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Pneumatic robotic device for early delivering of rehabilitation therapy

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Abstract— **This paper describes a new pneumatic rehabilitation robot for upper limbs to deliver Proprioceptive Neuromuscular Facilitation (PNF) therapies to the acute post-stroke patients, even if they are still in supine position. The robotic device assists the therapist in repetitive PNF therapies, learning the defined movement by therapist at the same time that the patient, and then repeating it with different level of assistance. Moreover, the rehabilitation device was designed to be used for relearning daily living skills like: take a glass, drinking, etc. The proposed solution is composed by two robotic arms actuated by pneumatic swivel modules and a virtual environment for the motivation of the patient.**

I. INTRODUCTION

It is well known that the demand for rehabilitation services is growing apace with the aging of the population. According to the World Health Organization (WHO), senior citizens at least 65 years of age will increase in number by 88% in the coming years. Cerebrovascular accident or stroke in aging population is the primary cause of disability and the second leading cause of death in many countries, including Spain (300,000 people). Although the mortality rate of stroke has declined, the incidence and prevalence of stroke continue to rise. The major symptoms of stroke are loss of muscle power, spasticity and in-coordination of muscle activation. The goal of rehabilitation is to help stroke patients to achieve as much functional independence as possible and to maintain quality of life.

In consequence of lacking inhibition within the central nervous system, abnormal coordination of movement patterns combined with abnormal postural tone are two of the major plastic responses that impede restoration of motor functions for patients with post stroke hemiparesis [1]. On account of weakness-related neurological deficits, the patients would rely unconsciously on various compensatory attempts to move limb segments that result in atypical synergy patterns and enhanced hypertonus during the rehabilitation process [2]. Therapeutic intervention therefore focuses on relearning normal movements through experience with active participation of the patients. Correct movement patterns can be facilitated with appropriate application of proprioceptive, cutaneous, or reflexive inputs in the beginning of the recovery phase. Reinforced successful sensorimotor experiences could expedite recovering from upper limb paralysis of stroke patients with manual stretch [3], tactile stimulation [4], or joint compression [5]. As the individual becomes more effective and independent in the motor task, this handling of external sensory inputs is gradually withdrawn, in replace of strengthening exercises against resistance [6] with designed patterns and training of goal-oriented and skilled movements [1]. A number of neurological treatment approaches have been proposed to facilitate motor recovery of stroke patients, including Bobath, Brunnstrom, Proprioceptive Neuromuscular Facilitation (PNF) [11], Motor Relearning Program (MRP), constraint-induced movement therapy (CIMT), task-related training and bilateral training [7].

The design of the rehabilitation robot presented in this paper was born from the need of automation of delivering Proprioceptive Neuromuscular Facilitation (PNF) therapies to patients with reduced mobility in supine and sitting position. The movement patterns which will be assisted by the robotic device are:

- D1 Flexion: The D1 flexion pattern begins with the shoulder and elbow extended at the patients side and the wrist supinated. The terminal position for the D1 flexion pattern is the shoulder and elbow are flexed, internally rotated, and adducted, the wrist in supination. The patient should look as though he or she is reaching across the body to touch the opposite anterior deltoid, with the dorsal side of the hand.
- D1 Extension: This time, the patient begins in the terminal position of the D1 flexion pattern, with the patient reaching across the body to touch the opposite anterior deltoid. The D1 extension pattern is to extend the shoulder and elbow, externally rotate the humerus, abduct the arm, and supinate the wrist.
- D2 Flexion: The D2 extension pattern begins with the shoulder and elbow flexed and adducted, the humerus internally rotated, and the wrist pronated. The patient should look as though he or she is touching the ASIS of the opposite hip. The movement consists of abducting the shoulder, externally rotating the humerus, and supinating the wrist. One may describe it as taking a sword out of its holster and raising it up to the sky.
- D2 Extension: The D2 flexion pattern is again, the counter movement to the D2 extension pattern. The patient starts in the terminal position of the D2 extension patter with the shoulder and elbow extended and adducted, the humerus externally rotated, and the wrist supinated. The movement occurs when the patient flexes shoulder and elbow, adducts the arm, internally rotates

the humerus, and pronates the wrist.

