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Pneumatic robotic systems for upper limb rehabilitation

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Abstract The aim of rehabilitation robotic area is to research on the application of robotic devices to therapeutic procedures. The goal is to achieve the best possible motor, cognitive and functional recovery for people with impairments following various diseases. Pneumatic actuators are attractive for robotic rehabilitation applications because they are lightweight, powerful, and compliant, but their control has historically been difficult, limiting their use. This article first reviews the current state-of-art in rehabilitation robotic devices with pneumatic actuation systems reporting main features and control issues of each therapeutic device. Then, a new pneumatic rehabilitation robot for proprioceptive neuromuscular facilitation therapies and for relearning daily living skills: like taking a glass, drinking, and placing object on shelves is described as a case study and compared with the current pneumatic rehabilitation devices.

keywords Rehabilitation robots · Pneumatic technology · Upper limb

1 Introduction

According to the World Health Organization, the number of people over 65 years will increase by 73 percent in the industrialized countries and by 207 percent worldwide. By 2050, the percentage of the European population over 65 years should almost double from 12.3 to 20.6 percent (from 40 to 80 million). This age group is particularly prone to cerebral vascular accident, also known as stroke. The relative incidence of stroke doubles every decade for people over 55 years old. In fact, stroke is the leading cause of permanent disability in industrialized nations. Over 920,000 Europeans and 700,000 North Americans have a stroke each year; more than a half survive but often with severe impairments. The main symptoms are loss of muscle strength, spasticity, and lack of coordination of muscle activation [45]. Therefore, an interdisciplinary rehabilitation program to provide integrated care for people that survive a stroke is required. In short, attending motor aspects, speech aspects, visual disturbances, activities of daily living (ADL) and disabling long-term effects like spasticity, stroke survivor can be able to reach sufficient degree of independence on their usual activities. Regarding this, a great number of therapies to help stroke patients in their recovery motor skills have been developed, i.e., Bobath [3], Brunnstorm [37], proprioceptive neuromuscular facilitation (PNF) [12], motor relearning program [8], constraint-induced movement therapy [41], task-related training [11], and bilateral training [27, 42].

The rationale for systematic application of robotics to rehabilitation directly originates from recent findings in medical science which clearly demonstrate how physical exercises based on voluntary movements are able to produce significant clinical results in motor recovery. In fact, such exercises not only promote functional recovery after traumatic central nervous system injury [19], but also promote the neurogenesis process [21]. Moreover, voluntary exercises stimulate mechanisms, mediated by neurotrophic cerebral factors, which enhance neural plasticity.

It is well known how neural representation of body parts is continuously modulated in response to activity, behavior,

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and skill acquisition [20], so a perturbed sensory and motor experience that occurs for the loss of motor output and sensory feed-back induces a deprivation-dependent neural reorganization that affects the body part representation in the nervous system. It seems that these phenomena involve cortical and subcortical areas as thalamus, brainstem, and spinal cord and even the peripheral nervous system. The neural reorganization could follow different types of central and peripheral nervous system injuries such as transient deafferentation, peripheral nerve lesion, amputation, spinal cord and cerebral injury, and damage [33, 6] and regards not only the somatosensory and motor pattern but also the visual system and the auditory systems as well.

The use of robotic devices, as a possible rehabilitation strategy to achieve motor recovery, can be justified because of its potential impact on better therapeutic treatment and motor learning. Researchers have demonstrated the effectiveness of repetitive grasp and release exercises [5], constraint-induced therapy for the paretic limb [40, 44], increased intensity or duration of therapy including external manipulation [10], bio-feedback [49], bilateral movement training [26, 27], and robot-assisted therapy [1, 24, 46, 13] in restoring motor function in the paretic upper limb during acute and chronic stages of stroke recovery. In any case, the therapeutic approach is well structured and repetitive in order to promote cortical reorganization after stroke [31, 38]. Recently, upper-extremity robot-assisted therapy has already achieved Class I, Level of Evidence A for stroke care in the outpatient and chronic care settings; and it has achieved Class IIa, Level of Evidence A for stroke care in the inpatient settings according to the guidelines published by the American Heart Association in the Comprehensive Overview of Nursing and Interdisciplinary Rehabilitation Care of the Stroke Patient [28].

