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ciated with clinical evaluation to determine an individual's potential benefit from a robotic device, training, service delivery, and up keep or repair of the robot which are beyond the scope of this article, but have been addressed elsewhere [53].

Despite decision criteria regarding device functionality, there are design recommendations from many fields which contribute to developing interface criteria. From the field of industrial robotics and telerobotics, we learn that

- a "+" sign should be associated with right, forward, up and clockwise
- for a joint controlled robot, training should introduce the user to a robot-centered reference system where the reference frame moves with the robot [20]
- as little as a 30 msec time delay in a sensory feedback system may negatively influence performance [29].

Consequently, the field of rehabilitation robotics continues to benefit from research conducted in other fields.

Currently, the available assistive manipulation devices or rehabilitation robots are typically joint controlled, cartesian coordinate controlled or execute pre-programmed interactions [17, 45, 57, 3]. If designing an interface for one of these devices or for a different device, characteristics to be included in the design are:

- physical specifications (size, weight, etc.)
- tactile cues
- visual cues
- auditory cues.

These items influence the success with which a user executes tasks with the robot. Another criteria for successful interaction is the "conceptual model" or interaction scheme. Elements of a "good conceptual model" which result in the user being able to predict the outcome of an event are:

- visibility
- conceptual mapping
- feedback [41]
- modeless interaction
- error recovery or reversible actions [27].

These design elements should assist in minimizing complexity, maximizing consistency and providing appropriate feedback, the goals in improving an interface design [14]. In addition, the safety of the robotic device can be improved with a more "intuitive" interface design.

Evaluation of a device remains a challenge. The field of human computer interaction provides theoretical models used for evaluation, however, the application of these models to rehabilitation robotics are not straight forward. Previous attempts at incorporating a model in the rehabilitation field have demonstrated limitations [40]. Interface design, however, will very likely benefit by incorporating users into the design loop early in the interactive cycle of design implementation.

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adjustments are typically possible, they are non-trivial and can add significant time to an evaluation protocol. *Retention over time* may be compounded by understanding how the robotic device operates and understanding the requirements for task execution. This measure is also compounded by frequency of use, or infrequency of use, which is typically the case with rehabilitation robotic devices. *Subjective satisfaction* is quite obtainable, but difficult to quantify, especially with small subject numbers.

As an alternative to evaluating the robotic interface intact, researchers could run a simulation of a robotic interaction. Although a simulation could be constructed to eliminate *time to learn* how the robot operates, the *speed of performance* of the robot, and the *rate of error* associated with understanding how a robot operates, the simulation would also potentially eliminate all of the relevant factors associated with actual robot operation, thus negating the relevance of the study. This criticism is also found in human computer interaction as observed in a quotation about using scenarios to evaluate interface design, "The danger in using design scenarios to drive evaluation of a fully instantiated design is that the design may have been tuned to the scenario execution." [56, pp. 294].

The argument against using simulations or scenarios leads to the current debate within human computer interaction regarding the methodology employed in evaluating an interaction scheme [37]. The debate is between ethnographers and experimentalists. Ethnographers argue that:

- the laboratory is not real world,
- one cannot control all variables that affect a behavior,
- an effort is made to eliminate context rather than understand it,
- subjects are given highly constrained, artificial tasks with a very short time frame,
- the subject's observations are not incorporated.

Alternatively, the experimental method provides measurable differences between opposing perspectives [37]. In human computer interaction, the solution is likely to be a well designed hybrid of ethnography and experimental method. In evaluation of a rehabilitation robotic interface, application of the experimental method remains a challenge.

Single Subject Analysis: Single subject analysis has been most frequently applied to experimental psychology and AAC [6, 35]. The basis of single subject analysis is to collect a baseline, typically over several days, introduce a single condition and record the parameter of interest over an equal length of time to see if there is change, then remove the condition to see if there is a return to baseline, then re-introduce the condition and record the pertinent data. This protocol is an A-B-A-B design. Other variations of introducing a condition are also possible. The underlying assumption in single subject analysis, however, is the presence of a baseline. An individual who may benefit from using a rehabilitation robot does so precisely because he or she is unable to perform the activity otherwise, making a fundamental "baseline" comparison impossible. A variation of a single subject design, comparing one interface against another for instance, confronts all of the difficulties enumerated under the five measurable criteria for evaluating an interface.

Conclusion

In the development of the Star system, Smith et al. [52, pp. 246] "learned from the Star the importance of formulating the fundamental concepts before software is written rather than tacking on an interface afterward." As outlined in this article, "formulating the fundamental concepts" is a considerable challenge for rehabilitation robotics. The users and their social and physical environment, task needs, physical and cognitive abilities, age, background, culture, and education vary tremendously. There are many other issues asso-

fied so far in our experience." [30, pp. 283]. Another criticism of modeling is the limited capability for modeling a person's capacity for making an error, or the cognitive process used to recover from that error [11]. Finally, theoretical models are criticized for their restricted scope, failure to deal with the real context of the work, and failure to accommodate fine details [7].

User Participation in Design: As a supplement or alternative to modeling, the human computer interaction field is advocating the need to bring the user into the designing loop in the early stages of product development. This approach views design as an iterative process where users are brought in on many occasions during implementation of the design [24]. The approach of incorporating users into the interface design is being conducted with rehabilitation robotic interfaces, but on a small scale [38]. A highly effective method of evaluating a human computer interface is to monitor user action while collecting concurrent verbal protocols to help understand what is actually going on [7, pp 114]. Techniques for conducting user observation have been outlined in detail both in The Macintosh Interface Guidelines [27, pp. 43-46], and in The Art of Human Computer Interface Design [18, pp. 85-90]. The labor intensive nature of observation, however, generally require the studies to be confined to a very small number of subjects and tasks [7].

Evaluation Techniques: For the evaluation of a human computer interface design, Shneiderman [51] outlines five measurable criteria for evaluating an interface:

- Time to learn
- Speed of Performance
- Rate of errors by users
- Retention over time
- Subjective satisfaction.

Applying these criteria to a rehabilitation robotics interface is plagued with complications stemming from task execution and the subject's disabling condition. It is difficult to separate an evaluation of an interface from an evaluation of the robot, the later of which is extraordinarily time consuming and complicated [21, 22, 34, 36]. In addition, large, statistically significant studies with severely physically disabled individuals are nearly impossible because of the huge variation between individuals, the small sample size, difficulty in transportation to a research laboratory, fragile health conditions of the subject, and many other complicating issues.

When considering each element of the evaluation criteria in particular, the *time to learn* is compounded by learning about the robot. *Speed of performance* is frequently compounded by a user's disability which, in many cases, intrinsically prevents performing speedily. In addition, interaction strategies used by people with disabilities often complicate recording the speed of performance. For instance, if someone is using a mouthstick and drops the mouthstick or, more likely, spends time adjusting the mouthstick, this is a compounding factor in calculating the *speed of performance*. The *rate of error* is generally difficult to calculate with most robotic tasks, especially in unstructured environments, which is largely the kind of interaction that users request. In addition, these three factors are only relevant when a comparison is made between two alternatives. Potential rehabilitation robotics users typically have only one optimal body site, and potentially one method of interaction, which can complicate a comparison between two interface techniques. In addition, set-up is complicated by issues which are not addressed when evaluations are conducted with able-bodied individuals. For instance, an able-bodied person can position themselves to see a computer screen or use an input device. For someone who is disabled, the computer screen may have to be adjusted to accommodate a lack of mobility or the bulk of an electric wheelchair, and the input device will have to be mounted so that the user can access the device optimally. While such

The National Advanced Robotics Research Centre, Safety and Standards for Advanced Robots, “Predictability (is) a key attribute for safety. The design must emphasize transparency for the operator” [49, pp. 26]. Finally, a deliberate disruption in the flow of an activity serves the purpose of alerting the user to a potentially dangerous situation [42]. For example when the DeVAR system is operating in close proximity to the user’s face, the system is designed to interrupt the flow of activity. After receiving the initial command, the system asks the user “Are you sure?” and waits for a confirmation before proceeding.

Evaluation of Interfaces for Assistive Manipulators

Any interface design must be evaluated as a means of measuring its effectiveness. Theoretical models are available to describe desirable interaction characteristics and are sometimes used as a means of evaluation. The following section will review some of the pertinent models and their application to rehabilitation. This section then discusses the advantages of incorporating users into the design process, then concludes with a discussion of evaluation techniques and how they might be applied to evaluating an interface device for a rehabilitation robot.

Theories, Models, and Evaluation: Theories and models are used to describe the multiple aspects of interactive systems. High level theories or models offer a framework in which to discuss issues that are application independent. Some theories are explanatory while others are predictive. Explanatory theories are helpful in observing behavior, describing activity, conceiving of designs, and comparing high-level concepts of two designs. Predictive theories enable designers to compare proposed designs for execution time or error rates, focusing on perceptual tasks, and motor-task performance [51]. The goals, operators, methods, and selection rules, (GOMS) model is an example of a perceptual task predictive theory. It is based on the postulation that users formulate *goals*, use an *operator* to achieve that goal though a *method* chosen from the *selection rules* [10, 51].

The application of other theories or models as a method of assessing the use of a particular device for an individual or as a method of evaluation are currently under lively debate in both with clinical rehabilitation and human computer interaction. Within the rehabilitation field of Augmentative and Alternative Communication (AAC), there have been attempts to generate models of device use which predict performance of the operators using particular systems [19, 26]. One model has yet to be applied beyond the research lab in which it was developed and a second has sparked controversy regarding the limitations of the model [40]. The second model for AAC prediction is based on the GOMS technique [10, 26]. The model is criticized because the GOMS technique, “fails to capture the user’s fatigue, individual differences or mental work load” [46, pp. 223]. The model is further criticized because of the wide range of individual differences in physical and/or mental abilities which the model is applied to. Opponents of the model claim that it is “unlikely that a single model can be used to characterize any non-trivial task” [40 pp. 89].