The physiotherapist moves the patient through the range of motion initially, to allow the patient to understand how the limb will be moving before adding resistance; this is the same for all diagonal patterns. Once the patient understands the movement, the clinician applies manual resistance to the patient as he or she moves along the range of motion. Simple, one word verbal cues from the clinician are important to achieve maximal results from the patient

Moreover, the rehabilitation device was designed to be used for relearning daily living skills: like take a glass, drinking and placing object on shelves. The virtual reality system creates a necessary virtual world for the activity and the robot assists the patient during the execution of a preconfigured activity of daily living. Of course, these activities of daily living can be adjusted in function of the evolution of the patient.

In the scientific literature, there are some rehabilitation robotic devices for upper limb rehabilitation based on pneumatic actuation systems, like iPam developed by the University of Leeds [12], Rupert developed by Arizon State University [13] and Pneu-wrex developed by the University of California [14]. Pneumatic actuators originally limited to simple motion between two hard stops, are now becoming more and more popular, and substituting in many cases electric drives. Especially robots intended to cooperate with humans requires drives compliant and safe. The most apparent property of a pneumatic system is that of compliant actuation by virtue of the compressibility of air. Moreover, this kind of actuators can exert enough driving power despite being lightweight and having a small size because the ratio of its output power to its weight is large. Nevertheless, their main drawback is their control due to the nonlinearity nature of air compression. The pneumatic swivel modules have been selected as actuator for the rehabilitation robotic system for upper limbs presented in this paper.

II. SYSTEM DESCRIPTION

The designed robot solution comprises two arm robots, one of three active degrees of freedom to control the patients' hand and one more of three active degrees of freedom to control the movements of the patients' elbow (Figure 1). This configuration tries to mimic the way that the physiotherapists do the manual PNF movements. In a first aspect, the proposed rehabilitation robot is a robotic system for controlling a movement of a user's arm, said robotic arm forming a kinematic chain extending from a proximal to a distal end and comprising a grip for positioning said user's hand at a distal end, characterised in that the kinematic chain possesses redundancy in a distal region, such that the movement of the user's hand can be decoupled from other parts of the kinematic chain. A patient places his or her hand in the grip provided at the distal end. In this region, redundancy in the kinematic chain is provided, which means that the whole kinematic chain except for the hand grip might perform movements while the hand grip (and thus the patient's hand) does not move. This presents a major improvement in comfort and safety for patients and attending physicians. If a certain movement is to be performed, the kinematic chain can normally be moved to its appropriate position without having to move the hand grip. The patient does not need to change his position or orientation and the robotic arm is able to perform all its movements without hitting the patient or physician.

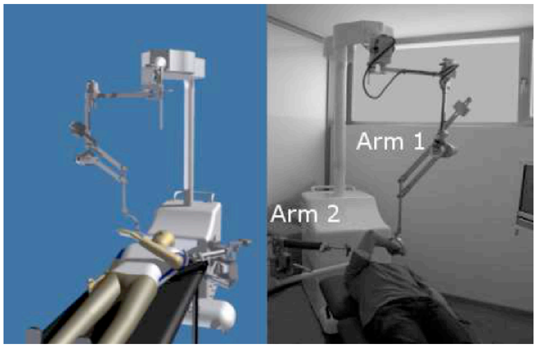

Fig. 1. Pneumatic Rehabilitation Robot

From our point of view, one of the main features to take into account in the design of rehabilitation robotics is safety. For this reason, pneumatic actuators has been selected. Moreover, this kind of actuators can exert enough driving power despite being lightweight and having a small size because the ratio of its output power to its weight is large. In short, a pneumatic swivel module with angular displacement encoder (DSMI manufactured by Festo) has been used as an actuator for each joint. The semi-rotative drives are being controlled by two proportional pressure valves (MPPE manufactured by festo). The valve MPPE is designed so that pressure output is proportional to voltage input through a proportional electromagnet. In this configuration (two proportional valves and a pneumatic actuator), the pressure of the two chambers of the pneumatic drive can be regulated to get a desired output force and to track a desired trajectory [8].