Most of the rehabilitation robots of upper limb therapy are actuated by electric drives. Electric drives are a good selection for robots in typical industrial applications (high accuracy, high mechanical stiffness, and high bandwidth) but not the most convenient selection for robot in rehabilitation scenarios (lightweight, high strength, complaint, and low impedance). Pneumatic actuators can potentially meet the requirements of rehabilitation robots because they have a high power-to-weight ratio, are mechanically compliant because of the inherent compliance of air, and are force controllable. They also have some disadvantages, including non-linearities in both force and airflow dynamics, and the requirement of an external source of compressed air and mechanical noise that is annoying during the rehabilitation therapies. This article is a review of the rehabilitation robots of upper limb therapy actuated by pneumatic drives and the description in deep of a new pneumatic rehabilitation robot for early delivering of rehabilitation therapies.

This article is structured as follows. In Sect. 2, a review of the most remarkable pneumatic rehabilitation robots for upper-extremity robot-assisted therapy is presented including a short description of pneumatic technology at the beginning of this section. Then, Sect. 3 presents a new pneumatic robotic device for early delivering of rehabilitation therapy: its main features/functions, control aspects, advantages/drawbacks, and validation are described in this section. Finally, the advantages/drawbacks of the devices cited in Sects. 2 and 3 are presented and commented in Sect. 4.

2 Review of pneumatic rehabilitation devices

2.1 Introduction

One of the most important issues when developing a rehabilitation robot is the safety in the interaction with humans and even more if people with a diminished motor function like patients with brain damage is considered. There are two possibilities to provide safety during the interaction: by one hand, to provide security by controlling the actuators and on the other hand, to use intrinsically safe actuators to absorb unwanted forces produced by human-robot interaction tasks.

One way to obtain intrinsically safety is using pneumatic actuators; they use air as main energy source. Due to the compressibility of air, these actuators are able to absorb unwanted forces. Another advantage is that the actuators based on this technology have usually a high force/weight ratio. Thanks to this feature, robots are getting lighter and have less inertia, resulting in a more secure system than a system with heavy weights and big inertias. Currently, there are three kinds of pneumatic actuators that are commonly used in robotics: pneumatic cylinders, pneumatic muscles, and pneumatic motors. Pneumatic cylinders provide a linear motion depending on the supply pressure of each cylinder chamber. Typically, pneumatic cylinders consist on two chambers which apply a different pressure to get motion. The main advantage of these actuators is the high force/weight ratio and their main drawbacks are the control due to the nonlinearity nature of air compression and the high flow consumption due to the volume flow used to full fill the cylinder chambers. The pneumatic muscles mimic the human muscles, applying air inside its chamber produces its retraction so the length of the muscle is reduced and an unidirectional linear motion is achieved. Bidirectional motion can be achieved using, e.g., two muscles in antagonistic configuration. Normally, displacement of these muscles is limited around 10–20% of the total length of the muscle. In the same way as pneumatic cylinders, the positioning of the pneumatic muscles is not easy because of their nonlinearity nature and their flow consumption is high as well. Finally, there are several types of pneumatic motors. The most used in robotics are the swivel modules where their operation mode is similar to the pneumatic cylinders but the obtained movement is rotational. In this case, the flow consumption is low and this feature reduces the flow escapes and mechanical noise. On the other hand, there are several control strategies to achieve a safety system for interaction with patients. One of the most used is impedance control, where for a variation in motion, the system produces a change in effort to limit the forces produced. Another strategy is an admittance control, where for a variation in effort, the system produces a change in motion to minimize the forces produced. Due to the use of these control laws, the robotic system acts according to the forces produced by interaction with human, limiting and avoiding huge forces to the patient. The system must be capable of measuring the efforts and the positions of each joint. Therefore, it is often necessary to provide the system with position and force sensors. So, it is necessary to have a control law which would combine position and force signals. As a result, the PID controllers based on position are not enough valid because they ignore the forces produced. PID controllers based on position act according to the error signal produced between reference set-point and real position of robot, without considering the forces carried by the robot. But, control laws such as impedance control modify the behavior of these controllers according to the signals obtained by force sensors or another kind of these sensors. There are several notably robotic devices for upper limb rehabilitation driven by pneumatic actuators. In the following sections, a review of this systems will be presented describing the following main aspects: features/functions, control aspects, performance, safety, and validation/studies. Figures 1, 2, 3, and 4 show different images of the reviewed devices: iPam, Rupert, PNEU-WREX, and SRE. The main features of the presented devices are described in Table 1. In this table, the name of the device, the institute where was developed, the type of device, and a brief description of the system are shown.