In the field of human computer interaction, the limitations of modeling are prevalent on many fronts. Karat and Bennett [30] describe the process in which a user-centered design framework supports the design of a system to meet user requirements. They found that, “quantitative estimates available from our modeling based on cognitive science theory did not address the range of design issues we see as essential”, and that they “found it more beneficial to represent human-computer interaction scenarios in natural language than in formal notations.” They conclude, “The costs in terms of time required to learn and use various formal techniques have not seemed justi-

able to accomplish any task from any point within the system [27, 52]. This idea is consistent with Norman's concept of *visibility*, arguing that the control mechanism should not be hidden. Other human computer interaction guidelines also list *forgiveness*, meaning that in an error condition, the actions are reversible [27].

The concepts of visibility, modeless interaction, feedback, and forgiveness can be applied to an interface design for either a wheelchair mounted manipulator or a desktop system using a computer interface. Visibility of the system indicates that the function of any button or selection is clearly defined for the user. This, in coordination with "modeless interaction" would mean that there are no hidden levels which the user must jump to in order to reach a function or command for moving the manipulator. Mapping, which indicates a relationship between a control and its effect, can assist in determining how the operation of the input device is associated with control of the manipulator. For instance, if using a joystick to control a robot in the X-Y plane, pushing the joystick away from you should "map to" having the robot arm move away in the same direction. Feedback allows the user to know that a command has been successfully selected. Finally, forgiveness, or a reversible action is essential for all manipulators, especially from the perspective of safety. When a user makes a selection in error, the system must "forgive" and allow the user to retract the selected command with minimal penalty in time loss and interaction with the system.

When designing an interface, the designer must consider physical characteristics of the user, the user's social context and user's physical environment. The device must fit into the space and input strategy which works for the user. The tactile, visual, and auditory cues from the interface must be considered for optimal interaction, and the layout needs to cognitively map to the users expectations. With all this in mind, the interface inherently provides an additional means of safety for the user when operating an rehabilitation robot.

Designing the Interface for Additional Safety: The safety of the user can be improved by many aspects of the interface device including: 1. Providing redundancy in the interface feedback; 2. Decreasing the cognitive load on the users; and 3. Designing for an interruption in the flow of activity when operating in a potentially dangerous mode. Redundancy is achieved by providing multiple methods of feedback such as using both auditory and visual feedback. Redundancy can also facilitate safety by designing the device to accept multiple input signals. This is especially useful in an error condition or when a malfunction has occurred. For instance, a voice operated robot could be programmed to stop activity for a variety of commands including saying "stop" in a calm voice, shouting "STOP", or saying "wait", "halt" or "oh *!@#". A device is safer when the cognitive load required for operating the device has been minimized. This is achieved with good conceptual mapping and using standard cues like a red LED to indicate an "alarm" situation. The safety aspects of good cognitive mapping are exemplified in an unexpected condition because the more a user is required to "remember" to execute an activity, the more likely he or she will be to forget the required steps to achieve a result under duress. In human computer interaction, a "see and point" interface requires less cognitive processing than a "remember and type" kind of interface [42, 52]. The equivalent of a "see and point" kind of interface for a rehabilitation robotic device is potentially much safer than one which requires significant memorization. Again, in the field of human computer interaction, low visual momentum decreases problem solving performance [58]. In contrast, one can imagine that high visual momentum would result in facilitating problem solving performance with a rehabilitation robotic interface and potentially prevent an unexpected situation from becoming dangerous. In the words of

output of the interface can conceptually correlate or "cognitively couples" the device state to the user's expectations. Although "cognitive coupling" is highly dependent on the user's cultural and historical background, this issue is beyond the scope of this article.

Another aspect of integrating the user's vision to improve the cognitive coupling between the user and the interface is visual momentum. Visual momentum is how a user interprets data from successive glances at a specific location. In the field of human computer interaction, designing for high visual momentum facilitates the user's interpretation of the information on a computer screen. A display system structure which provides a visual frame of reference that describes the relationship between the interface and the task to be executed decreases the user's mental workload. Mis-matches in the man-machine cognitive system increases the mental workload because the demands placed on the user's processing systems are increased and additional, irrelevant mental tasks are imposed on the user. Low visual momentum degrades the user's ability to extract information from a display system [58].

Designing for high visual momentum may be particularly important for rehabilitation robotic systems which require the use of a computer screen. Spatial representations and spatial access provide structural information which reflect meaningful relationships between the computer screen, the input device, and the action taken by the robot. In addition, the layout of a spatial representation can be used to indicate semantic relationships, and the spatial representation can provide physical or functional relationships between successive views [58]. If a user's path through a display is consistent with the path necessary to execute an activity or if the interface provides the user with a perceptual or internal map, then the mental load on the user is minimized and the user can concentrate on the activity instead of the interface.

Sound provides an additional avenue for interface design because the human brain can integrate many different sounds simultaneously and auditory information can be perceived simultaneously with other perceptual signals [1, 4]. In the field of telerobotics, auditory feedback has been used to improve performance in a simulation of a robotic teleoperator task [29]. As with visual information available to the user, auditory information can reflect the state of the device in order to allow the user's cognitive process to map to auditory signals with task execution. For instance, the auditory volume and tone used to denote a state of emergency should be different form one used to denote an error condition, and different yet from an auditory tone used to denote a particular system state. A rehabilitation robotics system which provides auditory feedback could facilitate interaction which enhances the cognitive process of executing a task. For instance, properly designed auditory feedback may be incorporated into the interface in a way which is similar to the auditory cues from an automobile's manual transmission which inform the driver that is time to shift gears.

Cognitive Mapping: The physical, visual, and auditory aspects of the interface provide a conceptual model of how the interface can be used to execute a task. The layout of the interaction scheme also impacts the conceptual model of the interface. According to cognitive psychologist Donald Norman, "A good conceptual model allows us to predict the effects of our actions" [41, pp. 52]. Norman defines, a "good conceptual model" for a human interface design as one which has good *visibility*, *conceptual mapping*, and *feedback*. By *visibility* he means that the controls are visible to the user and are not hidden, *mapping* means that there is a relationship between a control and its effect, and *feedback* means that the result of a function is obvious to the user [41, 27]. In addition to *feedback*, the field of human computer interaction specifies a need for *modeless interaction,* which means that a user should be

that information based on the process of *movement control*. An optimally designed interface integrates sensory feedback from the device in such a way that compliments a human's ability to cognitively process that information. As a consequence, interacting with the interface seems effortless and the user can concentrate on the task instead of the interface. According to Ben Shneiderman, one of the world's leading authorities on user interface design, "Creating an environment in which the tasks are carried out almost effortlessly and the users are 'in the flow' requires a great deal of hard work from the designer." [51, pp. 9]. To design an interface for a rehabilitation robot which allows the user to be 'in the flow' as an integrated part of the interaction process, the designer must consider: 1. The physical characteristics of the input device including its size, range of motion and strength required for activation, and whether the device is a joystick, single switch, or other mode of input; 2. The sensory information provided by the input device including tactile feedback, visual feedback, and auditory feedback; 3. The layout or mapping of the interaction scheme which allows the user to associate or 'cognitively map' his or her interaction with the interface to the intended and appropriate action of the rehabilitation robot.

Physical Characteristics: There are two aspects to consider with respect to the physical characteristics of the input device. The first is how the user physically interacts with the device and the second is how the device fits into the users' environment. Individuals with severe physical disabilities are limited in the movements that they are able to perform. Consequently, the first step in determining the physical characteristics of the input device is to determine the body site which will be used to access the device. This may be limited hand movement, movement with a toe, elbow, knee, chin, or other limited movement. The next step is to design the device so that it can be positioned for optimal access to that body site and be activated by the movement which that body site performs well [9]. These requirements, when coupled with the need to mount the input device on an electric wheelchair, indicate that the device's physical characteristics are required to be small, light weight, and require little power.

Sensory Characteristics: Sensory information from the interface back to the user is predominately touch, visual and auditory. As of yet, smell and taste have not been incorporated into a sensory feedback system in rehabilitation robotics. The sense of touch incorporates what the 'feel' of the input device is, including the amount of pressure required to push a joystick or activate a single switch, whether or not the top of the switch is concave to hold a finger tip in place, and a wide range of similar physical attributes. As mentioned in the review of rehabilitation robotic devices, a proprioceptive feedback system is under research but is not yet close to production. Consequently, for rehabilitation robotic systems available, the sense of touch provides the user with information about how he or she has interacted with the input device, and not about the state of the robot or manipulator. It is important to note that some disabilities will cause an impaired sense of touch, even with the optimum body site.

As noted earlier, visual observation is the primary method for knowing what action is being carried out by the robot. Consequently, the user is required to employ vision to both determine the robot's activity, and to observe the interface. Visual cues on the interface device can serve to define the state of the device and can be particularly useful when the device is not operating as expected. Under these circumstances, visual cues should follow standard guidelines. For instance, the color of an LED on an interface should consistent with the accepted norms which correlate color with machine status: green should be associated with active, red with stop or alarm, and yellow with standby [4]. This is an example of how

arm or device.

