

Task-Orientated Biofeedback System for the Rehabilitation of the Upper Limb

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Abstract— Stroke forms one of the leading causes of disability in most industrialized countries. Robot mediated task-orientated physiotherapy is the recent answer to the shortage of staff and the cost associated with the treatment of strokes. The role of biofeedback as a rehabilitation tool has also being acknowledged recently.

In this paper we present Rehab Lab, a multi-modal environment for implementing task-orientated therapy. The work focuses on how an arm exoskeleton operating in 3D space can be used in conjunction with rehabilitation software for training patients in relearning daily motor tasks as well as providing them with quality feedback. The Salford Rehabilitation Exoskeleton (SRE) is used as an assistive device which helps individuals retrain in performing motor tasks by assisting them to complete therapy regimes.

Index Terms – exoskeleton, rehabilitation, upper arm, biofeedback

I. INTRODUCTION AND BACKGROUND

Every year, over 10,000 people in the U.K. suffer strokes, with 10,000 under retirement age [1]. Ischemia or hemorrhage in the brain may be the cause of cerebral vascular accidents which result in strokes [2]. Fortunately, over two-thirds survive the incident, but the majority is left with sensory and motor impairments, particularly in the upper limb. These impairments can be of varying degrees. Hemiplegia, the most common impairment resulting from a stroke, leaves the survivor with a stronger unimpaired arm and a weaker impaired one. Impairments such as muscle weakness, loss of range of motion, decreased reaction times and disordered movement organization, create deficits in motor control which affect patients' independent living [2].

Evidence has shown that intensive and repetitive physiotherapy may be necessary to modify neural organization [5] and recover functional motor skills, however:

i) Upper-limb disability rates low on the priority list for urgent medical assistance because it is seldom considered life-threatening. Therefore, physiotherapy tends to follow days or even weeks after admission.

ii) Manipulative physiotherapy procedures are extremely

labour intensive with several arm flexing movements per day and require high levels of one-to-one attention from highly skilled personnel.

iii) Therapies must be tailored to each patient's needs.

However, if patients do not receive the amount of physiotherapy required, they tend to use their unimpaired limb in all tasks, making recovery for the weaker arm even more difficult [3]. The need for longer, more intensive regimes and the shortage of trained staff means that power assistive devices able to provide intelligent assistance to therapists by re-training functional independence in everyday tasks, collect objective measurements and provide the opportunity for self-administered, intense practice individualized for each patient, are increasingly viewed as potential replacement for the physical labour leaving the therapists with greater time to develop their treatment plan.

There has been a lot of work on power-assisted device therapy. The increasingly wide and diverse range of systems, have been extensively reviewed by Hillman [4]. The two systems that have undergone extensive clinical trials are the MIT-MANUS robot and the Palo Alto/VA Stanford Mirror Image Motion Enabler (MIME). GENTLE/S system has also undergone some clinical trials. Details regarding these systems can be found at [6-9]. The main findings of these trials reinforce the hypothesis that task specific robotic training does indeed influences brain recovery. All 3 systems seek to motivate the patients by performing tasks

i) In a real environment, having a table and a few objects as a domain in the case of MIME

ii) In a computer-generated video game environment in the case of MIT-MANUS rehabilitator or a virtual environment in the case of GENTLE/S.

In all cases, muscle activation levels and motor control have significantly improved in the patients who received robotic therapy instead of/in addition to conventional manipulative physiotherapy. Results however did not indicate significant improvement in terms of functional skills in daily life activities (ADLs).

In the case of MIT-MANUS, a follow-up study indicated a significant increase in the functional ability of the persons provided with robotic therapy. Although both groups of persons (robot-trained and non robot-trained) had

comparable damaged tissues of comparable volume, the difference in functional score could be attributed to initial differences in cognitive and functional ability between the two groups [7].

