprioceptive feedback” [60]. If movement of the prosthesis is physically linked to body movement, not only is it unaffected by external forces, but it also provides proprioceptive feedback, and hence, a closed-loop system.

Body movement control can be divided into discrete and continuous inputs. Discrete signals that are effected by body movements include switches operated by residual digits, the shoulder, and feet [14]. This is analogous to commands given to systems using currently available speech recognition systems or keyboards modified for poor or limited hand movements. The disadvantage of discrete control is that it usually relates the duration of switch closure to the distance moved. This relationship does not conform to natural modes of control, and coordination of multijoint movement becomes difficult.

The more intuitive control scheme is when a continuous signal is available. If a cable is used to link a control site, such as bicipital movement of the shoulders to the flexion and extension of the prosthesis elbow, the user has a sense of being linked to the arm. Force exerted on the cable moves the artificial joint and the movement at the joint is linked to the amount of movement permitted at the shoulder. The prosthesis therefore acts as an extension of the user and provides force and position information to the user. This exchange of information and energy signals is termed bilateral control and is a current area of research in telerobotics [23], [33]. Bilateral control, and the related area of impedance control [30], share much in common with powered prosthesis control using body movements.

B. Teleoperation

Teleoperation was first developed for use in the nuclear industry in the 1940's [22] and has since found applications in undersea exploration, waste management, and space exploration. Early teleoperated devices were mechanically linked, kinematically similar master and slave manipulators, or linear-amplifier systems, such as Handyman [49]. These systems evolved into more sophisticated teleoperated robot systems that were more dexterous and allowed the operator to be physically separated from the slave [67]. Present day systems can employ geometrically dissimilar master and slave manipulators and the system can be controlled through high-level commands, which make it convenient for the user [21], [28].

In early telemannipulation systems, each joint of the (slave) robot was controlled by a very stiff position servo. Consequently, the human operator had to control a very stiff system. While a stiff telerobot is well-suited to operation in free space, when it comes into contact with objects, excessive forces may result.

Kinesthetic feedback significantly improves the performance of the teleoperated system. This involves feeding back the forces and moments sensed at the end-effector to the human operator [2], [15], [24], [35], [39]. The goal is to allow the operator to control the position (and orientation) of the slave robot while feeling the forces (and moments) exerted by the slave. This is referred to as telepresence [59]. The dynamics of the environment are transferred to the human operator so that the human operator feels as though he/she is directly interacting with the environment.

Bobgan and Kazerooni [6] presented a control architecture for a master/slave system in which the dynamic behavior of the master and slave are functions of each other. Stability conditions between human, master, slave, and load were also derived and verified experimentally with a single degree-of-freedom system. Hogan [30]–[32] investigated impedance as the variable that characterizes energetic interactions between dynamic systems, including man/machine and manipulator/environmental systems. He stressed the use of the
“spring like” properties of muscles in controlling posture and movement.

Work by Stein and Paul [62], [63], describes telerobotics in the presence of delay. This challenge is typical of undersea and space applications but is also relevant to the consideration of interface strategies in rehabilitation robotics. A computer model of the remote environment is presented to the user and a graphical representation of the slave responds to movements of the master. The interactions of the slave in this “virtual world” are sent to the remote location as program instructions where they are executed. When discrepancies between the virtual and physical world are noted by the slave, these are transmitted back to the master system so that the operator can diagnose the problem and make the necessary corrections.

Work at the Applied Science and Engineering Laboratories has looked at transferring these concepts to rehabilitation, and Fig. 1 shows a test mechanism to allow head control of a robot to be as intuitive as a mouthstick [54]. While the importance of force feedback and position control capability is clearly understood, there are additional considerations for prosthesis control and, more generally, for rehabilitation robots. These are:

1) Limited number of available human input sites.
2) Requirement of an “unbeatable position-servo,” whereby the master and slave move in unison, emulating a rigid connection between the person and the robot.
3) Capacity to augment strength.