A second requirement for designing interfaces is understanding the users [4, 51]. This, too, is a broad and poorly defined area for rehabilitation robotic devices. The potential users of a rehabilitation robotic system vary tremendously in their cognitive and physical abilities. In addition, individuals will experience a change in their physical abilities over time. For example, children grow and learn, progressive diseases become increasingly debilitating, and the process of aging changes functionality over time, especially with the geriatric population. Users will also vary with respect to background, education, culture, and physical characteristics. Disability is non-discriminatory. The needs and abilities of a child with arthrogryposis will be very different from a teenager who has muscular dystrophy, a six foot, 200 pound man who has had a high level spinal cord injury or an elderly woman who has had a stroke, yet each of these individuals may benefit from using a device which assists with manipulation of the physical environment.

The next consideration is the individual and his or her environment [4]. This includes both the social environment and the physical environment. The rehabilitation field is different from telerobotics or human-computer interaction in that the "user" is not the only person who is influenced by the system. Individuals with severely disabling conditions require the assistance of others for activities of daily living. This care is typically provided either by family members or by employing assistants and medical professionals. A rehabilitation robotic device will have a significant impact on all of the individuals who are a part of the end-user's daily routine. In some cases, this will be predominately one family member, but is frequently a team of individuals many of whom will also take part in the care and maintenance of the robotic device.

There are already a number of "devices" in the environment which must also be attended to by the user and his or her assistants. Many potential users of a rehabilitation robotic system also use an electric wheelchair. The location of an input device must be integrated with the joystick or system used to operate the wheelchair. In addition, the user may also operate an environmental control unit (ECU), computer, telephone, and other devices. For severely physically involved individuals, there is typically one body site which is optimum for interacting with a device, complicating the process of designing a specialized input mechanism for a rehabilitation robot. To address this issue, a research group is investigating a single, integrated input device which operates many different outputs including the wheelchair, an environmental control unit, and the Manus wheelchair mounted manipulator [44]. Several companies who sell assistive devices are also producing integrated input devices which operate a variety of outputs [15, 39, 12]. However, a robotic interface has not yet been successfully integrated into one of these commercially available interfaces. The command structure and interaction strategies of an interface device for operating a rehabilitation robot is sufficiently different from other devices, like a wheelchair or ECU, that designing an integrated input device is a considerable challenge.

Device Characteristics: With consideration for other devices in the environment aside, there are design recommendations for an interface device based on the way in which people perceive information made available to them and the cognitive process which people use to act on that information. People interact with the their environment as a result of the information they take in from the five senses: touch, vision, hearing, taste, and smell [1]. They then act on that information through the cognitive process of *perception*, *intellection* and *movement control* [4]. A person *perceives* the information from the outside, uses *intellection* to know what the information means, and cognitively decides what response to make to

system with a force reflecting input device. Although all of these issues would have to be researched with a disabled population, able-bodied data serve as a model and a baseline.

Jacobus et al. [29] recommend that a force reflecting handcontroller have operator selectable control modes for task dependent operation. They recommend a combination of force reflection techniques be available to the operator and that operators have the flexibility to control the damping, velocity, and force or position envelope. These "user-adapted" aspects of a controller interface for applications of telerobotics in space are appropriate for the disabled population for at least two reasons. First, the applications that a disabled user may encounter are likely to require a variety of manipulation tasks. For instance, if a manipulator were used to assist in preparing an egg for breakfast, it would have to be gentle enough to retrieve the egg without breaking it, but strong enough to lift a pan or a microwave dish for cooking the egg. Second, different disabling conditions result in widely varying abilities and different needs for an interface. For instance, a person with a high spinal cord injury has very different abilities than someone who has muscular dystrophy. In addition, progressive diseases change over the course of time and the interface devices will need to change as the user's abilities change. Building in flexibility, however, can potentially increase the cost of the device and the complexity of the interface.

The design of an interface for a rehabilitation robotic device addresses several mutually exclusive design trade-offs and complications. Users, by the nature of their potential benefit from a rehabilitation robotic device, are also very limited in the ways in which they can interact with the device. Simultaneously, device specification is variable. Some of the desired tasks require that the manipulator be mobile and have an ability to interact with an unstructured environment. However, interactive task execution is tedious. Executing a preprogrammed task is much faster, yet such systems cannot meet some of the user's requirements and the effort required to program a task has been criticized [47]. A need has been voiced for a non-technically oriented person to be provided with the tools for programming tasks [47]. The conflicting constraints are to maximize flexibility while minimizing the length of time it takes to perform a task and minimizing the cognitive load placed on the user [16]. While these difficulties pose many challenges, the fields of cognitive science, human computer interaction, and human factors engineering provide direction for solutions to an interface design.

Designing the Interface

User Requirements: The first step in designing a user interface is understanding the functionality required [51] or understanding how the application will be used [5]. When designing a rehabilitation robotic system, determining required functionality is a non-trivial task. A summary of user surveys has been researched [54]. This summary identified seven rehabilitation research groups who conducted pre-development surveys with potential rehabilitation robotics users and post-development surveys with those who had some experience with a particular rehabilitation robot or device for assisted manipulation. A total of 139 individuals took part in four separate pre-development surveys while a total of 65 individuals took part in five different post-development surveys. All surveys identified reaching and picking up objects, especially from the floor or off a shelf, as an important priority. Other task priorities identified were eating or drinking, preparing food, conducting personal hygiene and taking part in recreation or leisure activities. This task list of functionality suggests that users require the flexibility to manipulate objects in an unstructured environment. Many of these tasks suggest the need for a mobile or wheelchair mounted robotic

with adding a vision system to a workstation robot are beyond the scope of this article. An alternative to the joint controlled verses pre-programmed system is a hybrid system which offers both joint control and pre-stored commands, as seen with CURL.

All of the systems described above rely entirely on the operator using visual feedback to know where the arm is and what activity the robot or manipulator is executing. Research in the field of prosthetics has demonstrated that prostheses which provide the user with proprioceptive or sensory feedback improve the users' acceptance of the device because the user does not have to rely entirely on visual feedback for control of the prosthesis. A teleoperator or telemanipulator is a machine which extends a person's sensing and/or manipulating capability to a location remote from that person. A telerobot is an advanced form of a teleoperator with which a human operator supervises through a computer intermediary [50]. Telerobotics are used in hazardous or remote environments by able-bodied individuals who conduct manipulation tasks remotely with the benefit of sensory feedback from the robot interacting with the environment. Research endeavors are in the process of investigating sensory feedback mechanisms for rehabilitation robotic systems [23]. Although product development is still many years away for the rehabilitation field, it is valuable to take advantage of the expertise in telemanipulation research conducted by those in other fields.

Telerobotic applications are comparable to rehabilitation robotics because tasks executed with a teleoperator are varied and take place in an unstructured environment. Consumer questionnaires indicate that many of the desired tasks to be conducted by a rehabilitation robot take place in unstructured environments [54]. Most industrial robotic applications, on the other hand, take place in extremely structured environments and the executed tasks are repeated continuously at a very fast speed where people remain outside of the robot's working envelope. After the robot has been set up, there is little or no human interaction. This is quite different from the telerobotic system, where there is a continual interaction between the user and the robot to accomplish a task. Consequently, research in the field of telemanipulation serves as a resource for investigating potential interface criteria for devices used by physically disabled individuals which assist in manipulating the physical environment.

Force reflecting hand controllers have been investigated for space station telerobotic applications [29]. Force reflection techniques are incorporated to provide the user with an enhanced ability to successfully execute tasks with the robot. Very few studies have been done which directly assess teleoperation with force reflection. Of those performed, the systems used to conduct the experiment have inevitably biased the results by virtue of the task or machines involved. However, literature indicates that a force reflection of about 20-40 pounds should be applied from the force reflecting hand controllers back to the user. While it is true that a person who could benefit from using an assistive manipulator probably has severely impaired hand function, many of these individuals are competent electric wheelchair users, and frequently operate the wheelchair with a joystick. A number of the force-reflecting handcontrollers are joystick type devices. Consequently, an appropriately adapted force-reflecting handcontroller may provide an enhanced method of interaction for assistive manipulators. Other parameters regarding force-reflection handcontrollers also potentially contribute to the design of interfaces for assistive manipulators. For instance, a time delay influences force reflection. Some studies indicate that as little as a 30 ms time delay can negatively impact the human operator, although this data may be task specific [29]. Scaling, position error and a combined force and position error will also adversely affect a teleoperator's command of a robotic

University in collaboration with the Palo Alto VA Rehabilitation Research and Development Center, is a Unimation PUMA-260 industrial robotic arm with an Otto Bock Greifer prosthetic hand and is voice operated with the VOTAN VPC-2100 voice unit which recognizes voice commands and produces digitized voice messages to confirm the user's intentions [22]. The Robotic Assistive Appliance, developed by the Neil Squire Foundation, is a workstation based robot mounted on a lateral arm which travels over a worktable [8, 48]. The system is operated through an MS-DOS compatible computer by way of any interface which an individual uses to interact with the computer including morse code, direct keyboard, expanded keyboard, scanning, or voice recognition [48]. Voice recognition systems for robotic workstations typically require that the user "train" the computer system to recognize his or her voice with the list of command phrases or words that are associated with robot's task. After training the system to recognizes a particular person's voice, the user must recall the exact phrase or words associated with the desired task to be executed.

The CURL program provides for robot control in three different domains: pre-programmed procedures, command line instructions, or joint control. The control language is currently specified for the RTX robot, but should be available for a number of robotic systems in the future. With this language, the user can execute a pre-programmed function by calling a procedure, can perform a novel task with joint control, or has the ability to combine the different modes. The system operates from a Microsoft Windows environment, potentially facilitating access to other computer tasks like word processing [13]. As with the Robotic Assistive Appliance, any interface which is used to operate the computer should be available for operating within the CURL environment. When a modified keyboard, mouse, joystick, single switch, or similar device is employed for operating the robot, the user has three areas to attend to: 1) the computer display, 2) the input device, and 3) the robot. Attending to these three areas simultaneously may be particularly difficult for those with limited mobility who could benefit from using an assistive manipulator.