Cognitive and functional ability as well as sensorimotor status influence greatly the degree of motivation during a patient's engagement in any given therapy. Motivation can also be influenced by the quality of biofeedback provided to the patients, especially the ones with cognitive and sensorimotor impairments. According to [10] the use of biofeedback can provide these patients with the opportunity to better assess their physiological responses and possibly to learn to control those responses. Earlier forms of biofeedback ranged from visual or audio representations of EMG (Electromyogram) signals, positional, angular or force data in real time [11, 12]. Researchers also theorize that biofeedback may enhance neural reorganization by engaging auxiliary sensor inputs through existing cerebral and spinal pathways [12]. Therefore the role of biofeedback as a rehabilitation tool is very crucial.

One of the more recent forms of biofeedback lies in multimedia and virtual reality based representations. Computer generated three-dimensional environments (VEs) can provide visual, auditory and physical (haptic) interactions in a way that engages a patient's attention while at the same time keeping him/her motivated. Therefore, the role of VEs in rehabilitation can be considered as dual: they provide the therapists with a set-up for repetitive functional ADL training while at the same time giving quality feedback to the patients helping them control their physiological responses in an engaging and entertaining way.

From the brief background given, it becomes clear that there are some issues of concern which could be transformed to design requirements for a system that delivers efficient, device-mediated therapy. These issues include:

- i) Provision of a multi-modal task-orientated computer generated training environment
- ii) Intuitive, high-quality feedback to both patients and therapists
- iii) Patient progress evaluation

In this paper, the authors propose a rehabilitation system for the upper limb which aspires to tackle all the above mentioned issues. Previous work has presented details and evaluation of the mechanical device [13, 16] as well as early developments of the computer generated training environment: Rehab Lab [17]. The current paper focuses on the latter as it has been redesigned to address all the above mentioned issues, giving details of the concept behind the

design, design issues, implementation and task examples which demonstrate the therapy modes available.

II. REHABILITATION SYSTEM OVERVIEW

Our suggested rehabilitation system utilizes the University of Salford upper arm exoskeleton as the power-assisted device that delivers the therapy. It provides a very suitable rehabilitation medium as it was designed to take advantage of the simultaneous multi-jointed actions that are needed for task-orientated therapy.

The Salford Rehabilitation Exoskeleton (SRE) is a multi-jointed gravity compensated upper arm assistive exoskeleton. The use of novel pneumatic actuation techniques provides a design with accurate position and forced controlled paths, compliance and a high level of inherent safety that is capable of controlled path and force trajectories in a complex 3D workspace. SRE's mechanical design, Fig. 1, has 7 degrees of freedom (DOF). Three of these DOF are located at the shoulder permitting flexion/extension, abduction/adduction and lateral/medial rotation. Two are located at the elbow permitting flexion/extension and pronation/supination of the forearm. The remainders are located at the wrist permitting flexion/extension and abduction/adduction. More details about the mechanical structure can be found here [13].

The exoskeleton framework is light due to its fabrication in aluminum with stressed components in steel (approx. weight 2kg) although the use of gravity compensation means that a user does not need to support any load if this is required. It is attached to the user at the elbow via a Velcro strip, which makes it comfortable to wear, easily fitted and more acceptable to the patients. The workspace of the system permits motion over 75% of the volume of normal operation [13] permitting excellent duplication of the motions needed in completion of real world tasks.

The drive source for the system uses braided pneumatic Muscle Actuators (pMA). Their "soft" nature makes them suitable for physiotherapy applications since they have inherent properties that give them characteristics that on a macroscopic scale are reminiscent of natural muscle. Details of the construction and control of the muscles, the hardware and the control system of the University of Salford exoskeleton can be found in [13-15]. Antagonistic pairs of muscles work together around each joint, simulating a biceps-triceps system to provide the bi-directional motion/force.

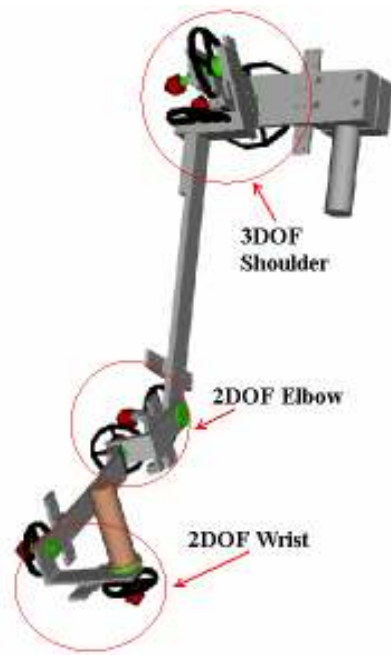


Fig. 1 University of Salford Rehabilitation Exoskeleton (SRE)

The design of the exoskeleton shoulder joint generates a singularity in the middle of the human arm workspace. In the case where the arm is parallel to the ground, a movement in the horizontal plane cannot be performed. This fact, however, does not prevent the use of SRE as a rehabilitation device as most of the tasks that are incorporated in the shaping treatment regimes can be replicated very well.