III. EARLY NORTH AMERICAN RESEARCH ON REHABILITATION ROBOTICS

Rehabilitation robotics not only draws on teleoperation and prosthetics but also commercial and research robotics, rehabilitation research, and broader fields, such as human-computer interaction. A distinction is possible between a class of assistive robots that supports and moves the arm of a person with upper extremity paralysis in order to augment all residual function, and one which is a functional replacement for a person with poor or limited limb function. Terms used for the former include “powered orthosis,” “extender,” or “man-amplifier” [40], names for the latter include “manipulator,” “rehabilitation robot,” or “telethesis” [42].

Early work on a powered orthosis was done at Case Institute of Technology in the early 1960’s [44]. The manipulator was configured as a floor-mounted, four-degree-of-freedom, externally powered exoskeleton. Direct control was achieved via myoelectric signals and a head-mounted light source to trigger light sensors in the environment. A number of preprogrammed movements were also possible and were stored on a magnetic tape [56].

This work led to one of the first successes in rehabilitation robotics: the Rancho “Golden” arm, developed at Rancho Los Amigos Hospital in Downey, CA in 1969 [1]. This was a six-degree-of-freedom powered orthosis that used seven tongue switches in a sequential mode to successfully maneuver the arm in space. According to Reswick [56] “...no other manipulator or powered orthosis was as successful outside of a research or clinical setting as the Rancho ‘Golden’ arm.”

Reswick goes on to state that this level of success is due, in large part, to intact sensory function present in the users.

Leifer [46] noted that the “Golden” arm was difficult to control and unreliable, and quoted Corker in 1979 as saying that “fitting a manipulator to the specifics of an individual’s anatomy and range of motion makes construction and control very difficult.” The principle of the underlying thesis remained and the success of the Case Arm and the “Golden” Arm, can be attributed to the vital role that proprioceptive feedback plays in the control of a human extremity.

A telescoping four-degree-of-freedom “powered reacher” was developed by Carl Mason at the VA Medical Center in New York [47]. This was wheelchair mounted and yielded Cartesian control through analog electronics. This device, however, was not programmable and had reliability problems. Second generation versions of the VA, arm developed by General Teleoperators, had voice input and were used at the Jet Propulsion Laboratory, the Denver Research Institute, and the University of Santa Barbara [44]. Corker gives a more detailed review [16], and evaluated the General Teleoperators arm, the Rancho “Golden” arm, and the Johns Hopkins manipulator system. Corker stated that reliability in the voice system was hampered due to a low recognition rate and called for increased
reliability and reduction in the mental burden associated with control.

The Johns Hopkins arm [58] evolved from a prosthesis and consisted of four degrees-of-freedom plus grasp that were controlled by three motors. Tasks were executed in preprogrammed and direct modes by a chin manipulateum and other body-powered switches. Sensory feedback was absent and the system was bulky and unreliable.

Work by C. Fu at the Boeing company in Seattle used a prototype RTX robot to deal with book and paper handling at a workstation set up for a programmer with quadriplegia [20]. An attempt to market this device was made by a USA company, Prab Robotics in 1986, however, this effort closed down within a few years.

IV. ONGOING NORTH AMERICAN RESEARCH ON REHABILITATION ROBOTICS

Table I gives an overview of the characteristics of rehabilitation research projects with a primary emphasis on North America. This section elaborates on some of the more pertinent examples of this work.

The Palo Alto Rehabilitation Research and Development division of the Department of Veterans Affairs Medical Center, together with Stanford University, have an extensive history in rehabilitation robotics research [65] (and elsewhere in this issue). Their philosophy on the human-machine interface has been to emphasize autonomy of the robot during operation, and, although this results in more rapid times to complete a task, there is a subsequent burden in programming. This burden was a necessary compromise that recognized the limitations in existing robot technology. To alleviate this problem, later work by Lee and Leifer investigated a "story board" graphical interface and reported that this offered an easier method for both technical and nontechnical users to write utilities [45]. The progress of robotic technology has allowed this work to study integration of force sensing into the programming environment and the authors reported that programs that used the force information available from a wrist sensor were more robust to changes in the environment.