The five systems listed above represent a range of interaction strategies employed with currently available rehabilitation robotic or manipulation devices. On one end of the spectrum, the assistive manipulative device is electro-mechanically simple; the user is required to move each joint sequentially to achieve a task and there is no stored information to recall. The next stage is a device which still requires the user to carry out the activity by continually instructing the movements of the arm. However, the user is able to command direction, like forward and back, as opposed to commanding each joint. This allows the user to think of a movement in terms of the end-point goal, like "reach the floor", as opposed to having to think of the movement in discrete joint commands. On the other end of the spectrum, the user needs only to think of the action to be performed, and not about the robot's method of interaction at all. A DeVAR voice command of "get phone" requires only that the user remember the exact phrase which corresponds to the desired activity. In this circumstance, the user is not required to know anything about joint level control of the robotic device. Execution of pre-programmed movements are also the fastest way of having a task accomplished because all robots can execute a task faster than a human can instruct a robot to execute the task. However, to take advantage of such a system, the environment is required to be stationary and each task must be programmed in explicitly. If a coffee mug is set down on the table in a different place, the rehabilitation robotic device is unable to locate that mug, unless a vision system is also in operation. The costs, computational and otherwise, associated with adding vision to a workstation robotic system are significant. The issues involved

orientations resulted in a difference in the users perception of how to move the robot with the teach pendent or joystick provided to the subject. Subjects with a robot-centered reference system were less likely to make errors in movement commands. It was also observed that all subjects associated a “positive” label with movements described as right, forward, up, or clockwise [20]. This information is quite pertinent to the rehabilitation field as many of the manipulator systems are designed for operation in the cartesian coordinate or joint coordinate reference frame.

Most of the rehabilitation robots available today are either a wheelchair mounted manipulator or a desktop system which make use of a modified industrial robot. Rehabilitation robots are typically operated in unstructured environments which require that the user move the joints of the arm to achieve a task, or they operate in a highly structured environment where the user commands the execution of a pre-programmed task. Some systems allow both modes of operation. Wheelchair mounted manipulators facilitate interaction with the array of unstructured environments in which a wheelchair can travel. However, they do not currently allow a user to execute a pre-programmed task like “pick up the telephone”. Two examples of wheelchair mounted devices are the Inventaid Arm and the Manus manipulator.

The Inventaid Arm, available from Papworth of England, is a wheelchair mounted, joint controlled manipulator made with Flexator air muscles. It is powered by a tank of compressed air, also located on the wheelchair. The interface for the arm is a keypad. Separate keys on the keypad operate the two directions of each joint plus the gripper [34]. A palatal controller is being developed, but is not yet available [25]. The Inventaid Arm has no computing power associated with the manipulator. While this reduces the cost of the system, it also prevents an ability to recall previously executed movements and requires that the user move each joint, one at a time, to execute a task.

The Manus, marketed by Exact Dynamics of The Netherlands, is a wheelchair mounted manipulator which is powered by the wheelchair battery and operates from an on-board controller also mounted on the wheelchair [2, 31]. The input device which comes with the Manus is a 16 key keypad, which commands the arm to move: up/down, forward/back, left/right; the wrist to move: pitch, yaw, and roll, and the gripper to open or close. Joystick interfaces have also been developed for the Manus, however, some method of switching between modes is also necessary [43, 55]. The controller of the Manus manipulator permits the arm to operate in a cartesian coordinate mode. The controller calculates and coordinates individual joint movements so that the entire arm will move forward, back, right or left when told to move in those directions by the user. The computerized link between the interface and the manipulator allows the user to associate arm movement with the direction that the arm should go instead of requiring the user to understand which joint should be moved to get to a specific location.

Desktop systems are typically designed to operate in a structured environment performing pre-programmed tasks like “answer the telephone” or “get paper”. Examples of desktop systems are DeVAR, the Robotic Assistive Appliance, and the RTX robot using the Cambridge University Robot Language (CURL) [8, 13, 22]. All of these systems operate in conjunction with computer control. The computer controller facilitates programming specific tasks and allows the task to be associated with a command which the user can execute to recall the pre-programmed movement. The systems available are either operated by voice commands or by way of another interface to the computer like a mouse, joystick, modified keyboard or switch.

DeVAR, the DEsktop Vocational Assistant Robotic workstation, developed by Stanford

human operator’s physical environment [50]. All of these fields offer a perspective on the design of an interface for a rehabilitation robotic device.

Previous work has compared a robot user interface to a graphic user interface [33] as a method of developing the criteria for the human interface design of a rehabilitation robot. Other work has focused on the interface for a particular rehabilitation robotic environment [47] or has focused on human factors issues for the interface device of an augmentative and alternative communication (AAC) system [14]. While all of these perspectives contribute to the interface design for assistive manipulators, this article addresses general considerations for a generic assistive manipulator interface design by reviewing contributions from man-machine telerobotic systems, rehabilitation robotics systems, and human-computer interaction.

Rehabilitation Robotics as a Man-Machine System

The concept of the “man-machine system” came about with the advent of World War II. The highly technical war time systems developed at that time put exceedingly heavy demands on the human operator and failure to meet these demands had drastic consequences. The operators were highly trained and most problems arose after skillful performance broke down. For instance, it was determined that an airplane that was prone to crash during landing had a lever which retracted the landing gear very close to the one used for breaking. By re-designing the levers, pilots were able to select the correct one while paying close attention to the rapidly approaching landing strip which reduced the likelihood of crash during landing. This is an example of the way in which psychologists of the time studied the human being and the machine as an operating unit and how they offered useful suggestions to improve system design [32]. With the explosion of advanced technology during the past fifty years, many disciplines have contributed to and benefited from the perspective of the man-machine system, including the field of robotics. The concept of the “human-robot system” is quite young and a great deal has yet to be understood about how an interface should be designed for industrial robots, teleoperated robots, and assistive manipulators developed for people with disabilities.

All robots, regardless of their functional use, operate on the world as a result of a person’s cognitive process of instructing the machine. In industry, this person is frequently a highly trained technician with a teach pendent. In rehabilitation, the person is someone with a severe physical disability. The design of a good interface for either population benefits from understanding how the operator perceives the machine. In the rehabilitation field, robotic systems which have been the focus of most studies are anthropomorphic in nature with approximately six degrees of freedom [17, 45, 57, 3]. Although there are robots in industry which have two or three degrees of freedom, they will not be included in the scope of this article. To determine people’s expectations and perceptions of an anthropomorphic robot, 96 undergraduate production engineering students took part in a three-stage experimental protocol with a Unimation PUMA 560 robot [20]. Experimental results indicated that there was agreement on describing the joints referred to as the “arm”, “elbow” and “wrist”, but there was difficulty in distinguishing the wrist joints. Joint movement was described either as clockwise/anti-clockwise, or as left/right and up/down. There were also two different perceptual orientations of how the robot moved: either the subjects used a robot centered reference point which “moves with” the robot when it’s configuration changes, or they used an observer-centered perceptual reference which remains consistent to themselves regardless of changes in the robot configuration or observer-robot orientation. These two

Designing the User Interface for an Electro-Mechanical Assistive Manipulator

by

Carol A. Stanger

Abstract

Rehabilitation robots or electro-mechanical assistive manipulators are designed to provide individuals who have severe physical disabilities with a means of interacting with their environment. The person-machine interface for assistive manipulators serves both as a method for commanding robot functionality and provides an additional avenue in which the safety of using the device can be assured. This paper will address the issue of designing an interface for an assistive manipulator from three perspectives. First, the robotics field will be addressed to outline interface designs of currently available rehabilitation robots and manipulators, and to consider how the rehabilitation field benefits from telerobotics and industrial robotics. Second, other fields of human-machine interface design will be addressed by looking at the contributions of cognitive science, human factors engineering and human computer interaction, and finally, this paper addresses the issues of evaluation and approaches taken towards determining the value of a specific interface design.

Introduction

The goal of rehabilitation robotics is to provide individuals who are not able to physically move the objects around them, a way to do so with the assistance of an electro-mechanical device. Not all electro-mechanical assistive manipulation devices are thought of as a "robot". Consequently, the term "assistive manipulator" is used in this paper along with "rehabilitation robot". With terminology aside, these devices are only useful if the severely physically disabled person is able to independently operate the robot or manipulator. With an optimal design, the interface can assist in minimizing the complexity of the manipulator for the user and maximize consistency of how the manipulator operates. The interface can also provide appropriate feedback to facilitate the user's knowledge about the state of the device or the task that the manipulator is taking part in.

In the 1980's the field rehabilitation robotics was regarded as showing great promise for serving the needs of people who are unable to motorically operate on their environments [28]. A large number of factors have prevented this promise from reaching fruition. At present, of the rehabilitation robots and similar devices available for assisting in manipulation tasks, very few are doing the manipulating for those who need them. One of the deterrents to widespread use of rehabilitation robotic systems is the shortcoming of the man-machine interface [33].

Designing the user interface for an electro-mechanical assistive manipulator benefits from a multi-disciplinary approach. There are many fields of expertise which contribute to interface design including psychology, computer science, ergonomics, and robotics. In particular, the fields of cognitive science and human-computer interaction have a history of expertise with understanding what a user "thinks" when interacting with a device and what the interface should look like for an optimal execution of an activity. Ergonomics considers individuals' physical and cognitive interaction scheme. With telerobotics, the user is viewed as a part of the causal loop of decision, communication, control and feedback through the

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ciated with clinical evaluation to determine an individual's potential benefit from a robotic device, training, service delivery, and up keep or repair of the robot which are beyond the scope of this article, but have been addressed elsewhere [53].