The main advantages of this exoskeleton are:

i) The use of pneumatic muscle actuators as opposed to electric motors or hydraulics. This feature makes the system compliant and inherently safer for close contact with patients.

ii) The ability to control either position or torque separately or simultaneously. For the purposes of our exercise regimes though, position control is used.

iii) The ability to generate and follow complex 3D trajectories that replicate real world tasks with a work volume covering 75% of “normal”.

iv) The ability to monitor the physical efforts of the user at a joint level providing real time feedback of the performance and permitting tracking of daily performance records.

SRE interfaces with a Pentium 4 based PC (which we will refer to as the Control Station) which contains dedicated data acquisition hardware and is responsible for running the software modules related to the low-level position or torque control schemes. Additional software modules associated with the exoskeleton interfacing also run on the Control Station. Dedicated software permits the control of the

exoskeleton in three different modes: joint position control, joint torque control and impedance control respectively. Details of the control system can be obtained in [13-15].

The Control Station is connected to a second PC which we will refer to as Physiotherapy Station. Information exchange between the two stations is accomplished through a 115Kbps serial link at a bandwidth of 300Hz. The Physiotherapy station also contains data acquisition hardware and is responsible of running Rehab Lab, the computer generated task-orientated therapy environment.

Information is exchanged between the two stations in the following way:

Within Rehab Lab, a protocol is selected to be performed. The protocol is then broken down into a number of sub-tasks. These sub-tasks are translated into a series of low-level commands which are in turn broken down into position and/or torque values which are transmitted to the Control Station via the serial link. These values feed the dedicated Low-Level Control module (LLC) on the Control Station and through interfacing hardware initiate the exoskeleton pneumatic valves switching sequence. The valves in turn regulate the amount of air passing through the pMAs and as a result of antagonistic muscle movements, exoskeleton motion is achieved.

While the exoskeleton is moving, dedicated hardware samples the data coming back from position and torque sensors and the low-level control module transmits them back to the Physiotherapy Station via the serial link. This information can then be used in a variety of ways which we will describe in more detail in the next section.

Fig. 2 shows the overall system architecture.

III. REHAB LAB

Rehab Lab is the software application running on the Physiotherapy Station which is responsible for the implementation of task-orientated therapy regimes. Its unique design incorporates features such as:

i) A multi-modal task-orientated three-dimensional computer generated training environment

ii) Intuitive, high-quality feedback both for the patient and the therapist

iii) Objective patient assessment and progress evaluation

iv) An extensive database including patient information, medical records, treatment regimes, progress evaluations.

In addition to the above, a highly modular object-oriented framework has been developed which can be easily extended further to include more components and features. The main framework components grouped by functionality along with the flow of data among them, are depicted in Fig. 2.