In Vancouver, Canada, the Robotic Assistive Appliance (RAA) was developed at the Neil Squire Foundation. The RAA resulted from eight years of research in rehabilitation robotics and has six degrees-of-freedom with either programmed or direct control [10]. A variety of interfaces have been demonstrated, including sip-and-puff, Morse Codes, and voice control. An attempt at limited commercialization of the arm under the name "Regensity" was made, primarily for the purpose of extended assessment, and devices were installed at two sites in Canada and one in the U.S. [5]. This commercial venture ended in 1993 and work on the arm is ongoing with clinical evaluations and a study to investigate ways of improving the interface and safety of the arm [4].

One early design decision that has a profound effect on the eventual technology is the choice of actuators. Most groups choose robots or actuators based on electric motors. Two groups in North America, however, have chosen robots with pneumatic motors. The principal advantages of pneumatic motors are their inherent compliance and a high force-to-weight ratio. Their disadvantages include noise of the valves and power source, nonlinearity, difficulty in obtaining accurate control, the energy storage in the compliance, and speed of response [52]. Kawamura's group at Vanderbilt University uses a Japanese arm based on the RubertorauTM, and is investigating a novel closed-loop control system whereby the position of the person's head is sensed using a computer vision system, thus modifying the path of the robot delivering food on a spoon [38]. Mattie and Hannah are using the pneumatically powered Papworth Arm with children with muscular dystrophy [48]. A survey has identified the need for an arm of this nature but found several limitations of the existing device, including noise and speed.

The Applied Science and Engineering Laboratories (ASEL) are carrying out a range of projects concerning rehabilitation robotics; for example, Fig. 2 illustrates a vocational workstation using the RTX robot [25]. Although there is a movement away from workstation robots, vocational assessment and placement remain as areas where this style of system may succeed. Two of the ASEL projects that are of particular note in this discussion are a project on providing proprioceptive sensory feedback to a person using head movements to control a robot and a study of interactive planning and command of a robot for rehabilitation applications [12], [54]. These two approaches represent two extremes of a user interface that seek to exploit modalities other than the operator's vision to have effective control of a robot for handling light objects in a rehabilitation setting. The philosophy of the project studying proprioceptive head control is that there should be a direct correspondence between the movement of the person's head and that of the robot in the world, including situations when the robot makes contact. To achieve this, the forces exerted by the robot are measured and proportionately reflected to the head control mechanism (see Fig. 1). In contrast, the second project uses the measurement of forces exerted by the robot in local control loops simply to monitor and control interactions. The concept is to provide the operator with graphical information about the state and world representations that the robot can use to navigate and interact with the world. The operator can then make executive decisions on how a plan should be executed, and when it completes or fails, can understand the reasons and redirect movements at his or her leisure.

Most projects use the rehabilitation robot to separate the person from the environment, however, residual function invariably surpasses any abilities a robot can replace. Power-assisted orthotics seek to utilize this residual function as far as possible and two projects in North America are studying methods to achieve this end. Work by Romilly and Anglin [57] proposes a body worn, powered orthosis and work by Ramanathan et al. [55], in a project overseen by the authors, proposes that the orthosis be attached to the person's wheelchair.

Alternate methods of providing control information to a robot are also an area of research. Burrow et al. propose using implanted sensors in the motor cortex and pattern recognition techniques to learn the commands a person may wish to provide [7]. Bush et al. use a more conventional and less intrusive method whereby electro-myograpal signals are
### TABLE 1

