Assistive Exoskeleton for Task Based Physiotherapy in 3-Dimensional Space

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Abstract – **Stroke forms one of the leading causes of death amongst adults in industrialized countries, and although survival rates are comparatively high in up to 1/3 of patients there is functional impairments (particularly in the upper limbs) that can persist even after rehabilitation training. Tasked based rehabilitation therapy (shaping) is a new approach that seems to offer good success compared to traditional methods, however, the technique requires very intensive and prolonged treatment. Robot mediated physiotherapy is the recent answer to the shortage of staff and the cost associated with this.**

In this paper a robotic approach to task based therapy is shown. The work focuses on how a robotic exoskeleton operating in a 3D volume can be used in conjunction with a Virtual Environment rehabilitation suite for training patients in relearning daily motor tasks. 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. EMG recordings are used to show the capacity of the system to mediate the level of assistance provided from full assistance to zero aid.

Index Terms – **exoskeleton, rehabilitation, upper arm, EMG feedback**

I. INTRODUCTION

Every year, over 100,000 people in the UK suffer strokes, with 10,000 of them under retirement age [1]. Fortunately over 65% of patients survive but the majority do have residual disabilities with up to 1/3 having severe disabilities particularly in the upper limb [2]. These limitations are most commonly due to motor dysfunction as a result of hemiparesis. Approximately 40% of stroke survivors experience chronic hemiparesis in the upper extremity, meaning the functional ability of the upper extremity is limited by deficits in motor control and coordination, synergy patterns, spasticity, and pain [3].

It has been shown that early and intensive physiotherapy can improve outcomes [5], however:

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

ii) Manipulative physiotherapy procedures are extremely labour intensive with 300/400 arm flexing movements per day forming part of a rehabilitation regime that is not untypical.

iii) Manipulation requires high levels of one to one attention from highly skilled medical personnel, but there is an international shortage of physiotherapists.

iv) Therapies must be customised for each patient

This need for long treatment periods, more intensive regimes and the shortage of trained staff means that robotic and powered assistive techniques are increasingly viewed as a potential replacement for the physical labour leaving the therapists with greater time to develop the treatment plan.

The first work on robotic mediated therapy and assistive devices began in the 1960s with the CASE and the Rancho Los Amigos manipulators and since this period they have been an increasing wide and diverse range of systems that have been extensively reviewed by Hillman [4].

Recent applications of robot mediated therapeutic tools include, the MIT-MANUS, that was used to demonstrate that arm function benefited from interacting with a planar device in the sub-acute stages of recovery [6]. Subsequently, two the Mirror Image Movement Enabler (MIME) [7], expanded the investigations of therapeutic applications of robots into the chronic stroke population. The GENTLE/S uses the haptic master to generate a flexible, high intensity rehabilitation workspace that promotes robot mediated therapy to stimulate and motivate patients, and monitor recovery [8].

Recent research into patient recovery strategies has indicted that stroke or traumatic brain injury patients may benefit from a behaviour-based therapy called shaping, a technique that may help them recover more efficiently than other treatments. Shaping therapy (training, repetition and working with an affected limb) is based on conditioning behaviour where patients are trained to perform increasingly more complex everyday activities with their weakened arm. Typical scenarios include pressing a light switch, drinking a glass of water, cleaning teeth, moving a chair and pulling up socks. The research suggests [9] that prior to shaping, the patients' affected arms had reached a low-functioning plateau for several months or years, however after implementing the shaping approach patients continue to make progress and the brain continues to adapt.

Daily shaping sessions are typically 90 minutes in duration [9].

From the review of the current state of the art in rehabilitation it is clear that there is a demand for robotic techniques to augment the activities of the physiotherapist. In particular, given the opportunities available in task based planning there is a need for multifunctional systems having a high number of degrees of freedom and a workspace comparable to unrestricted motion. At the same time this must be combined with safe operation, low complexity, and portability (to permit operation at home if required).

In this paper a robotic assistive device is presented designed to provide complex simultaneous multi-jointed motions for task based therapy scenarios. The device plays a dual role: rehabilitation as well as an assistive tool. In assistive mode, it helps the patient complete a task-based treatment regime. The assistance levels depend on how good the motor skills of the patient are. Initially a brief overview of the design and operation of the software suite and the exoskeleton will be presented before considering an assistive scenario that merges robotic and VR technology. The effectiveness of the exoskeleton as an assistive device and the level of support provided will be demonstrated using a series of EMG mediated tests to study the muscle activity levels. Levels of assistance will be varied showing effective changes in the effort need by the user to sustain any particular output. The paper will conclude with consideration of the future possibilities regarding the system.