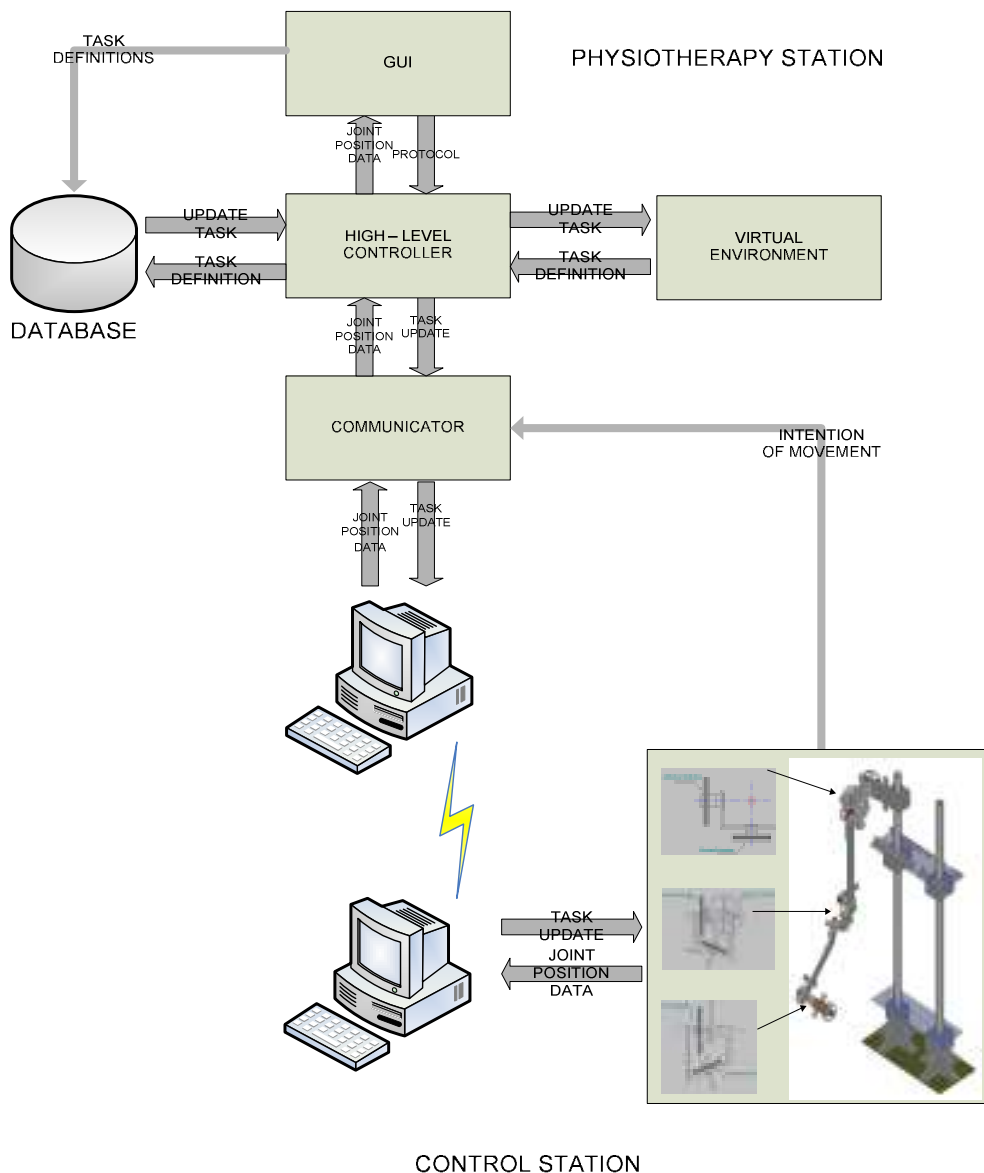


Fig. 2 Overall system architecture with major components

A. Description of module groups

Through the graphical user interface (GUI), the therapist can select a protocol or create a new one. A protocol can be synthesized by combining basic tasks which comprise its building blocks. A basic task can be very simple e.g. elbow flexion or shoulder extension or more complex e.g. reaching for a mug. Other attributes of a protocol are the number of repetitions and the resting period between two consecutive tasks. The simplest tasks that can comprise a protocol are the possible movements around all the upper arm joints and we call them *primitive*. Table 1 lists all primitive tasks. Primitive

TABLE I
LISTING OF ALL PRIMITIVE TASKS

Task Name
Shoulder Adduction/Abduction
Shoulder Flexion/Extension
Shoulder Medial/Lateral Rotation
Elbow Flexion/Extension
Elbow Supination/Pronation

tasks have attributes such as start and stop angles and speed. Non primitive tasks can also have their speed adjusted.

In order to synthesize a protocol, the therapist combines a number of tasks (primitive or non-primitive) with information about the number of repetitions, the interval after each repetition and the resting period between the different tasks. The speed and range of movement should be prescribed as clinically this is important due to potential problems with altered levels of muscle tone or any other limitations to range of movement e.g. pain or joint stiffness. An example protocol is listed in Table 2.