<table>
<thead>
<tr>
<th>Project</th>
<th>DOF*</th>
<th>Date(^a)</th>
<th>Actuator</th>
<th>Control Mode</th>
<th>Continuous Inputs</th>
<th>Discrete Inputs</th>
<th>Sensory Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rancho Los Amigos</td>
<td>6+</td>
<td>1969</td>
<td>electric</td>
<td>joint</td>
<td>2 d.o.f manipandum</td>
<td>3 tongue switches</td>
<td>n none</td>
</tr>
<tr>
<td>Kecklak(^2)</td>
<td>4+</td>
<td>1970</td>
<td>pneumatic</td>
<td>joint (programmed)</td>
<td>world</td>
<td>EMG, switches</td>
<td>y none</td>
</tr>
<tr>
<td>Case research arm and II</td>
<td>4+</td>
<td>1975</td>
<td>electric</td>
<td>world</td>
<td>2 axis chin</td>
<td>5 position switch</td>
<td>n none</td>
</tr>
<tr>
<td>VAPEC</td>
<td>4+</td>
<td>1975</td>
<td>electric</td>
<td>manipulum</td>
<td>switch</td>
<td></td>
<td>y none</td>
</tr>
<tr>
<td>Mako(^7)</td>
<td>4+</td>
<td>1975</td>
<td>electric</td>
<td>modified VAPEC arm</td>
<td>joint</td>
<td>voice</td>
<td>y none</td>
</tr>
<tr>
<td>JPL</td>
<td>6+</td>
<td>1978</td>
<td>electric</td>
<td>modified VAPEC arm</td>
<td>joint</td>
<td>voice</td>
<td>y none</td>
</tr>
<tr>
<td>UCSB (JPL)</td>
<td>6+</td>
<td>1978</td>
<td>electric</td>
<td>modified VAPEC arm</td>
<td>joint</td>
<td>voice</td>
<td>y none</td>
</tr>
<tr>
<td>Denver(^6)</td>
<td>6+</td>
<td>1978</td>
<td>electric</td>
<td>modified VAPEC arm</td>
<td>joint</td>
<td>1 tooth click</td>
<td>y none</td>
</tr>
<tr>
<td>Johns Hopkins</td>
<td>5+</td>
<td>1978</td>
<td>electric</td>
<td>chin manipulum</td>
<td>switch</td>
<td></td>
<td>y none</td>
</tr>
<tr>
<td>Magpie</td>
<td>4</td>
<td>1987</td>
<td>body</td>
<td>powered</td>
<td>joint</td>
<td>foot control</td>
<td>n pro-</td>
</tr>
<tr>
<td>Boeing</td>
<td>6+</td>
<td>1986</td>
<td>electric</td>
<td>UMI RTX</td>
<td>world, joint</td>
<td></td>
<td>y none</td>
</tr>
<tr>
<td>Hugh McMillan orthosis</td>
<td>1+</td>
<td>1989</td>
<td>electric</td>
<td>joint, elbow and wrist coupled</td>
<td></td>
<td>joystick</td>
<td>y none</td>
</tr>
<tr>
<td>Georgia Tech</td>
<td>6+</td>
<td>1991</td>
<td>electric</td>
<td>world</td>
<td>none</td>
<td>joystick</td>
<td>y none</td>
</tr>
<tr>
<td>Barrow(^8)</td>
<td>6+</td>
<td>1993</td>
<td>electric</td>
<td>joint</td>
<td>none</td>
<td>switch keypad</td>
<td>y none</td>
</tr>
<tr>
<td>McAllister arm</td>
<td>5+</td>
<td>1993</td>
<td>electric</td>
<td>Cyber robot</td>
<td>world</td>
<td>switch</td>
<td>y none</td>
</tr>
<tr>
<td>Handy II</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>UMI RTX</td>
<td>world</td>
<td>joystick, keyboard</td>
<td>y none</td>
</tr>
<tr>
<td>MasterRAID</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>UMI RTX</td>
<td>world</td>
<td>joystick</td>
<td>y none</td>
</tr>
<tr>
<td>DeVAR</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>FUMA robot</td>
<td>world, tool, joint</td>
<td>trackball, joystick, keyboard, voice</td>
<td>y grip opening</td>
</tr>
<tr>
<td>Neil Square</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>world, joint</td>
<td>none</td>
<td>switch, voice</td>
<td>y none</td>
</tr>
<tr>
<td>Foundation (RAA)</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>world, joint</td>
<td>none</td>
<td>voice keyboard</td>
<td>y none</td>
</tr>
<tr>
<td>Hugh McMillan myoelectric arm</td>
<td>4+</td>
<td>1994</td>
<td>electric</td>
<td>joint</td>
<td>1 emg</td>
<td>none</td>
<td>y none</td>
</tr>
<tr>
<td>ISAC</td>
<td>5</td>
<td>1994</td>
<td>pneumatic</td>
<td>shoulder</td>
<td>world</td>
<td>voice</td>
<td>y none</td>
</tr>
<tr>
<td>Keenware(^2)</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>UMI RTX robot</td>
<td>world, joint</td>
<td>joystick, polysense</td>
<td>y none</td>
</tr>
<tr>
<td>A.L. DuPont</td>
<td>6+</td>
<td>1994</td>
<td>electric</td>
<td>ZEBRA ZERO</td>
<td>joint, world</td>
<td>load movements</td>
<td>none force</td>
</tr>
</tbody>
</table>