II. REHAB LAB AND SRE

Rehab Lab is a virtual rehabilitation suite that uses the University of Salford upper arm exoskeleton in tasks developed to take advantage of the simultaneous multi-jointed actions that are needed for task based therapy (shaping).

The Salford Rehabilitation Exoskeleton (SRE) is a 7 DOF multi-jointed gravity compensated upper arm assistive device forming an exercise medium used for physiotherapy and rehabilitation purposes. 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.

The SRE mechanical design, Fig. 1, has 7 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 remainder are located at the wrist permitting flexion/extension and abduction/adduction. More details about the mechanical structure can be found here [10].

The exoskeleton framework is light due to its fabrication in aluminium 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 (and in some applications at the bicep) via a Velcro strip, which makes it comfortable to wear, easily fitted and more acceptable for patients. The workspace of the system permits motion over 75% of the volume of normal operation [10] permitting excellent duplication of the motions needed in completion of real world tasks.

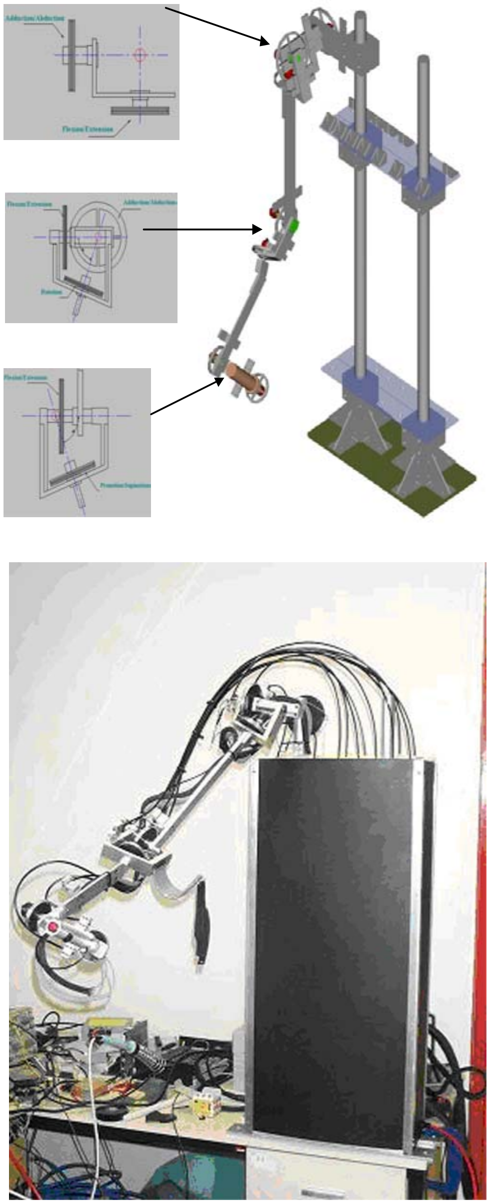

Fig. 1 University of Salford Rehabilitation Exoskeleton (SRE)

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. Also, friction has been incorporated in the model of the control system and that acts as the main damping force of the system. Details of the construction and control of the muscles, the hardware and the control system of the University of Salford exoskeleton can be found here [10-12].

The design of the exoskeleton shoulder joint generates a singularity in the middle of the human arm workspace. In the case that the arm is parallel to the ground, there cannot be a movement in the horizontal plane. The latter fact does not prevent us using the exoskeleton as a rehabilitation device as most of the tasks that are incorporated in the shaping treatment regimes can be implemented by the particular exoskeleton.

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. 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.

A. Rehab Lab Physiotherapy System Architecture

A distributed architecture was developed to implement physiotherapy regimes. This consists of two stations namely the physiotherapy and control stations. Information exchange between the two stations is accomplished through a 115Kbps serial link at a bandwidth of 300Hz, Fig. 2.

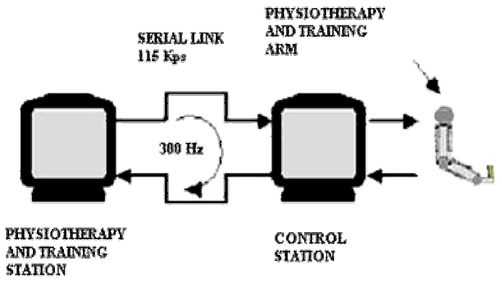

Fig. 2 Physiotherapy system architecture

B. Control Station

The control station is responsible for running the software modules with data on and related to the low-level position or torque control schemes. Additional software modules associated with the exoskeleton interfacing run also in the control station. The station uses a Pentium 4 based PC with dedicated data acquisition hardware. The control station 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 here [11-12].