According to the protocol in Table 2, the patient starts the treatment (selected by the therapist) by warming up all the joints of the upper limb. That is performing all the basic movements 10 times around each joint. Shoulder rotations are performed at a slower speed than elbow pronations/supinations and after each rotation there is a 40 sec resting period. For primitive tasks, it is also possible to set a start and stop angle according to the patient's joint Range of Motion (ROM) recorded from previous treatments.

After a protocol is synthesized, the therapist can save it in the Database where it can be globally accessed. Primitive tasks will exist by default in the database and will be available as protocol building blocks. Alternatively, the therapist can select a protocol from the database and customize its parameters for each patient. In order for the protocol to be executed, the GUI module passes it on to the High-Level Controller (HLC) where it gets resolved to its

TABLE 2
EXAMPLE PROTOCOL

Task Name	Speed (deg/sec)	x Times	Interval (sec)
Shoulder Adduction/ Abduction	5	10	10
Resting time		40 sec	
Shoulder Flexion/ Extension	5	10	10
Resting time		40 sec	
Shoulder Medial/Lateral Rotation	5	10	10
Resting time		40 sec	
Elbow Flexion/ Extension	10	10	10
Resting time		40 sec	
Elbow Supination/ Pronation	10	10	10
Resting time		40 sec	
Reaching for a mug	15	5	10
Resting time		40 sec	
Drinking tea	20	5	10

building blocks and then further resolved to a series of values that get transmitted to the Control Station via the Communicator Module (CM). The CM in turn feeds the Low-Level Controller (LLC). More details about the Low-Level Controller (LLC) can be found here [14].

Vice versa, sensor data is passed on to the CM which in turn, is sent to the HLC. From there, the data can:

- i) Update the virtual environment with cues generated within the HLC (and which represent the feedback to the user and therapist)
- ii) Update the GUI by providing angular, positional and force information
- iii) Be stored in the database, after being processed by the HLC modules

A block diagram of the protocol while it is executing along with the data flow among the system components is depicted in Fig. 3.

B. Modes of Operation

Rehab Lab is able to operate in three modes. These modes vary from full assistance from the exoskeleton to no