2.2 iPam

The iPam was developed by the University of Leeds [17]. It is designed for sitting therapies and it is necessary that the patient is fixed in the chair with a harness. This system uses two symmetric arms with three active degrees of freedom in each robotic arm. One of them grips the patients wrist and the other one grips the patients arm. Also includes three passive degrees of freedom in each grip to the patient. This system can be used in patients with damage in both (right/left) sides due to the symmetry of the robotic arms.

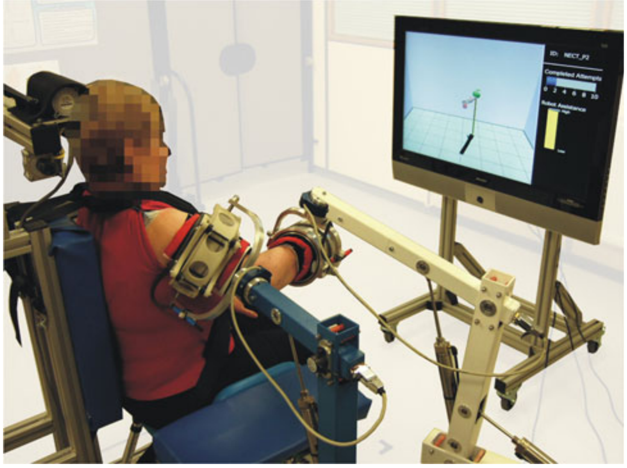

Fig. 1 iPam extracted from [9]

Fig. 2 Rupert extracted from [2]

Fig. 3 PNEU-WREX extracted from [48]

This system is linked to a user interface for the rehabilitation arm exercises with a 3D representation of the patients arm and the targets to aim for. Also the interface

Fig. 4 SRE extracted from [7]

provides information about the session, like the totals of targets and attempts. A comparison between the previous and the current session is displayed. This robot uses low-friction pneumatic cylinders to provide actuation at the active revolute joints which are controlled using six proportional control valves. Regarding the operation mode of the device, highlights the gravity compensation mode where the patient can move freely his or her arm in three planes while the robot supports its own weight and the patients arm weight. Moreover, the hand trajectory mode where the robot which is attached to patients wrist, acts like a gravity compensator and the second arm follows an admittance control allowing patient movement through a trajectory. The third and final mode is the joint control, where both robot arms use an admittance control law to ensure coordination of movements to help the patient to perform the movement of his/her arm. Future works on this device include impedance control of each joint in order to control the dynamic behavior of the interaction with the patient. A key aspect to consider in the operation of this robot is that the position of the two robotic arms should be restricted to the kinematics of the human arm. If the requirements of the kinematics of human arm are not satisfied, the patient may suffer serious damage [18]. For this reason, a cooperative control for both arms has been integrated. Furthermore, this robot is equipped with force sensors to measure the effort made by the therapist and to be replicate later during therapy. The iPam robot was installed in the local hospital of St Mary in Leeds PCT in the UK, within the rehabilitation unit in order to obtain clinical results in trials with patients with disabilities. The test demonstrated the suitability of different modes depending on the severity of patients disabilities [16]. The main advantages of this robot are: comfort, safety, and a simple system to attach to human arms. Moreover, the grip to the human arm is comfortable, safe, and easy to fix. Although, the whole workspace of the two robotic arms and the human arm is validated through the use of a motion capture software and infrared cameras. The main drawback of this iPam system is that the free space usually needed by the therapist to assist the patient during the rehabilitation task has not been taken into account in the design of this rehabilitation robotic system.