\(^a\) Degrees of Freedom.

\(^b\) Date of last known publication.

\(^c\) Completed.

\(^*\) Orthosis.

Transduced from the frontalis muscles and are used to change modes and command movement on a wheelchair-mounted manipulator [9]. A version of this device is shown in Fig. 3.

Mobile robot technologies have also been explored for rehabilitation applications, and Levine et al. have studied the use of sonar information in shared control methods to control electric wheelchairs [3]. Joystick movements are analyzed to identify the person's intended movement direction. This information is coupled with information from the sensors on the wheelchair so that obstacles can be avoided while the chair moves in the intended direction.

Work by Kumar offers an alternate application of robot technology by using two cooperating arms attached to a wheelchair that assist in mobility. The arms do not only assist.
with manipulation but also assist a person through a door, over obstacles, and up steps [41].

V. OVERVIEW OF COMMERCIAL SYSTEMS

Recent growth in rehabilitation robotics has prompted some fledgling companies to explore the potential market. It is unlikely that any of the companies are expecting a buoyant market at this time. Fig. 4 shows the relationship between price and the number of degrees-of-freedom in a device. Other rehabilitation devices are included in this graph for comparison. There is a wide range in price and complexity for these products and each uses a different reasoning to justify its niche. The Appendix gives details of the individual products under discussion. Details of the underlying technology are included in Table I and, where relevant, in the preceding section. Although most products lie on a straight line on the log-linear plot, the outliers can be identified. The Magpie is an outlier because it is mechanically simple, having no actuators. It is also an effective eating aid for people with poor arm movements, good leg movement, and reasonable proprioception. It also illustrates that devices with four or fewer degrees-of-freedom can be used effectively by direct proportional control, provided the person can get a sense of the forces encountered by the device in the environment. It remains to be seen whether a person can have simultaneous control of five or more degrees-of-freedom of a robot, control forces of contact, and still keep an intuitive interface.

The high end devices, such as DeVAR, the RAID workstation, and Manus, have primarily been sold to sites for teaching and assessment, or to research institutes for extended evaluation. The costs of these devices are justified by amortizing the cost with respect to expected benefit over a number of years for an individual. This argument is particularly effective when it can be shown that an individual can maintain full-time and productive employment with the robot, but the fulfillment of this argument has yet to be shown in practice. Lower cost devices, such as Handy II and the Magpie, have forfeited reliability and flexibility but have had more success with eventual users in efficient but specific achievement of a preset task, in both cases allowing the user to eat a meal with a spoon.

Two of the products illustrated, the Prab arm and Regenesis, are no longer produced commercially. Regenesis was intended
to be a limited commercialization while the Prab arm failed in the market in the late 1980’s. The failure of the Prab systems can be attributed to lack of reliability, lack of utility, cost, and a poor user interface.

A lower priced wheelchair-mounted robot arm has recently been produced by a Massachusetts company. The Helping Hand appears to meet many of the consumer needs of cost, size, and portability, but it is too early to judge its success as an aid to manipulation. The current commercial robot has three degrees-of-freedom but the manufacturers are developing a new version with a fourth axis located at the wrist.

An observation of the majority of these devices is that they are based on position controlled servo mechanisms and, in general, are programmed so that contact with the environment is minimized.