The core of the control system is a motion controller board (DMC-40) manufactured by Galil. It operates standalone or interfaces to a PC with Ethernet 10/100Base-T or RS232. The controller includes optically isolated I/O, high-power outputs capable of driving brakes or relays, and analog inputs for interfacing to analog sensors. Six analog outputs from the DMC-40 board are used to control each pneumatic actuator through two proportional pressure valves. An electronic board(it is called distributor) has been designed to convert each joint's control signal in two voltage inputs for its respective proportional pressure valves(It is assumed that the valves behavior is identical). This enables the pressure difference across the pneumatic drive to be specfied by the control software changes alone and also allows the individual chamber pressures to be regulated by the valves themselves.

Virtual reality combined with mechatronic devices can also improve the results of the robotic therapy. It has been shown that patients can be more successful in their training or their rehabilitation when incentives are used in the train-

Fig. 2. Virtual reality software of the Pneumatic Rehabilitation Robot

ing. Virtual reality can provide this kind of incentives. For example, a patient will normally be interested in recovering movements from everyday life such as grabbing an object from a table. Virtual reality can provide an environment, in which the patient may under the control of the robotic arms grab such an object. Virtual reality can also aid in showing that the patient is improving (since grabbing the object is easier). A computer with a Human Machine Interface based on Virtual reality techniques is connected to the motion control board via ethernet link.

The virtual activities implemented on the control software for the rehabilitation robot presented in this paper can be classified as activities of daily living and activities for therapies based on PNF. The activities within the PFN therapy represent an innovation in this field. In the first phases of PNF therapy, where the patient is fully assisted by the robot, the patient is motivated by his or her own image (like a mirror), through the use of an integrated webcam, to stimulate the mirror neurons. In the phase where the robot offers resistance, the software displays visual activities in coordination with the robots movement to motivate the patient. The start and end positions of the movement and the path of the movement are highlights to be made by the patient. In activities of daily living, the patient is immersed in the virtual environment where he or she performs activities such as taking a glass from the table and drink or placing an object on the shelf. To increase the degree of reality force feedback is applied to real world from virtual world through the robot, e.g. the weight of the object to be handled in the virtual environment, giving the patient a greater sense of reality. Figure 2 shows a capture of the virtual environment software for the pneumatic swivel modules robot.

III. VIRTUAL REALITY

Virtual reality combined with mechatronic devices can also improve the results of the robotic therapy. It has been shown that patients can be more successful in their training or their rehabilitation when incentives are used. Virtual reality software allows to work with the robot in supine or sitting position. The virtual enviroment changes the activities according to the configuration of the patient. This software provides five operational levels in supine position for PNF therapies. Where the level 1 assists completely the movements of the patient's arm. In level 2 assists partially the movement and the intervention of the patient is necessary to complete the movement. In level 3 the patient moves his or her arm with the robot in gravity compensation mode. In level 4 the robot offering resistance to the movement of the patient. Finally, in level 5 the operation is the same than level 4 but offering more resistance. Otherwise the virtual environment proposes activities like games to motivate the patient and a mirror application where the patient see his or her own movement in the screen with the purpose to reactivate mirror neurons. In sitting position the virtual reality provides activities of daily living, like take a glass, drinking and placing object on shelves. The development software creates a necessary virtual world for the activity and the robot creates the interaction between the real world and the virtual world through simulation of the object's weight which is manipulated (Figure 2). These activities of daily living can be adjusted as a function of the evolution of the patient. This is possible by modifying three parameters:

- The size of the object to be manipulated: With this parameter, the accuracy for catching the object is adjusted.
- The amplitude of the movement: The workspace of the patient's arm is modificated depending of the patient mobility.
- The maximum time to execute the exercise:This parameter establishes the maximum time to execute a patient movement depending of his/her skills.