Despite decision criteria regarding device functionality, there are design recommendations from many fields which contribute to developing interface criteria. From the field of industrial robotics and telerobotics, we learn that

- a "+" sign should be associated with right, forward, up and clockwise
- for a joint controlled robot, training should introduce the user to a robot-centered reference system where the reference frame moves with the robot [20]
- as little as a 30 msec time delay in a sensory feedback system may negatively influence performance [29].

Consequently, the field of rehabilitation robotics continues to benefit from research conducted in other fields.

Currently, the available assistive manipulation devices or rehabilitation robots are typically joint controlled, cartesian coordinate controlled or execute pre-programmed interactions [17, 45, 57, 3]. If designing an interface for one of these devices or for a different device, characteristics to be included in the design are:

- physical specifications (size, weight, etc.)
- tactile cues
- visual cues
- auditory cues.

These items influence the success with which a user executes tasks with the robot. Another criteria for successful interaction is the "conceptual model" or interaction scheme. Elements of a "good conceptual model" which result in the user being able to predict the outcome of an event are:

- visibility
- conceptual mapping
- feedback [41]
- modeless interaction
- error recovery or reversible actions [27].

These design elements should assist in minimizing complexity, maximizing consistency and providing appropriate feedback, the goals in improving an interface design [14]. In addition, the safety of the robotic device can be improved with a more "intuitive" interface design.

Evaluation of a device remains a challenge. The field of human computer interaction provides theoretical models used for evaluation, however, the application of these models to rehabilitation robotics are not straight forward. Previous attempts at incorporating a model in the rehabilitation field have demonstrated limitations [40]. Interface design, however, will very likely benefit by incorporating users into the design loop early in the interactive cycle of design implementation.

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adjustments are typically possible, they are non-trivial and can add significant time to an evaluation protocol. *Retention over time* may be compounded by understanding how the robotic device operates and understanding the requirements for task execution. This measure is also compounded by frequency of use, or infrequency of use, which is typically the case with rehabilitation robotic devices. *Subjective satisfaction* is quite obtainable, but difficult to quantify, especially with small subject numbers.

As an alternative to evaluating the robotic interface intact, researchers could run a simulation of a robotic interaction. Although a simulation could be constructed to eliminate *time to learn* how the robot operates, the *speed of performance* of the robot, and the *rate of error* associated with understanding how a robot operates, the simulation would also potentially eliminate all of the relevant factors associated with actual robot operation, thus negating the relevance of the study. This criticism is also found in human computer interaction as observed in a quotation about using scenarios to evaluate interface design, "The danger in using design scenarios to drive evaluation of a fully instantiated design is that the design may have been tuned to the scenario execution." [56, pp. 294].

The argument against using simulations or scenarios leads to the current debate within human computer interaction regarding the methodology employed in evaluating an interaction scheme [37]. The debate is between ethnographers and experimentalists. Ethnographers argue that:

- the laboratory is not real world,
- one cannot control all variables that affect a behavior,
- an effort is made to eliminate context rather than understand it,
- subjects are given highly constrained, artificial tasks with a very short time frame,
- the subject's observations are not incorporated.

Alternatively, the experimental method provides measurable differences between opposing perspectives [37]. In human computer interaction, the solution is likely to be a well designed hybrid of ethnography and experimental method. In evaluation of a rehabilitation robotic interface, application of the experimental method remains a challenge.

Single Subject Analysis: Single subject analysis has been most frequently applied to experimental psychology and AAC [6, 35]. The basis of single subject analysis is to collect a baseline, typically over several days, introduce a single condition and record the parameter of interest over an equal length of time to see if there is change, then remove the condition to see if there is a return to baseline, then re-introduce the condition and record the pertinent data. This protocol is an A-B-A-B design. Other variations of introducing a condition are also possible. The underlying assumption in single subject analysis, however, is the presence of a baseline. An individual who may benefit from using a rehabilitation robot does so precisely because he or she is unable to perform the activity otherwise, making a fundamental "baseline" comparison impossible. A variation of a single subject design, comparing one interface against another for instance, confronts all of the difficulties enumerated under the five measurable criteria for evaluating an interface.

Conclusion

In the development of the Star system, Smith et al. [52, pp. 246] "learned from the Star the importance of formulating the fundamental concepts before software is written rather than tacking on an interface afterward." As outlined in this article, "formulating the fundamental concepts" is a considerable challenge for rehabilitation robotics. The users and their social and physical environment, task needs, physical and cognitive abilities, age, background, culture, and education vary tremendously. There are many other issues asso-

fied so far in our experience." [30, pp. 283]. Another criticism of modeling is the limited capability for modeling a person's capacity for making an error, or the cognitive process used to recover from that error [11]. Finally, theoretical models are criticized for their restricted scope, failure to deal with the real context of the work, and failure to accommodate fine details [7].

User Participation in Design: As a supplement or alternative to modeling, the human computer interaction field is advocating the need to bring the user into the designing loop in the early stages of product development. This approach views design as an iterative process where users are brought in on many occasions during implementation of the design [24]. The approach of incorporating users into the interface design is being conducted with rehabilitation robotic interfaces, but on a small scale [38]. A highly effective method of evaluating a human computer interface is to monitor user action while collecting concurrent verbal protocols to help understand what is actually going on [7, pp 114]. Techniques for conducting user observation have been outlined in detail both in The Macintosh Interface Guidelines [27, pp. 43-46], and in The Art of Human Computer Interface Design [18, pp. 85-90]. The labor intensive nature of observation, however, generally require the studies to be confined to a very small number of subjects and tasks [7].

Evaluation Techniques: For the evaluation of a human computer interface design, Shneiderman [51] outlines five measurable criteria for evaluating an interface:

- •Time to learn
- •Speed of Performance
- •Rate of errors by users
- •Retention over time
- •Subjective satisfaction.

Applying these criteria to a rehabilitation robotics interface is plagued with complications stemming from task execution and the subject's disabling condition. It is difficult to separate an evaluation of an interface from an evaluation of the robot, the later of which is extraordinarily time consuming and complicated [21, 22, 34, 36]. In addition, large, statistically significant studies with severely physically disabled individuals are nearly impossible because of the huge variation between individuals, the small sample size, difficulty in transportation to a research laboratory, fragile health conditions of the subject, and many other complicating issues.

When considering each element of the evaluation criteria in particular, the *time to learn* is compounded by learning about the robot. *Speed of performance* is frequently compounded by a user's disability which, in many cases, intrinsically prevents performing speedily. In addition, interaction strategies used by people with disabilities often complicate recording the speed of performance. For instance, if someone is using a mouthstick and drops the mouthstick or, more likely, spends time adjusting the mouthstick, this is a compounding factor in calculating the *speed of performance*. The *rate of error* is generally difficult to calculate with most robotic tasks, especially in unstructured environments, which is largely the kind of interaction that users request. In addition, these three factors are only relevant when a comparison is made between two alternatives. Potential rehabilitation robotics users typically have only one optimal body site, and potentially one method of interaction, which can complicate a comparison between two interface techniques. In addition, set-up is complicated by issues which are not addressed when evaluations are conducted with able-bodied individuals. For instance, an able-bodied person can position themselves to see a computer screen or use an input device. For someone who is disabled, the computer screen may have to be adjusted to accommodate a lack of mobility or the bulk of an electric wheelchair, and the input device will have to be mounted so that the user can access the device optimally. While such

The National Advanced Robotics Research Centre, Safety and Standards for Advanced Robots, "Predictability (is) a key attribute for safety. The design must emphasize transparency for the operator" [49, pp. 26]. Finally, a deliberate disruption in the flow of an activity serves the purpose of alerting the user to a potentially dangerous situation [42]. For example when the DeVAR system is operating in close proximity to the user's face, the system is designed to interrupt the flow of activity. After receiving the initial command, the system asks the user "Are you sure?" and waits for a confirmation before proceeding.

Evaluation of Interfaces for Assistive Manipulators

Any interface design must be evaluated as a means of measuring its effectiveness. Theoretical models are available to describe desirable interaction characteristics and are sometimes used as a means of evaluation. The following section will review some of the pertinent models and their application to rehabilitation. This section then discusses the advantages of incorporating users into the design process, then concludes with a discussion of evaluation techniques and how they might be applied to evaluating an interface device for a rehabilitation robot.

Theories, Models, and Evaluation: Theories and models are used to describe the multiple aspects of interactive systems. High level theories or models offer a framework in which to discuss issues that are application independent. Some theories are explanatory while others are predictive. Explanatory theories are helpful in observing behavior, describing activity, conceiving of designs, and comparing high-level concepts of two designs. Predictive theories enable designers to compare proposed designs for execution time or error rates, focusing on perceptual tasks, and motor-task performance [51]. The goals, operators, methods, and selection rules, (GOMS) model is an example of a perceptual task predictive theory. It is based on the postulation that users formulate *goals*, use an *operator* to achieve that goal though a *method* chosen from the *selection rules* [10, 51].

The application of other theories or models as a method of assessing the use of a particular device for an individual or as a method of evaluation are currently under lively debate in both with clinical rehabilitation and human computer interaction. Within the rehabilitation field of Augmentative and Alternative Communication (AAC), there have been attempts to generate models of device use which predict performance of the operators using particular systems [19, 26]. One model has yet to be applied beyond the research lab in which it was developed and a second has sparked controversy regarding the limitations of the model [40]. The second model for AAC prediction is based on the GOMS technique [10, 26]. The model is criticized because the GOMS technique, "fails to capture the user's fatigue, individual differences or mental work load" [46, pp. 223]. The model is further criticized because of the wide range of individual differences in physical and/or mental abilities which the model is applied to. Opponents of the model claim that it is "unlikely that a single model can be used to characterize any non-trivial task" [40 pp. 89].