2.3 RUPERT

RUPERT was developed by Arizona State University [2, 39]. The main objective of this robot is to assist the therapist in ADL. It can be classified as an exoskeleton robotic device with four active and three passive degrees of freedom. Due to exoskeleton shape, this device only allows its use in the sitting position. The single or multiple targets

Table 1 Pneumatic rehabilitation robots for upper limbs: type and brief description

System	Institute	Type	Brief description
iPam	Univ. of Leeds UK	Dual robot	DoF:6 active/3 passive 2 Symmetrical robotic arms Comfortable grip
RUPERT	Arizona State Univ. Phoenix, USA	Exoskeleton	4 active DoF Wearable exoskeleton Only for one human arm
PNEU-WREX	Univ. of California, Irvine, USA	Exoskeleton, Orthosis	5 active DoF Arm and hand rehabilitation.
SRE	Univ. of Salford, Manchester, UK.	Exoskeleton, Orthosis	7 active DoF Lightweight, about 2 kg Only one grasping point

to be reached and the real-time gesture of the arm are presented to the patient through a virtual reality presentation. The difficulty of therapy is determinate by the targets location and the time required for achieving the objective. It also allows the possibility of daily living tasks as bimanual such as unimanual like grooming, dressing, and eating. This robot, in its latest version, is driven by McKibben pneumatic muscles. These muscles are getting double compression effect by the action of compressed air and passive extension by a spring. The main control element is the gravity compensation that allows compensation of the weight of the patients arm. The control of each pneumatic muscles is via a PID controller with a process of self-tuning ILC (Iterative Learning Controller) for each patient. Therefore, it is necessary prior exercise for the regulator self-tuning to be adapted for the different symptoms of each patient, achieving an adaptive control loop and a feed-forward to increase the speed of system response. Fuzzy rules are used to solve the problem of nonlinearities. As result, it complicates the process of preparing the robot for each patient. Moreover, the control is performed by an embedded PC, so it is possible to plan joint trajectories so that the movements are soft and not sharp, thanks to information from the position and torque sensors built into the robot. This robot has been tested in patients using the Wolf Test [14] to assess the improvement of therapy using this robot. This test quantifies the capacity of upper limb movement by measuring the time between one or more movements and functional tasks. These test demonstrated the potential of RUPERT in improving motion function of the upper extremity of stroke patients, even in patient with more than a ten years stroke history [51]. The main advantages of RUPERT to be noted are: it is a lightweight robot, portable, inexpensive, safe, and easy to use. Another advantage is that it offers active safety by depressurizing the pneumatic muscles and limiting the torque offering by the joints. A disadvantage of this robot is that it has only one degree of freedom in the shoulder, still insufficient for the entire workspace of the human arm.

2.4 PNEU-WREX

PNEU-WREX is a pneumatic-driven robotic device for upper limb rehabilitation developed by the University of California [35, 47, 48] and it is an evolution of a previous work called WREX [32, 34].

PNEU-WREX device is an orthosis for the rehabilitation of arm and hand. This system uses five degrees of freedom, four of them on the shoulder and one for the elbow. This robot is capable of therapies for arm and hand, the therapy for the hand is only for a full opening and closing, like an on-off system. The device is immersed in a virtual environment designed specifically for rehabilitation therapies based on ADL. The system also provides information about the patients progress and, with this information, it is possible to evaluate the therapy progress.

The active degrees of freedom are driven by pneumatic cylinders. Each active degree of freedom uses a pressure low control loop in each chamber of the cylinder to control the force exerted by each cylinder. One valve for each chamber is necessary to implement the loop pressure in each cylinder. To solve the issues of friction in pneumatic cylinders, low-friction cylinders have been used.

It uses a passive gravity compensation to achieve both the compensation of its own weight and the weight compensation patients arm. The philosophy is based on building a sphere around the target point so that the diameter of the sphere is reduced as time goes by integral action. When the patient is out of the area, the high level control commands to the joints pairs so that the end-effector is approaching to the target. If the patient does fall within the sphere, the high control level operate completely free with the gravity compensator. With this operation mode, it is possible to assess patient's progress. An information table for each patient can be created for adapting the control to each patient individually.