Also visual and sound reinforcements are implemented to motivate the patient when he or she realise any activity succesfully. Otherwise, the implemented software shows images and plays sounds to relax the patient after any activity. Finally, the virtual environment makes a data base with all data patients and their evolution with the aim to make easier the study of the patients evolution and to decide the therapy by the therapist.

IV. CONTROL

The needed torque to move the robot to the target position is determinated by the external control loop. Where the output of this control loop is the input of the pressure control loop. The internal pressure control loop has an additional input to change the exerted torque anytime, see Figure 3.

In the levels 1 and 2, the robot is moved through the position control loop. While in the level 3 zero reference is fixed in the pressure loop to move the robot freely. Otherwise, the resistance of the level 4 and 5 is achieved through the additional input where the input signal is proportional to the patients movement velocity.

The external control loop is responsible of moving the robot in the same way that the therapist did. The combination of both control loops allows to guarantee the patient's safety and the execution of all scheduled activities, in resisted and assisted activities. In the first version of this device is integrated only the described control scheme. In future versions the robot will integrate dynamic control, impedance control and admittance control.

After identification and modelization of the system, different controllers were computed and tested with a good performance in simulation and also with the real system. In Figure 4, the results obtained with a PID controller computed using the information provide by the modelization of the system are presented. It is obviously that there is an error between the reference and the output of the system but this error is less than two degrees. The 3D trajectory of the pneumatic rehabilitation robot is presented in Figure 5. There is a tracking error between the reference and output of the system but the overall precision of the system is enough taking into account that is a robot for rehabilitation therapies and not a robot for industrial tasks.

V. CONCLUSIONS

The pneumatic robot presented was designed with the aim to cover the required characteristics for upper limbs robotic devices to work from the first stages of the rehabilitation (supine position) to advanced stages like activities of daily living. The ability to work both in supine position as seating position that this robot offers, makes it particularly valid in the first stage of rehabilitation that takes place at the hospital and in the following stages when the patient still needed regular therapy sessions. By other hand, this devices meets all functionality and operating capacity requirements like different control levels and virtual environment. The use of pneumatic swivel modules is presented as an innovation on this robot because these modules didnt used in later rehabilitation robots for upper limbs. The developed of the virtual environment has been created with the help of different therapist and neuropsychologist, to take account all the neuronal aspects of the patient to achieve the maximum benefit of the robotic rehabilitation therapy

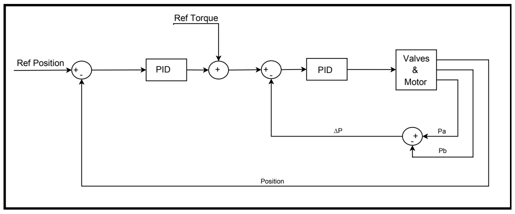

Fig. 3. Control scheme of each joint

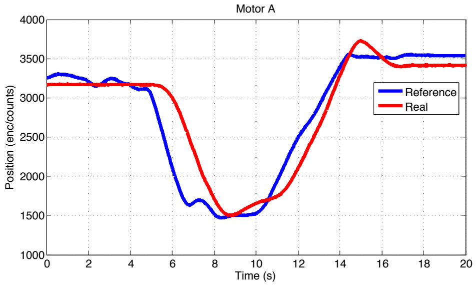

Fig. 4. Results with a PID controller

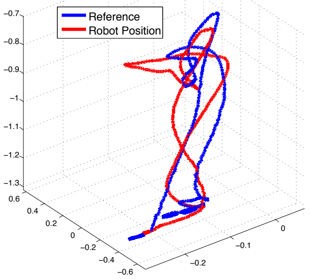

Fig. 5. 3D trajectory

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