An interesting comparison with other rehabilitation products is enlightening. Electric wheelchairs have a well developed market with several competing companies. Price and complexity vary widely and a simple chair with two degrees-of-freedom has a price range of between three and ten thousand dollars. Permobil have established a reputation for more adaptable chairs that allow the user to stand, recline, move, or raise and lower the chair height. These functions add three to four additional degrees-of-freedom to the product, as is shown in

Fig. 4. The success of the Permobil chairs illustrates that the complexity of devices such as DevAR and MANUS is justified if sufficient benefit can be shown.

The Winsford feeder provides an interesting comparison to the Magpie and Handy II. This is a two degree-of-freedom device compared with four in the Magpie and five in the Handy II. All three devices use a spoon to select food from a plate and position it so the person can use neck movements to take the food. The difference between these devices lies in the interface. Handy II can be used with a single switch control, food can be taken from any part of the plate and the location where the person transfers food to his or her mouth can be changed. It also has sufficient flexibility to allow other applications such as applying makeup. The Magpie requires more physical dexterity but gives the person the flexibility to choose food from any part of the plate and move it at will to a convenient location. The Winsford feeder has more rigid interface requirements but is considerably cheaper. It remains to be seen which parameters are most desirable in devices of this nature.

Finally, the Freedom lift has been included in Fig. 4. This is a three degree-of-freedom wheelchair lift mounted on the back of a pickup truck to allow farmers with paraplegia to transfer into and from farm machinery. The high price in comparison to products such as the Helping Hand is illustrative of the size and payload of the device. Of particular interest is the small potential market for this product, an estimated 150 farmers in the Canadian prairie have the disabilities that would require such a solution [19], although this would expand somewhat if the U.S. were included as a market.

VI. DISCUSSION

One perennial problem in rehabilitation robotics is identifying which of a user’s needs should be addressed by the product. It is a costly exercise to prototype a system so that it can be evaluated by a population of users who then identify several fundamental weaknesses. Although user surveys help to identify these needs [61], they provide simply a starting point for a design. During early design stages, there is some difficulty in identifying what a robot could or should do for a person since this phase of the work is plagued by poor information, which means that the designer may not be able to communicate well with potential users. This should not, however, be an excuse for design to continue without significant involvement from the ultimate consumers.

The discipline of rehabilitation engineering is in an ideal position to exploit the new concept of “consumer in the loop” design, but to do this the meaning of the word “consumer” must be extended. The consumer not only includes the primary user, but also the family, therapist, physician, administrator, spouse, caretaker, and anyone who has an influence on the method by which a new technology is acquired and used. These consumers are in an ideal position to judge not only the technological merit, but also qualities such as the social value, the aesthetics, and sensitivity to cost. In research projects, there is not necessarily a tangible end product to be visualized and the research must be placed in context within the broader
field so more effort is needed to gain meaningful consumer interaction.

The interface between the user and the machine continues to be a major research issue in rehabilitation robotics. The user needs to acquire a sense of the state of the machine. An example of this is the control of contact force in the environment. When intact proprioception can relay this information, the user can have direct experience of the event. This is inherent in a powered orthosis or telerobot. Indirect representations of the machine state could be to represent forces via tactile transducers. A third representation of the machine state is to use force information as part of an inner loop control and interrogate the user as to corrective actions should this force go out of preset bounds. The knowledge of key parameters in the machine state is vital since it is with this knowledge that the user can make effective decisions on what actions the robot can be expected to achieve and what corrective action may be needed to adapt to the changing environment.

The effectiveness of the robot is a primary criterion for success, according to consumers, and this relates directly to the human-machine interface. An interface that is hard to learn and difficult to use will not be effective in achieving timely completion of a desired task. The pleasure of eating may be lost if moving food from the plate to your mouth takes so long that the food becomes cold. The user should not have to focus on how to control the robot, but should be able to focus on the task at hand. A central research question remains as to how shared the control should be. There is a trade-off between the computational burden of processing a vast amount of information and the cognitive burden placed on the user.