The force control of each chamber is based in nonlinear control techniques because of the nonlinear nature of the system [50, 36]. Therefore, it is necessary to install pressure sensors in each camera. Due to control complexity, Kalman filters are used in combination with MEMs accelerometers and two levels of control. Moreover, methods for dead zone compensation in pneumatic systems are implemented [4]. Control runs on a personal computer in real time via a data acquisition card type XPC. So the reliability of the control loop depends on the reliability of the operating system used on the PC. The robot is capable of performing forces up to 89 N with a bandwidth around 4 Hz, what is according to the authors, near the bandwidth of the human arm. There are no published clinical trials with patients using the PNEU-WREX robot. But there are some results with T-WREX. These first studies indicate that the repetitive motor training with T-WREX can reduce motor impairment for chronic stroke survivors with moderate to severe upper extremity hemiparesis [15]. The authors expect similar results in clinical trial with the pneumatic version of the robot. This system intended to be a low cost system, keeping the passive gravity compensation of the previous version, and add only the devices necessary to expand the workspace and make attendance at therapy. As drawback, it has not all natural movement of human arm.

2.5 Salford rehabilitation exoskeleton (SRE)

The Salford rehabilitation exoskeleton (SRE) is a multi-jointed gravity compensated upper arm assistive exoskeleton developed at the University of Salford [22, 23].

This device has an exoskeleton configuration with seven degrees of freedom and three operation modes. With seven active degrees of freedom get the 75% of the complete movement of human arm, it is sufficient to assist in rehabilitation therapies of upper-limb. It is designed to work with adult patients, and is equipped with means of adjustment for each patient. This system has a 3D virtual environment, specially designed for ADL, which displayed several virtual objects on a virtual table and an avatar of the patient. The virtual environment is complemented by a database to store information and progress of each patient. The virtual environment has stored primitive movements so that the therapist determines which of them should be used on the patient. Another possibility offered by the virtual environment is the choice for the therapist to limit the speed of movement of the patient, so that it can be adapted for each patient. A prominent feature of the software is that it has pre-programmed routines for warming up the patients arm thus avoiding possible injury. Moreover, the software includes reinforcements for the patient, like playing music while completing an exercise and stop music when the exercise is over. This robot is based on antagonist configuration of pneumatic muscles which are placed in the base of the robot and motion carried by wire transmission from base to each joint. The muscles in antagonist configuration work very similar to human arm muscles, contributing in this way, more realism and comfort in use. The control law varies depending on the type of operation mode, which can be positioned at each joint, torque control at each joint or impedance control. One operation mode is totally assisted and the robot moves completely the patients arm. Another one is partial assistance mode, where through the biofeedback read the intention of moving the patient and help partially. The third and final operation mode, in which the patient moves freely and the robot returns reaction forces depending on the interaction with the virtual world. Always control of position and torque are separated. The control loop incorporates a force/torque sensor with six degrees of freedom in the wrist of the robot to detect the intention of moving the patient is employed. All control loops are integrated on a PC which is dedicated to control and to communicate with the rehabilitation software running on another computer.

There is no published clinical experimentation with this device. So it is difficult to evaluate the benefit of the therapy with the SRE robot. Although, this device can be used as exercise facility for joints of the upper limb as well as a rehabilitation/power assist orthosis for persons with loss of/reduced power in the limb [43].

A deficiency expressed by the authors is that the mechanical design has a singularity when the arm is parallel to the horizontal. Another drawback of the system is that the torque exerted by the mechanism of antagonistic pneumatic muscle depends on the position of each joint, complicating the control loop. Another fault is that the pneumatic muscle system causes a delay between the desired signal and the performed signal. Although, the delayed signal has the same form as the desired one, therefore, not influence the therapy results.

3 Case study: pneumatic robotic device for early delivering of rehabilitation therapy at Miguel Hernandez University

3.1 Introduction

The design of the rehabilitation robot presented in this section was carried out at Miguel Hernandez University (UMH) and born from the need of automation of delivering 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 axis 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 ADL can be adjusted in function of the evolution of the patient.

Most of the systems designed by engineers for medical applications lack of the involvement of final users of the system at the beginning of the design process of the mechatronic device. In our case, the philosophy of the development process was to involve health care professionals and people with stroke during the development process with the objective of maximizing the acceptation of the system by the end-user and the physiotherapists. The development process was similar to the one described on [17].

3.2 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. 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 upper limb, 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 moving 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.