C. Physiotherapy Station

The physiotherapy and training station runs a software application that allows the system to perform the physical therapy exercises. The main software modules are: the GUI module, the Database module, the 3D Graphics module and the Communication Controller.

The GUI module accepts input from the therapist and modifies or displays the outputs from other modules. The Database module contains all operations dealing with patient records and available exercises linked with information about the therapist who provides the treatment regime. It supports database operations such as add a new record, update/delete an existing one, browsing through existing records and so on. The Graphics module handles the graphics functions that create previews of the exoskeleton while executing a particular exercise.

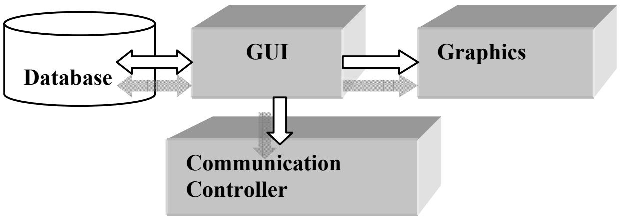

Fig. 3 Overall software architecture

The previews are animated 3D models of the exoskeleton. Finally, the Communication control module interacts with the control station. Fig. 3 shows the overall software architecture of the physiotherapy station.

III. VIRTUAL ENVIRONMENT

The virtual physiotherapy environment consists of a virtual desk on which there are several everyday objects that are task dependent e.g. to perform a "cutting a cucumber" task, a cucumber and a knife will be located on the table. For a task such as reaching for a mug of coffee, a mug is located on the table. All the appropriate objects are arranged on the table in a way designed to encourage the patient to look and reach out in a certain direction.

The therapist sets the nature of the exercise either by:

i) Recording an exercise by physically moving the exoskeleton or by

ii) Loading an existing exercise.

In order to record an exercise, the therapist moves the exoskeleton arm to form a predefined trajectory that is recorded using the exoskeleton joint angle sensors (300Hz sampling). The generated trajectory is saved in a file for later playback during the tasked based virtual exercise. Rehab Lab has also incorporated the isokinetic exercise capabilities of SRE. More details about isokinetic exercise implementation using SRE, can be found in [13].

Within the virtual environment, Rehab Lab, the therapist has to choose the appropriate rehabilitation task which must then be presented to the patient in such a way that they understand the eventual goal. Early in the rehabilitation training the therapist guides the patient as they explore the objects, recognize the problem and strive to find possible solutions. Irrespective of the nature of the task, the patient is guided in a similar way.

Once instructed in the task the exoskeleton is fitted to the patient. This is a simple process taking less than 1 minute. The patient is then asked to achieve the goal motion. If the patient has zero movement of the arm no motion occurs and the exoskeleton is used to provide full support for the arm and the completion of the task. Repetition of this action is possible 10s, 100s or 1000s of times depending on the procedure selected by the therapist. Rehab Lab is depicted in Fig. 4.

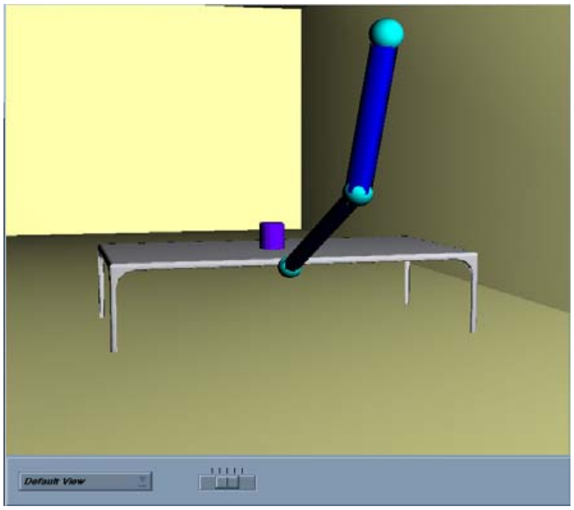

Fig. 4 Rehab Lab: A virtual rehabilitation suite

As the patient regains some movement in the limb sensors at the wrist monitor the input effort which can vary from minimal to full recovery.

In the early stages of rehabilitation the patient inputs are small and through a sensitivity scaling, any motion from the patient is amplified and used to provide assistive help from the exoskeleton. As the level of patient input is increased the sensitivity scaling is reduced and the exoskeleton assistance is also reduced until there is zero assistance apart from gravity compensation to remove the loading influence of the exoskeleton.