Rehabilitation robotics research leads constantly to questions of design, and early design decisions have profound effects. A decision to ensure that a person can pick things up from the floor is usually translated to a requirement that the device should be able to reach the floor. This then poses the issue of how to manage the robot when you no longer have visual contact with the gripper and presupposes that there is no better method, such as two mechanisms that can cooperate, to achieve the task. There has invariably been a high cost, either in the dollar value of the robot or in the difficulty with user control, in meeting this design decision. Future design work may be able to make use of modularity, thus allowing one product to meet a wider range of needs. The developments of lighter materials, flexible manufacturing methods, and robots that have inherent force sensing and control abilities will also have a substantial impact on the design of the human-machine interface in this field.

Safety continues to be a difficult issue, and questions as to what level of safety at what cost remain unanswered. There are well documented discussions on safety in this field [26], [66], but one interesting result from focus groups held during the 1994 ICORR Conference is that the designers and engineers may be too focused on safety at all costs whereas consumers would be willing to consider taking a greater risk if it resulted in a tangible benefit in their lifestyle. This opinion certainly highlights the need to involve consumers at all stages of work but may not hold sway once liability concerns of a commercial product are considered.

VII. CONCLUSION

The concept of rehabilitation robotics has matured from the simple application of a manipulator to replace impaired manual abilities, to a comprehensive consideration of the needs of the user and the impact of the technology on multiple aspects of the user's life. The concern for effective interaction techniques and strategies is likely to offer the user the opportunity to perform tasks in ways that are competitive with personal care attendants and specialized assistive technologies.

Rather than focus on individual demonstrations of robot effectiveness in limited situations, e.g., eating, workplace, etc., and argue for decreases in cost to promote use by consumers, current research addresses the human-machine interaction over a broad range of life activities. Significant increases in function that allow a user to effectively employ a robot may overshadow the cost of technology due to a higher ratio of benefit to cost. Furthermore, improvements in function that allow for competitive employment or increased independence with
reduction in the costs of personal care will promote the use of robots by individuals with disabilities.

The inclusion of consumer-focused research techniques with the opportunity for individuals with disabilities to play important roles in defining the functional specifications and in evaluating the performance of research systems is important in the success of these studies. Robotic systems that truly meet the needs of consumers are obviously more likely to be beneficial and justify the investment in research and development.

The investigation into the use of robots and manipulators by individuals with disabilities will continue to search for interaction techniques which offer users performance that is superior to other assistive technologies and systems.

APPENDIX

1) MANUS is based on work done by H. H. Kwee and others [42] and is sold by Exact Dynamics of the Netherlands.

2) The RAID Workstation is based on work done by J. M. Detriché and others [17] for the European RAID project, and is sold by Oxlim Limited, England.

3) Regenesis was a limited commercialization of the Neil Squire RAA project. Work on the RAA arm continues under the direction of G. Birch.

4) Prohab was an attempt to commercialize work done by C. Fu at Boeing and used the RTX robot as a basis of a workstation for programmers with quadriplegia.

5) DeVAR is based on work done by L. Leifer and others [65] at the Palo Alto Department of Veteran Affairs Medical Center. It is sold by Independence Works of California.

6) Helping Hand is a three-degree-of-freedom, wheelchair-mounted arm designed and sold by Chris Cobb of Kinetic Rehab of Hanover, MA.

7) Handy II is based on work done by M. Topping and others [64] and is sold by Rehab robotics of Keele, England. This system uses an educational robot arm based on stepper motors (the Cyber 310) to perform a number of programmed tasks, primarily to assist children with cerebral palsy to eat. A single switch-scanning mechanism allows the person to select food which is then automatically brought up to the mouth.

8) The Magpie is based on work done by M. Evans [53] and is sold by Oxford Orthopaedic Engineering Centre, England. The Magpie is a body-powered, cable-controlled, foot-operated robot and uses four foot movements to control a four degree-of-freedom wheelchair.

9) The Papworth arm is a wheelchair-mounted arm based on work done by J. Hennequin [27] and Papworth Industries. It is sold by Papworth Industries, England.

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REFERENCES


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