Both robotic arms are fixed to a mobile structure for transporting the robot. In this structure, the whole electronics, electrical, and pneumatic elements necessary to operate the robot are installed. The upper robotic arm is configured as a scara robot in its first two joints and a mechanical passive gravity compensator is designed for the third joint. In the second robotic arm, the first two rotational degrees of freedom drives are fixed to the structure, providing less inertial forces. The third active joint, a prismatic one, is actuated by a pneumatic cylinder. Both robotic arms are shown in the Fig. 5.

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

Fig. 5 UMH-pneumatic robotic device at clinical institution

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 [25] (Fig. 6).

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 specified 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 training. 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 article can be classified as ADL 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 ADL, 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

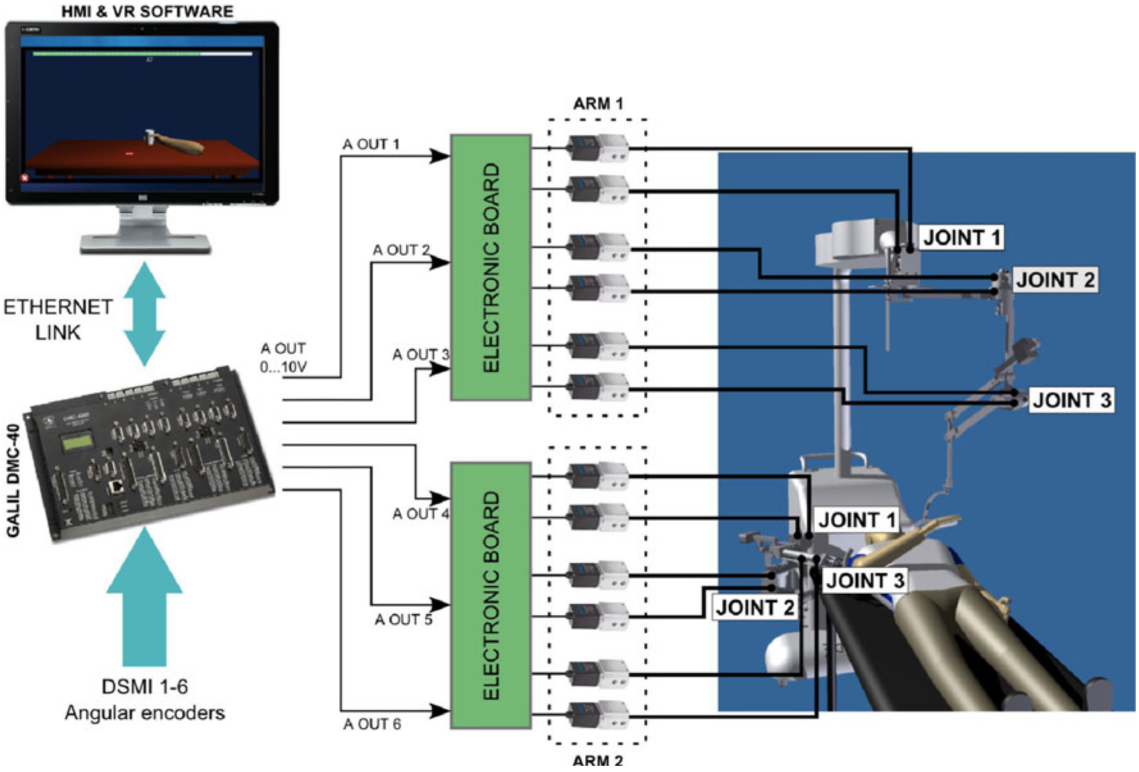

Fig. 6 Pneumatic rehabilitation robotic system: components and interfaces

weight of the object to be handled in the virtual environment, giving the patient a greater sense of reality. Figure 7 shows a capture of the virtual environment software designed for the pneumatic rehabilitation robotic system.

3.3 Virtual reality software

Virtual reality software allows to work with the robot in supine or sitting position. The virtual environment 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 the movements of the patient's arm completely. Level 2 assisting 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 ADL, like taking a glass, drinking, and placing object on shelves, etc. 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 (Fig. 7). These ADL 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 modified 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.

Fig. 7 Virtual reality software of the pneumatic rehabilitation robot

Moreover, visual and sound reinforcements are implemented to motivate the patient when he or she realize any activity successfully. 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.