In the field of human computer interaction, the limitations of modeling are prevalent on many fronts. Karat and Bennett [30] describe the process in which a user-centered design framework supports the design of a system to meet user requirements. They found that, "quantitative estimates available from our modeling based on cognitive science theory did not address the range of design issues we see as essential", and that they "found it more beneficial to represent human-computer interaction scenarios in natural language than in formal notations." They conclude, "The costs in terms of time required to learn and use various formal techniques have not seemed justi-

able to accomplish any task from any point within the system [27, 52]. This idea is consistent with Norman's concept of *visibility*, arguing that the control mechanism should not be hidden. Other human computer interaction guidelines also list *forgiveness*, meaning that in an error condition, the actions are reversible [27].

The concepts of visibility, modeless interaction, feedback, and forgiveness can be applied to an interface design for either a wheelchair mounted manipulator or a desktop system using a computer interface. Visibility of the system indicates that the function of any button or selection is clearly defined for the user. This, in coordination with "modeless interaction" would mean that there are no hidden levels which the user must jump to in order to reach a function or command for moving the manipulator. Mapping, which indicates a relationship between a control and its effect, can assist in determining how the operation of the input device is associated with control of the manipulator. For instance, if using a joystick to control a robot in the X-Y plane, pushing the joystick away from you should "map to" having the robot arm move away in the same direction. Feedback allows the user to know that a command has been successfully selected. Finally, forgiveness, or a reversible action is essential for all manipulators, especially from the perspective of safety. When a user makes a selection in error, the system must "forgive" and allow the user to retract the selected command with minimal penalty in time loss and interaction with the system.

When designing an interface, the designer must consider physical characteristics of the user, the user's social context and user's physical environment. The device must fit into the space and input strategy which works for the user. The tactile, visual, and auditory cues from the interface must be considered for optimal interaction, and the layout needs to cognitively map to the users expectations. With all this in mind, the interface inherently provides an additional means of safety for the user when operating an rehabilitation robot.

Designing the Interface for Additional Safety: The safety of the user can be improved by many aspects of the interface device including: 1. Providing redundancy in the interface feedback; 2. Decreasing the cognitive load on the users; and 3. Designing for an interruption in the flow of activity when operating in a potentially dangerous mode. Redundancy is achieved by providing multiple methods of feedback such as using both auditory and visual feedback. Redundancy can also facilitate safety by designing the device to accept multiple input signals. This is especially useful in an error condition or when a malfunction has occurred. For instance, a voice operated robot could be programmed to stop activity for a variety of commands including saying "stop" in a calm voice, shouting "STOP", or saying "wait", "halt" or "oh *!@#". A device is safer when the cognitive load required for operating the device has been minimized. This is achieved with good conceptual mapping and using standard cues like a red LED to indicate an "alarm" situation. The safety aspects of good cognitive mapping are exemplified in an unexpected condition because the more a user is required to "remember" to execute an activity, the more likely he or she will be to forget the required steps to achieve a result under duress. In human computer interaction, a "see and point" interface requires less cognitive processing than a "remember and type" kind of interface [42, 52]. The equivalent of a "see and point" kind of interface for a rehabilitation robotic device is potentially much safer than one which requires significant memorization. Again, in the field of human computer interaction, low visual momentum decreases problem solving performance [58]. In contrast, one can imagine that high visual momentum would result in facilitating problem solving performance with a rehabilitation robotic interface and potentially prevent an unexpected situation from becoming dangerous. In the words of

output of the interface can conceptually correlate or "cognitively couples" the device state to the user's expectations. Although "cognitive coupling" is highly dependent on the user's cultural and historical background, this issue is beyond the scope of this article.

Another aspect of integrating the user's vision to improve the cognitive coupling between the user and the interface is visual momentum. Visual momentum is how a user interprets data from successive glances at a specific location. In the field of human computer interaction, designing for high visual momentum facilitates the user's interpretation of the information on a computer screen. A display system structure which provides a visual frame of reference that describes the relationship between the interface and the task to be executed decreases the user's mental workload. Mis-matches in the man-machine cognitive system increases the mental workload because the demands placed on the user's processing systems are increased and additional, irrelevant mental tasks are imposed on the user. Low visual momentum degrades the user's ability to extract information from a display system [58].

Designing for high visual momentum may be particularly important for rehabilitation robotic systems which require the use of a computer screen. Spatial representations and spatial access provide structural information which reflect meaningful relationships between the computer screen, the input device, and the action taken by the robot. In addition, the layout of a spatial representation can be used to indicate semantic relationships, and the spatial representation can provide physical or functional relationships between successive views [58]. If a user's path through a display is consistent with the path necessary to execute an activity or if the interface provides the user with a perceptual or internal map, then the mental load on the user is minimized and the user can concentrate on the activity instead of the interface.

Sound provides an additional avenue for interface design because the human brain can integrate many different sounds simultaneously and auditory information can be perceived simultaneously with other perceptual signals [1, 4]. In the field of telerobotics, auditory feedback has been used to improve performance in a simulation of a robotic teleoperator task [29]. As with visual information available to the user, auditory information can reflect the state of the device in order to allow the user's cognitive process to map to auditory signals with task execution. For instance, the auditory volume and tone used to denote a state of emergency should be different form one used to denote an error condition, and different yet from an auditory tone used to denote a particular system state. A rehabilitation robotics system which provides auditory feedback could facilitate interaction which enhances the cognitive process of executing a task. For instance, properly designed auditory feedback may be incorporated into the interface in a way which is similar to the auditory cues from an automobile's manual transmission which inform the driver that is time to shift gears.

Cognitive Mapping: The physical, visual, and auditory aspects of the interface provide a conceptual model of how the interface can be used to execute a task. The layout of the interaction scheme also impacts the conceptual model of the interface. According to cognitive psychologist Donald Norman, "A good conceptual model allows us to predict the effects of our actions" [41, pp. 52]. Norman defines, a "good conceptual model" for a human interface design as one which has good *visibility*, *conceptual mapping*, and *feedback*. By *visibility* he means that the controls are visible to the user and are not hidden, *mapping* means that there is a relationship between a control and its effect, and *feedback* means that the result of a function is obvious to the user [41, 27]. In addition to *feedback*, the field of human computer interaction specifies a need for *modeless interaction,* which means that a user should be

that information based on the process of *movement control*. An optimally designed interface integrates sensory feedback from the device in such a way that compliments a human's ability to cognitively process that information. As a consequence, interacting with the interface seems effortless and the user can concentrate on the task instead of the interface. According to Ben Shneiderman, one of the world's leading authorities on user interface design, "Creating an environment in which the tasks are carried out almost effortlessly and the users are 'in the flow' requires a great deal of hard work from the designer." [51, pp. 9]. To design an interface for a rehabilitation robot which allows the user to be 'in the flow' as an integrated part of the interaction process, the designer must consider: 1. The physical characteristics of the input device including its size, range of motion and strength required for activation, and whether the device is a joystick, single switch, or other mode of input; 2. The sensory information provided by the input device including tactile feedback, visual feedback, and auditory feedback; 3. The layout or mapping of the interaction scheme which allows the user to associate or 'cognitively map' his or her interaction with the interface to the intended and appropriate action of the rehabilitation robot.

Physical Characteristics: There are two aspects to consider with respect to the physical characteristics of the input device. The first is how the user physically interacts with the device and the second is how the device fits into the users' environment. Individuals with severe physical disabilities are limited in the movements that they are able to perform. Consequently, the first step in determining the physical characteristics of the input device is to determine the body site which will be used to access the device. This may be limited hand movement, movement with a toe, elbow, knee, chin, or other limited movement. The next step is to design the device so that it can be positioned for optimal access to that body site and be activated by the movement which that body site performs well [9]. These requirements, when coupled with the need to mount the input device on an electric wheelchair, indicate that the device's physical characteristics are required to be small, light weight, and require little power.

Sensory Characteristics: Sensory information from the interface back to the user is predominately touch, visual and auditory. As of yet, smell and taste have not been incorporated into a sensory feedback system in rehabilitation robotics. The sense of touch incorporates what the 'feel' of the input device is, including the amount of pressure required to push a joystick or activate a single switch, whether or not the top of the switch is concave to hold a finger tip in place, and a wide range of similar physical attributes. As mentioned in the review of rehabilitation robotic devices, a proprioceptive feedback system is under research but is not yet close to production. Consequently, for rehabilitation robotic systems available, the sense of touch provides the user with information about how he or she has interacted with the input device, and not about the state of the robot or manipulator. It is important to note that some disabilities will cause an impaired sense of touch, even with the optimum body site.

As noted earlier, visual observation is the primary method for knowing what action is being carried out by the robot. Consequently, the user is required to employ vision to both determine the robot's activity, and to observe the interface. Visual cues on the interface device can serve to define the state of the device and can be particularly useful when the device is not operating as expected. Under these circumstances, visual cues should follow standard guidelines. For instance, the color of an LED on an interface should consistent with the accepted norms which correlate color with machine status: green should be associated with active, red with stop or alarm, and yellow with standby [4]. This is an example of how

arm or device.