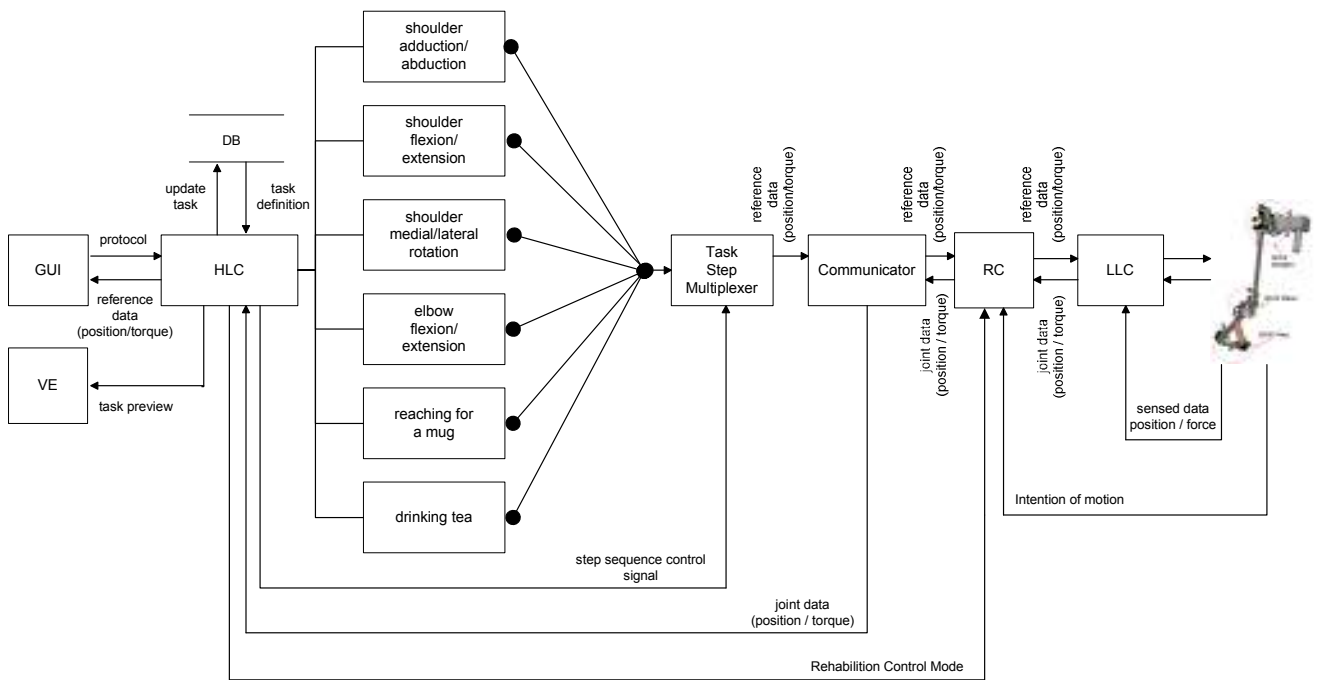


Fig. 3 Protocol execution with data interchange among system components

assistance (recording and monitoring only), according to the recovery stage the patient is in. The modes are: Full Assistive mode (FA), Partial Assistive mode (PA), Non Assistive mode (NA).

1) Full Assistive Mode

During the first stages of recovery and while the patient cannot move his/her limbs without assistance, the FA mode should be used in order for the protocols to be executed with full assistance from the exoskeleton. All protocol tasks are executed at a constant speed (which can be adjusted for different tasks). This mode extends the concept of isokinetic machines already used in rehabilitation. While isokinetic machines offer only single joint exercises, Rehab Lab can exercise multiple joints simultaneously. For primitive tasks, the start and stop angles as well as the speed, are the necessary parameters for the trajectory generation (TG) module of the High-Level Controller (HLC) to synthesize the waveform that feeds the LLC. The synthesized waveform is of the type:

$$f(x) = a + b * t \quad (1)$$

where b is the slope of the function, a the offset, and t are the temporal values.

For more complex tasks (non primitives) such as reaching for a mug, the reference angles that feed the LLC are produced by recording the task and then playing it back. In

order to record the task, the exoskeleton has to be physically moved (along with the patient's limb) to form a predefined trajectory that needs to be followed in order to complete the task. While the exoskeleton is following the trajectory, the position sensors record angular joint data. This is part of the calibration process for each complex task and it is tailored to each patient's range of motion. As the patient recovers, the task can be recorded again to reflect the improved ROM. For this category of tasks, the speed is also constant and represents the constant rate at which angular data is fed to the LLC.

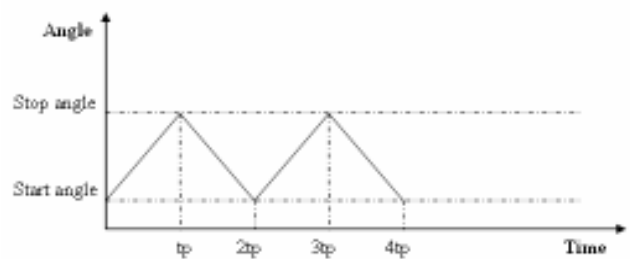


Fig. 4 Plot of the waveform used for generating reference angles used in full-assistive mode

2) Partial Assistive Mode

In order to provide SRE with assistive functionalities, we use a force/torque (F/T) sensor that was recently attached to

the wrist of the exoskeleton, Fig. 5. The sensor detects intention of movement (through a sensitivity scaling of the sensor's values) and Rehab Lab produces the necessary angular values that are fed to the LLC through the Communicator module. We use the following formula to derive the new desired position using the sensed force signal

$$x_E^i = x_{E-1}^i + \int x_f^i dt, i=1..6 \quad (2)$$

$$x_f^i = \begin{cases} k_a(F_s^i - a) & F_a^i > a \\ 0 & -a < F_a^i < a \\ k_a(F_s^i + a) & F_a^i < -a \end{cases} \quad (3)$$

where $x_E^i = [x_E^1 \dots x_E^6]^T$ is the desired Cartesian position vector, $F_s^i = [F_s^1 \dots F_s^6]^T$ is the force vector produced by the F/T sensor and k_a is a sensitivity coefficient that can be adjusted according to the patient's physical strength. A dead band of $a=0.3N$ has been applied in (3) to cut off sensor noise signals entering equation (2) Having computed the Cartesian vector, the desired joint position data are computed by means of the inverse kinematics and are used to feed the LLC . Fig. 6 shows the F/T sensor data generated in the X direction while the user flexes and extends the elbow while Fig 7 illustrates the resultant assistive motion of the elbow joint.