During the assistive actions the torque inputs from the patient at all joints are monitored and can be graphically displayed to provide feedback to the therapist and the patient. This data can be stored in the database to provide an indication of the progress in terms of torque generation achieved by the patient.

III. Tools And Experimental Setup

For the purposes of the experiment Rehab Lab, SRE and a DELSYS EMG acquisition system were used.

Qualitative EMG feedback was utilised in order to study the muscle activity at a particular task, and therefore gain insight into which muscles are active and which start or cease their activity. In order to measure the muscle activity levels, a monopolar electrode arrangement was used. The latter means that a surface electrode was placed over a muscle and a second electrode went over an electrically neutral site, such as a bony area. This arrangement is suitable for isometric contractions. Since EMG feedback was used only to measure muscle activity levels, and not to extensively analyse the signals in order to extract for example intention of motion like in [14], a monopolar electrode arrangement was suffice as opposed to a bipolar arrangement. All signals were fully rectified prior to their display in order to facilitate display. Also, all signals where scaled to represent percentages of the maximum isometric contraction of the biceps.

In order to provide SRE with assistive functionalities, we use a force/torque sensor that was recently attached to the wrist of the exoskeleton. The sensor detects intention of movement and Rehab Lab produces the necessary angular values that are fed in the controller through the Communication controller module.

IV. Tasks And Exercise Protocols

Our first goal is to prove that SRE, through Rehab Lab, is capable of following input trajectories that correspond to real life tasks. For this purpose, the subjects are instructed to reach out for a mug of coffee. Next, the assistive capabilities of SRE will be demonstrated by performing the same task having this time some assistance from the exoskeleton.

A. Task replication by SRE

In order to establish whether the SRE reliably replicates an input trajectory corresponding to a real-life task, the subjects are instructed to reach out for a full mug of coffee. The instructions were to reach out for the mug slowly, grasp it and bring it towards their mouth. There is no user input for this task i.e., the exoskeleton provides 100% assistance and guides the subjects in order to grasp the mug and bring it towards them. During this task, the deviation of the actual trajectory followed by the exoskeleton from the input trajectory is measured.

The results for a typical male subject were plotted in Matlab and displayed in Fig. 5. The blue thin line is the input trajectory whereas the thick red line is the data obtained from the sensors while the task was being performed. It can be seen that, the red trajectory is not as smooth as the blue trajectory. The red line however follows the blue line with a high level of correlation. The latter means that the output replicates well the input even when loaded with an arm. This is the required response from an effective rehabilitation exoskeleton.

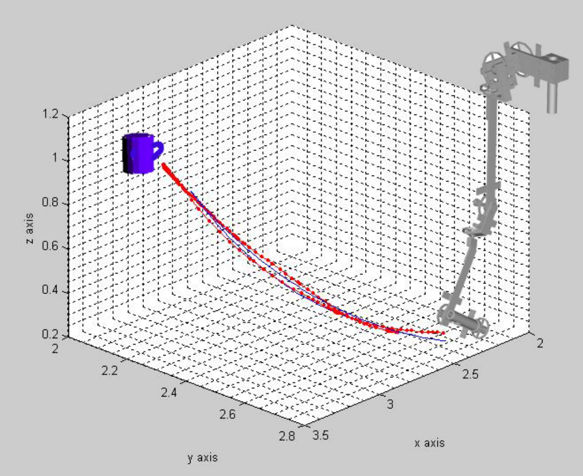

Fig. 5 Plot of the “reaching out for a mug” results

B. Variable exoskeleton assistance in tasks guided by the subject

To verify that the exoskeleton is providing the expected assistance and show that patient muscle guidance is not present, the EMG activity was assessed under two conditions.

The subjects were instructed again to reach out for full a mug of coffee. They were secured to the exoskeleton with an electrode attached to their biceps. The biceps muscle was chosen for electrode attachment due to the fact that it provides a cleaner signal in comparison to the signal coming from the other muscles of the arm that are involved in performing this task. As each subject initiated the movement, the exoskeleton detected the direction of their movement and helped them (partial assistance) complete the task.

As the exoskeleton tried to compensate for the weight, we measured the EMG activity of the subject while the subject’s arm was in a static isometric configuration. This configuration was chosen because during isometric contractions, the signal properties are linear. Fig. 7 displays biceps’s activity while the exoskeleton was close to fully compensate for the weight.

From the above measurement, we observe that there is minimal muscle activity when the exoskeleton is compensating for the weight of the object. This result is encouraging as it shows SRE’s potentials to be used as an assistive tool for implementing task-based therapy.