A second requirement for designing interfaces is understanding the users [4, 51]. This, too, is a broad and poorly defined area for rehabilitation robotic devices. The potential users of a rehabilitation robotic system vary tremendously in their cognitive and physical abilities. In addition, individuals will experience a change in their physical abilities over time. For example, children grow and learn, progressive diseases become increasingly debilitating, and the process of aging changes functionality over time, especially with the geriatric population. Users will also vary with respect to background, education, culture, and physical characteristics. Disability is non-discriminatory. The needs and abilities of a child with arthrogryposis will be very different from a teenager who has muscular dystrophy, a six foot, 200 pound man who has had a high level spinal cord injury or an elderly woman who has had a stroke, yet each of these individuals may benefit from using a device which assists with manipulation of the physical environment.

The next consideration is the individual and his or her environment [4]. This includes both the social environment and the physical environment. The rehabilitation field is different from telerobotics or human-computer interaction in that the "user" is not the only person who is influenced by the system. Individuals with severely disabling conditions require the assistance of others for activities of daily living. This care is typically provided either by family members or by employing assistants and medical professionals. A rehabilitation robotic device will have a significant impact on all of the individuals who are a part of the end-user's daily routine. In some cases, this will be predominately one family member, but is frequently a team of individuals many of whom will also take part in the care and maintenance of the robotic device.

There are already a number of "devices" in the environment which must also be attended to by the user and his or her assistants. Many potential users of a rehabilitation robotic system also use an electric wheelchair. The location of an input device must be integrated with the joystick or system used to operate the wheelchair. In addition, the user may also operate an environmental control unit (ECU), computer, telephone, and other devices. For severely physically involved individuals, there is typically one body site which is optimum for interacting with a device, complicating the process of designing a specialized input mechanism for a rehabilitation robot. To address this issue, a research group is investigating a single, integrated input device which operates many different outputs including the wheelchair, an environmental control unit, and the Manus wheelchair mounted manipulator [44]. Several companies who sell assistive devices are also producing integrated input devices which operate a variety of outputs [15, 39, 12]. However, a robotic interface has not yet been successfully integrated into one of these commercially available interfaces. The command structure and interaction strategies of an interface device for operating a rehabilitation robot is sufficiently different from other devices, like a wheelchair or ECU, that designing an integrated input device is a considerable challenge.

Device Characteristics: With consideration for other devices in the environment aside, there are design recommendations for an interface device based on the way in which people perceive information made available to them and the cognitive process which people use to act on that information. People interact with the their environment as a result of the information they take in from the five senses: touch, vision, hearing, taste, and smell [1]. They then act on that information through the cognitive process of *perception*, *intellection* and *movement control* [4]. A person *perceives* the information from the outside, uses *intellection* to know what the information means, and cognitively decides what response to make to

system with a force reflecting input device. Although all of these issues would have to be researched with a disabled population, able-bodied data serve as a model and a baseline.

Jacobus et al. [29] recommend that a force reflecting handcontroller have operator selectable control modes for task dependent operation. They recommend a combination of force reflection techniques be available to the operator and that operators have the flexibility to control the damping, velocity, and force or position envelope. These "user-adapted" aspects of a controller interface for applications of telerobotics in space are appropriate for the disabled population for at least two reasons. First, the applications that a disabled user may encounter are likely to require a variety of manipulation tasks. For instance, if a manipulator were used to assist in preparing an egg for breakfast, it would have to be gentle enough to retrieve the egg without breaking it, but strong enough to lift a pan or a microwave dish for cooking the egg. Second, different disabling conditions result in widely varying abilities and different needs for an interface. For instance, a person with a high spinal cord injury has very different abilities than someone who has muscular dystrophy. In addition, progressive diseases change over the course of time and the interface devices will need to change as the user's abilities change. Building in flexibility, however, can potentially increase the cost of the device and the complexity of the interface.

The design of an interface for a rehabilitation robotic device addresses several mutually exclusive design trade-offs and complications. Users, by the nature of their potential benefit from a rehabilitation robotic device, are also very limited in the ways in which they can interact with the device. Simultaneously, device specification is variable. Some of the desired tasks require that the manipulator be mobile and have an ability to interact with an unstructured environment. However, interactive task execution is tedious. Executing a preprogrammed task is much faster, yet such systems cannot meet some of the user's requirements and the effort required to program a task has been criticized [47]. A need has been voiced for a non-technically oriented person to be provided with the tools for programming tasks [47]. The conflicting constraints are to maximize flexibility while minimizing the length of time it takes to perform a task and minimizing the cognitive load placed on the user [16]. While these difficulties pose many challenges, the fields of cognitive science, human computer interaction, and human factors engineering provide direction for solutions to an interface design.

Designing the Interface

User Requirements: The first step in designing a user interface is understanding the functionality required [51] or understanding how the application will be used [5]. When designing a rehabilitation robotic system, determining required functionality is a nontrivial task. A summary of user surveys has been researched [54]. This summary identified seven rehabilitation research groups who conducted pre-development surveys with potential rehabilitation robotics users and post-development surveys with those who had some experience with a particular rehabilitation robot or device for assisted manipulation. A total of 139 individuals took part in four separate pre-development surveys while a total of 65 individuals took part in five different post-development surveys. All surveys identified reaching and picking up objects, especially from the floor or off a shelf, as an important priority. Other task priorities identified were eating or drinking, preparing food, conducting personal hygiene and taking part in recreation or leisure activities. This task list of functionality suggests that users require the flexibility to manipulate objects in an unstructured environment. Many of these tasks suggest the need for a mobile or wheelchair mounted robotic

with adding a vision system to a workstation robot are beyond the scope of this article. An alternative to the joint controlled verses pre-programmed system is a hybrid system which offers both joint control and pre-stored commands, as seen with CURL.

All of the systems described above rely entirely on the operator using visual feedback to know where the arm is and what activity the robot or manipulator is executing. Research in the field of prosthetics has demonstrated that prostheses which provide the user with proprioceptive or sensory feedback improve the users' acceptance of the device because the user does not have to rely entirely on visual feedback for control of the prosthesis. A teleoperator or telemanipulator is a machine which extends a person's sensing and/or manipulating capability to a location remote from that person. A telerobot is an advanced form of a teleoperator with which a human operator supervises through a computer intermediary [50]. Telerobotics are used in hazardous or remote environments by able-bodied individuals who conduct manipulation tasks remotely with the benefit of sensory feedback from the robot interacting with the environment. Research endeavors are in the process of investigating sensory feedback mechanisms for rehabilitation robotic systems [23]. Although product development is still many years away for the rehabilitation field, it is valuable to take advantage of the expertise in telemanipulation research conducted by those in other fields.

Telerobotic applications are comparable to rehabilitation robotics because tasks executed with a teleoperator are varied and take place in an unstructured environment. Consumer questionnaires indicate that many of the desired tasks to be conducted by a rehabilitation robot take place in unstructured environments [54]. Most industrial robotic applications, on the other hand, take place in extremely structured environments and the executed tasks are repeated continuously at a very fast speed where people remain outside of the robot's working envelope. After the robot has been set up, there is little or no human interaction. This is quite different from the telerobotic system, where there is a continual interaction between the user and the robot to accomplish a task. Consequently, research in the field of telemanipulation serves as a resource for investigating potential interface criteria for devices used by physically disabled individuals which assist in manipulating the physical environment.

Force reflecting hand controllers have been investigated for space station telerobotic applications [29]. Force reflection techniques are incorporated to provide the user with an enhanced ability to successfully execute tasks with the robot. Very few studies have been done which directly assess teleoperation with force reflection. Of those performed, the systems used to conduct the experiment have inevitably biased the results by virtue of the task or machines involved. However, literature indicates that a force reflection of about 20-40 pounds should be applied from the force reflecting hand controllers back to the user. While it is true that a person who could benefit from using an assistive manipulator probably has severely impaired hand function, many of these individuals are competent electric wheelchair users, and frequently operate the wheelchair with a joystick. A number of the force-reflecting handcontrollers are joystick type devices. Consequently, an appropriately adapted force-reflecting handcontroller may provide an enhanced method of interaction for assistive manipulators. Other parameters regarding force-reflection handcontrollers also potentially contribute to the design of interfaces for assistive manipulators. For instance, a time delay influences force reflection. Some studies indicate that as little as a 30 ms time delay can negatively impact the human operator, although this data may be task specific [29]. Scaling, position error and a combined force and position error will also adversely affect a teleoperator's command of a robotic

University in collaboration with the Palo Alto VA Rehabilitation Research and Development Center, is a Unimation PUMA-260 industrial robotic arm with an Otto Bock Greifer prosthetic hand and is voice operated with the VOTAN VPC-2100 voice unit which recognizes voice commands and produces digitized voice messages to confirm the user's intentions [22]. The Robotic Assistive Appliance, developed by the Neil Squire Foundation, is a workstation based robot mounted on a lateral arm which travels over a worktable [8, 48]. The system is operated through an MS-DOS compatible computer by way of any interface which an individual uses to interact with the computer including morse code, direct keyboard, expanded keyboard, scanning, or voice recognition [48]. Voice recognition systems for robotic workstations typically require that the user "train" the computer system to recognize his or her voice with the list of command phrases or words that are associated with robot's task. After training the system to recognizes a particular person's voice, the user must recall the exact phrase or words associated with the desired task to be executed.

The CURL program provides for robot control in three different domains: pre-programmed procedures, command line instructions, or joint control. The control language is currently specified for the RTX robot, but should be available for a number of robotic systems in the future. With this language, the user can execute a pre-programmed function by calling a procedure, can perform a novel task with joint control, or has the ability to combine the different modes. The system operates from a Microsoft Windows environment, potentially facilitating access to other computer tasks like word processing [13]. As with the Robotic Assistive Appliance, any interface which is used to operate the computer should be available for operating within the CURL environment. When a modified keyboard, mouse, joystick, single switch, or similar device is employed for operating the robot, the user has three areas to attend to: 1) the computer display, 2) the input device, and 3) the robot. Attending to these three areas simultaneously may be particularly difficult for those with limited mobility who could benefit from using an assistive manipulator.