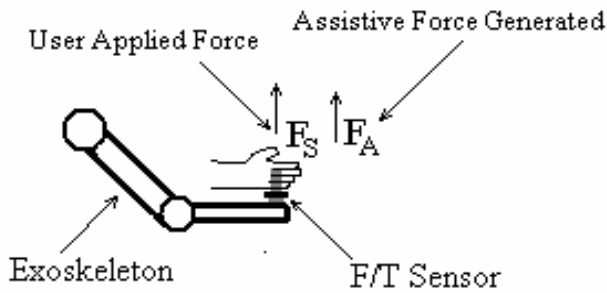


Fig. 5 Assistive mode setup

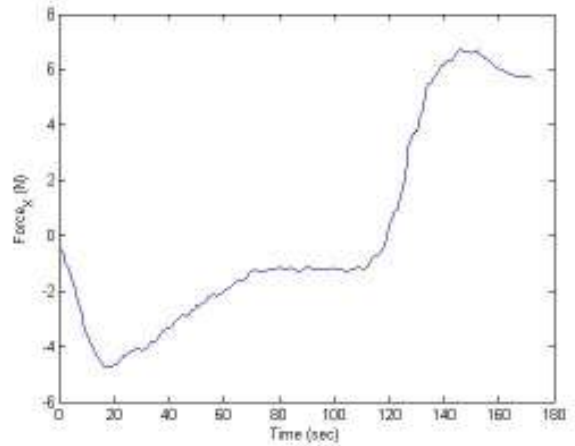


Fig. 6 F/T Sensor data in the X direction as the user pulls the exoskeleton handle to flex or extend the elbow joint.

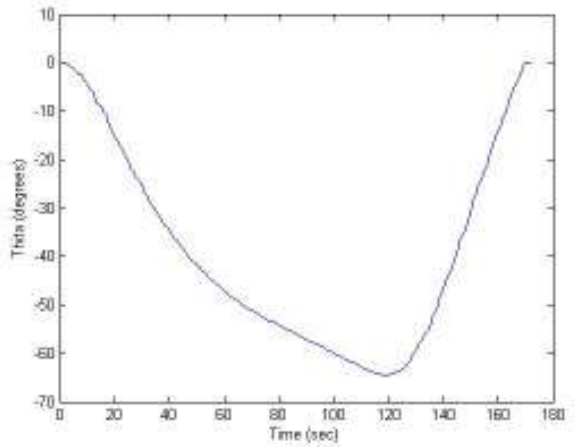


Fig. 7 Elbow assistive motion generated by the Rehabilitation Controller (RC)

3) Non Assistive Mode

In non assistive mode, the exoskeleton is configured to simulate the forces generated by an exercise. This mode of therapy should be used when the patient has regained enough strength to complete a protocol on his/her own. In this mode, the Low-Level Impedance controller LLI accepts as input the torques produced by the user and the control mode changes from position to impedance control.

The equation below calculates the required torques, given the Jacobian matrix of the arm and the properties of the exercise. The Jacobian matrix is obtained up to the position of the load applied. For example, if the load is to be applied at the elbow, then the Jacobian is obtained up to the elbow.

$$\tau_{joint} = -J^T \cdot (B_E \cdot \dot{x} + K_E \cdot (x - x_E) + F_{bias}) + G(q) \quad (4)$$

The task parameters consist of B_E and K_E that are the damping and the stiffness matrices respectively (6x6 diagonal matrices) and F_{bias} the force bias vector.

$G(q)$ is the gravity vector used to counteract the weight of the exoskeleton.