The same experiment was performed but this time the exoskeleton provided no assistance to the subjects. Again an electrode was attached to their biceps measuring the EMG activity while the subjects were trying to perform the task. Fig. 8 shows the EMG activity of a typical subject while trying to perform the task. We can clearly see that there is much activity. Fig. 6 shows the EMG activity of a typical subject while the exoskeleton was fully supporting the arm. Fig. 6 shows the EMG activity of the biceps muscle during full assistance from the exoskeleton. Clearly, the EMG amplitude range was lower than in both partially and no assistive modes.

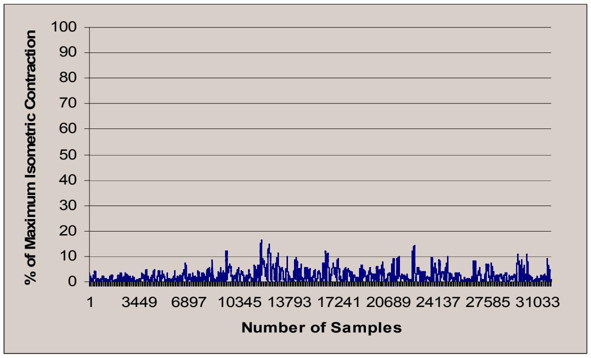

Fig. 6 EMG activity while in full assistive mode

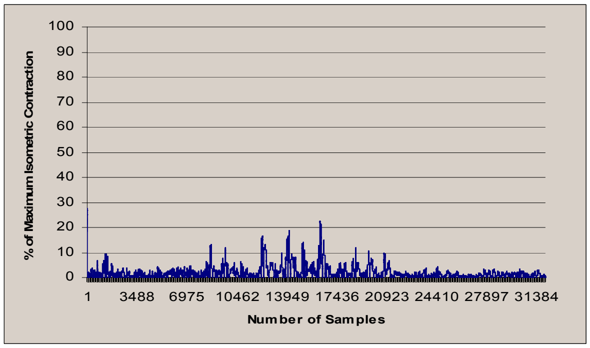

Fig. 7 EMG activity while in partial assistive mode

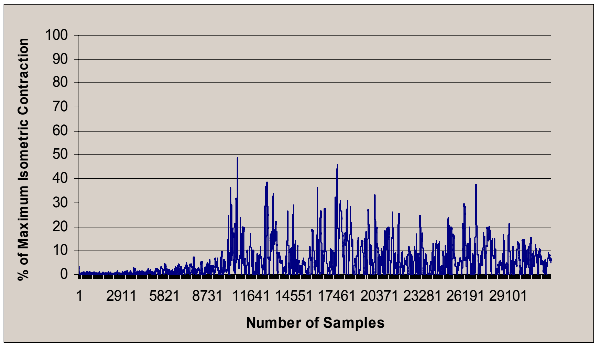

Fig. 8 EMG activity with no help from the exoskeleton

From the last two figures it can clearly be seen that the exoskeleton can be used as an assistive device since it augments the subjects in performing daily tasks by eliciting small muscular activity.

V. CONCLUSION AND FUTURE DIRECTIONS

In this paper we have presented Rehab Lab, a virtual rehabilitation studio for the Upper Limb. Rehab Lab uses SRE (Salford Rehabilitation Exoskeleton) as an exercise medium. SRE was designed to provide complex simultaneous multi-jointed motions for task based therapy scenarios.

A brief overview of the design and operation of the software suite and the exoskeleton have been presented along with an assistive scenario that merges robotic and VR technology

Finally, the effectiveness of the exoskeleton as an assistive device and the level of support provided was demonstrated by a series of EMG mediated tests to study the muscle activity levels. The levels of assistance were varied showing effective changes in the effort need by the user to sustain any particular output.

As far as future plans are concerned, first of all an overall improvement in the design of the virtual environment will take place. The rehabilitation studio strives to be a truly interesting and challenging environment that will provide patients with motivation to enhance the recovery. Secondly, more tasks will be incorporated in the repertoire of treatment regimes accompanied by an individual virtual scene for each of them. Assistive functionality will be extended in such a way that in every task, the assistance levels will automatically set as opposed to manually set by the therapist. Finally a neural network will be implemented with the capability to learn individualised trajectory patterns for each patient in an attempt to make therapy specific to each patient's needs.

In addition to all the functional improvements, a new broader and more systematic study will take place incorporating volunteers from diverse age spans as well as pathological conditions. From the first pilot study involving the first subjects, we have extracted useful information involving small mechanical adjustments (for example the position of the elbow strap) as well as additions that need to be implemented on the actual exoskeleton (emergency stop button available to the physiotherapist).

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