The five systems listed above represent a range of interaction strategies employed with currently available rehabilitation robotic or manipulation devices. On one end of the spectrum, the assistive manipulative device is electro-mechanically simple; the user is required to move each joint sequentially to achieve a task and there is no stored information to recall. The next stage is a device which still requires the user to carry out the activity by continually instructing the movements of the arm. However, the user is able to command direction, like forward and back, as opposed to commanding each joint. This allows the user to think of a movement in terms of the end-point goal, like "reach the floor", as opposed to having to think of the movement in discrete joint commands. On the other end of the spectrum, the user needs only to think of the action to be performed, and not about the robot's method of interaction at all. A DeVAR voice command of "get phone" requires only that the user remember the exact phrase which corresponds to the desired activity. In this circumstance, the user is not required to know anything about joint level control of the robotic device. Execution of pre-programmed movements are also the fastest way of having a task accomplished because all robots can execute a task faster than a human can instruct a robot to execute the task. However, to take advantage of such a system, the environment is required to be stationary and each task must be programmed in explicitly. If a coffee mug is set down on the table in a different place, the rehabilitation robotic device is unable to locate that mug, unless a vision system is also in operation. The costs, computational and otherwise, associated with adding vision to a workstation robotic system are significant. The issues involved

orientations resulted in a difference in the users perception of how to move the robot with the teach pendent or joystick provided to the subject. Subjects with a robot-centered reference system were less likely to make errors in movement commands. It was also observed that all subjects associated a "positive" label with movements described as right, forward, up, or clockwise [20]. This information is quite pertinent to the rehabilitation field as many of the manipulator systems are designed for operation in the cartesian coordinate or joint coordinate reference frame.

Most of the rehabilitation robots available today are either a wheelchair mounted manipulator or a desktop system which make use of a modified industrial robot. Rehabilitation robots are typically operated in unstructured environments which require that the user move the joints of the arm to achieve a task, or they operate in a highly structured environment where the user commands the execution of a pre-programmed task. Some systems allow both modes of operation. Wheelchair mounted manipulators facilitate interaction with the array of unstructured environments in which a wheelchair can travel. However, they do not currently allow a user to execute a pre-programmed task like "pick up the telephone". Two examples of wheelchair mounted devices are the Inventaid Arm and the Manus manipulator.

The Inventaid Arm, available from Papworth of England, is a wheelchair mounted, joint controlled manipulator made with Flexator air muscles. It is powered by a tank of compressed air, also located on the wheelchair. The interface for the arm is a keypad. Separate keys on the keypad operate the two directions of each joint plus the gripper [34]. A palatal controller is being developed, but is not yet available [25]. The Inventaid Arm has no computing power associated with the manipulator. While this reduces the cost of the system, it also prevents an ability to recall previously executed movements and requires that the user move each joint, one at a time, to execute a task.

The Manus, marketed by Exact Dynamics of The Netherlands, is a wheelchair mounted manipulator which is powered by the wheelchair battery and operates from an on-board controller also mounted on the wheelchair [2, 31]. The input device which comes with the Manus is a 16 key keypad, which commands the arm to move: up/down, forward/back, left/right; the wrist to move: pitch, yaw, and roll, and the gripper to open or close. Joystick interfaces have also been developed for the Manus, however, some method of switching between modes is also necessary [43, 55]. The controller of the Manus manipulator permits the arm to operate in a cartesian coordinate mode. The controller calculates and coordinates individual joint movements so that the entire arm will move forward, back, right or left when told to move in those directions by the user. The computerized link between the interface and the manipulator allows the user to associate arm movement with the direction that the arm should go instead of requiring the user to understand which joint should be moved to get to a specific location.

Desktop systems are typically designed to operate in a structured environment performing pre-programmed tasks like "answer the telephone" or "get paper". Examples of desktop systems are DeVAR, the Robotic Assistive Appliance, and the RTX robot using the Cambridge University Robot Language (CURL) [8, 13, 22]. All of these systems operate in conjunction with computer control. The computer controller facilitates programming specific tasks and allows the task to be associated with a command which the user can execute to recall the pre-programmed movement. The systems available are either operated by voice commands or by way of another interface to the computer like a mouse, joystick, modified keyboard or switch.

DeVAR, the DEsktop Vocational Assistant Robotic workstation, developed by Stanford

human operator's physical environment [50]. All of these fields offer a perspective on the design of an interface for a rehabilitation robotic device.

Previous work has compared a robot user interface to a graphic user interface [33] as a method of developing the criteria for the human interface design of a rehabilitation robot. Other work has focused on the interface for a particular rehabilitation robotic environment [47] or has focused on human factors issues for the interface device of an augmentative and alternative communication (AAC) system [14]. While all of these perspectives contribute to the interface design for assistive manipulators, this article addresses general considerations for a generic assistive manipulator interface design by reviewing contributions from man-machine telerobotic systems, rehabilitation robotics systems, and human-computer interaction.

Rehabilitation Robotics as a Man-Machine System

The concept of the "man-machine system" came about with the advent of World War II. The highly technical war time systems developed at that time put exceedingly heavy demands on the human operator and failure to meet these demands had drastic consequences. The operators were highly trained and most problems arose after skillful performance broke down. For instance, it was determined that an airplane that was prone to crash during landing had a lever which retracted the landing gear very close to the one used for breaking. By re-designing the levers, pilots were able to select the correct one while paying close attention to the rapidly approaching landing strip which reduced the likelihood of crash during landing. This is an example of the way in which psychologists of the time studied the human being and the machine as an operating unit and how they offered useful suggestions to improve system design [32]. With the explosion of advanced technology during the past fifty years, many disciplines have contributed to and benefited from the perspective of the man-machine system, including the field of robotics. The concept of the "human-robot system" is quite young and a great deal has yet to be understood about how an interface should be designed for industrial robots, teleoperated robots, and assistive manipulators developed for people with disabilities.

All robots, regardless of their functional use, operate on the world as a result of a person's cognitive process of instructing the machine. In industry, this person is frequently a highly trained technician with a teach pendent. In rehabilitation, the person is someone with a severe physical disability. The design of a good interface for either population benefits from understanding how the operator perceives the machine. In the rehabilitation field, robotic systems which have been the focus of most studies are anthropomorphic in nature with approximately six degrees of freedom [17, 45, 57, 3]. Although there are robots in industry which have two or three degrees of freedom, they will not be included in the scope of this article. To determine people's expectations and perceptions of an anthropomorphic robot, 96 undergraduate production engineering students took part in a three-stage experimental protocol with a Unimation PUMA 560 robot [20]. Experimental results indicated that there was agreement on describing the joints referred to as the "arm", "elbow" and "wrist", but there was difficulty in distinguishing the wrist joints. Joint movement was described either as clockwise/anti-clockwise, or as left/right and up/down. There were also two different perceptual orientations of how the robot moved: either the subjects used a robot centered reference point which "moves with" the robot when it's configuration changes, or they used an observer-centered perceptual reference which remains consistent to themselves regardless of changes in the robot configuration or observer-robot orientation. These two

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by

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Abstract

Rehabilitation robots or electro-mechanical assistive manipulators are designed to provide individuals who have severe physical disabilities with a means of interacting with their environment. The person-machine interface for assistive manipulators serves both as a method for commanding robot functionality and provides an additional avenue in which the safety of using the device can be assured. This paper will address the issue of designing an interface for an assistive manipulator from three perspectives. First, the robotics field will be addressed to outline interface designs of currently available rehabilitation robots and manipulators, and to consider how the rehabilitation field benefits from telerobotics and industrial robotics. Second, other fields of human-machine interface design will be addressed by looking at the contributions of cognitive science, human factors engineering and human computer interaction, and finally, this paper addresses the issues of evaluation and approaches taken towards determining the value of a specific interface design.

Introduction

The goal of rehabilitation robotics is to provide individuals who are not able to physically move the objects around them, a way to do so with the assistance of an electro-mechanical device. Not all electro-mechanical assistive manipulation devices are thought of as a "robot". Consequently, the term "assistive manipulator" is used in this paper along with "rehabilitation robot". With terminology aside, these devices are only useful if the severely physically disabled person is able to independently operate the robot or manipulator. With an optimal design, the interface can assist in minimizing the complexity of the manipulator for the user and maximize consistency of how the manipulator operates. The interface can also provide appropriate feedback to facilitate the user's knowledge about the state of the device or the task that the manipulator is taking part in.

In the 1980's the field rehabilitation robotics was regarded as showing great promise for serving the needs of people who are unable to motorically operate on their environments [28]. A large number of factors have prevented this promise from reaching fruition. At present, of the rehabilitation robots and similar devices available for assisting in manipulation tasks, very few are doing the manipulating for those who need them. One of the deterrents to widespread use of rehabilitation robotic systems is the shortcoming of the man-machine interface [33].

Designing the user interface for an electro-mechanical assistive manipulator benefits from a multi-disciplinary approach. There are many fields of expertise which contribute to interface design including psychology, computer science, ergonomics, and robotics. In particular, the fields of cognitive science and human-computer interaction have a history of expertise with understanding what a user "thinks" when interacting with a device and what the interface should look like for an optimal execution of an activity. Ergonomics considers individuals' physical and cognitive interaction scheme. With telerobotics, the user is viewed as a part of the causal loop of decision, communication, control and feedback through the

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