Depending on the type of the task, the therapist can accordingly set the K_E and B_E to zero matrices and the F_{bias} to a certain set of values in order to simulate a simple training weight or set F_{bias} to zero and K_E , B_E to some values in order to simulate spring-type tasks. Except for stiffness, damping and weight, protocols maintain the aforementioned properties namely the number of repetitions, the interval after each repetition and the resting period between the different tasks.

C. Virtual Environment

The Virtual Environment (VE) in Rehab Lab plays a dual role. It provides the setup for the tasks to be performed as well as a means of biofeedback. Currently, only one set-up exists which contains a table and a number of objects placed on its surface. Therefore, the tasks that can be performed are for the time being limited. Nevertheless, it is easy to incorporate other set-ups since Rehab Lab has been re-designed to use 3D-State graphics engine. 3D-State is a powerful games engine which can be used in conjunction with C++ to create and manipulate compelling three dimensional worlds. The current environment within Rehab Lab is shown in Fig. 8.

After the therapist selects the suitable protocol for the patient, he/she can preview it in the VE. A female avatar is demonstrating the protocol so that the patient has a better idea of the sub-tasks to be performed. Once instructed in the protocol, the exoskeleton is fitted to the patient. This is a simple process taking less than 1 minute. The patient is then asked to complete the sub-tasks.

While the patient is performing non primitive tasks, there is an option to trigger auditory cues and when selected, a music clip can be heard in the background. The music clip raises awareness in the patient as a result of providing him/her with auditory stimulation. If the patient follows the trajectory closely (according to a threshold criteria derived by the amount of deviation between the desired and the actual trajectory), the volume remains the same. When the patient diverts from the trajectory, the volume lowers. This auditory cue serves as a guide to the patients in the sense that it intuitively lets them know that they are doing well or need to correct their trajectory in order to complete the task. When the task is complete, the music stops. Musical cues help patients control their physical responses as in order for a task to be successfully completed, the volume must remain

uniform throughout the task. If the volume changes, patients quickly realize that they have deviated from the desired trajectory and they try to adjust their strategy of accomplishing the task in order to return to the desired path.



Fig. 8 Current set-up of the Virtual Environment

During the protocol, the patient can see a reflection of his/her movements in the virtual environment. That is, a virtual character is sitting in exactly the same position as the patient and his arm is moving exactly the same way as the patient's. The virtual character's arm position is updated by the exoskeleton's position sensors. In addition to the musical cue, the actual perception of their own actions gives them a way to assess their physical responses. This awareness helps them establish the boundaries of their limb with respect to the environment and the objects they have to manipulate and therefore learn how to control their responses.

Except for the virtual environment as a means of biofeedback and the auditory cueing, there is also EMG biofeedback available in Rehab Lab. The Physiotherapy Station also includes data acquisition hardware and software to interface with DELSYS EMG acquisition system. More details can be found here [17].

Other forms of biofeedback supported by Rehab Lab include the torque inputs from the patient at all joints as well as position and angular data. All these types of biofeedback are handled by the GUI where they can be graphically displayed for both the therapist and the patient. This information is also stored in the database in order to provide an indication of the progress in terms of torque generation achieved by the patient as well as the ROM improvement.

D. Discussion and Conclusions

This paper presents the architecture of a task-orientated environment for the rehabilitation of the Upper Limb. Task-orientated rehabilitation seems to be a key to effective recovery from stroke as it trains patients in performing every day tasks involving coordinated multi-joint actions. Biofeedback also seems to be the key for effective control of patients' physical responses. Therefore robotic rehabilitation interventions should incorporate these features in order to create effective solutions that will provide training environments for stroke patients that offer intensive and repetitive training with quality feedback.

As far as future plans are concerned, there are a lot of ideas as to how to improve the current system. Now that the VE generation has been redesigned, a few more set-ups need to be incorporated in order to include a wide variety of tasks. Research has to be done in order to incorporate better and more intelligent ways of cueing within the VE so that the guidance will not confuse the patient but will be very intuitive in order to grasp their attention. Finally, we would like to enrich the assistive mode in order to incorporate EMG-triggered assistance from the exoskeleton.

On-going trials are taking place to test the system's integration and the first experimental results will shortly become available.

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