3.4 Control software

On one hand, this robot device achieves safety from the structure using low-weight materials. On the other hand, the compliance is achieved by controlling the torque exerted by the pneumatic actuators regulating the pressure of their chambers. The needed torque to move the robot to the target position is determined 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 Fig. 8. The combination of the two control loops can ensure both patient safety and the implementation of all rehabilitation activities planned both assisted and resisted. A detailed description of the control system can be found in [29, 30].

The operation modes of this rehabilitation robotic system for delivering PNF therapies can be seen in Fig. 8: acquisition mode and assisted rehabilitation therapy. In the first one, the physiotherapist record the movement patterns of the PNF method only assisted by inertial control algorithm. In the second one, the physiotherapist configure the operational levels and then the robot replicate the movements patterns recorded previously in an autonomous way.

3.5 Validation

The Pneumatic rehabilitation robotic system developed at Miguel Hernandez University is currently undertaking the first exploratory clinical trials. It is planned that more than 50 stroke patients from different local institutions will use the system, accumulating over more that 45 h of robot-mediated therapy per patient during three months. The test of the system with healthy subjects has been concluded with a good level of success (Fig. 9).

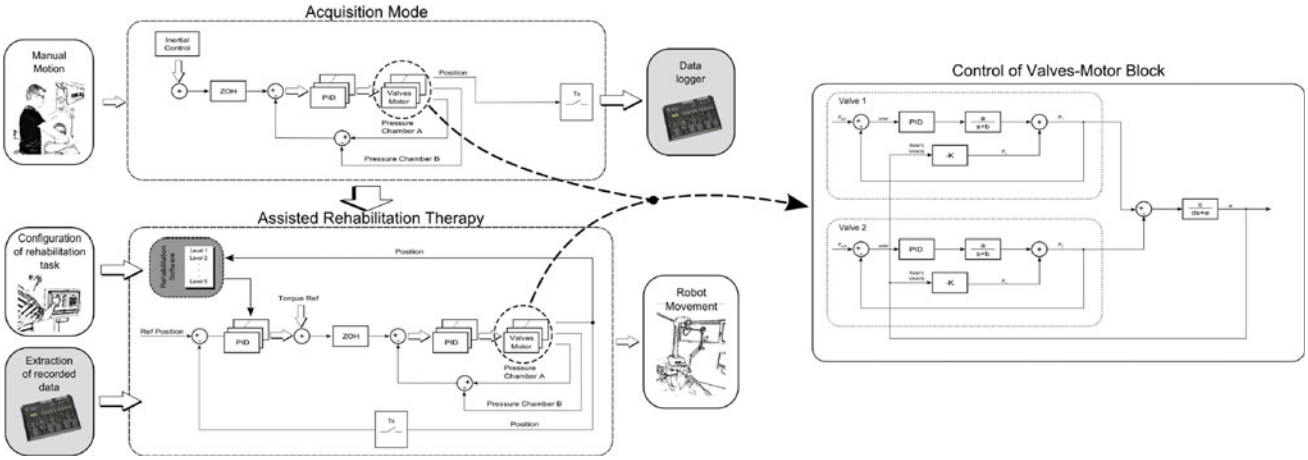

Fig. 8 Pneumatic rehabilitation robot: modes and control scheme

Fig. 9 Test of the system with healthy subjects

4 Discussion

The main important rehabilitation robotic devices for upper limb based on pneumatic technology are presented in this article. A brief description of these robots focusing on the actuator system and control type are shown in Table 2.

They provide intrinsic safety to the system due to the air compressibility, which absorbs the unwanted energy produced by the interaction forces between the robot and patient. Also, control laws used in robotic devices have the priority of acting to prevent damage in patients all the time.

The first step to recovery from stroke occurs when the patient enters to the hospital. Once the doctor determines the type of stroke, establishing the first treatment, administer medication, or surgery in the case of blood clots. The rehabilitation phase usually begins when the patient still remains in the hospital and is medically stable. It is very important to begin the rehabilitation process as soon as possible, to maximize the chances of recovery. Therefore, the patient in this stage of the disease remains in the supine position in bed in the hospital. According to [14], rehabilitation therapy must begin in the acute phase. This important feature for the rehabilitation of stroke patients are not satisfied by the robotics devices reviewed in Sect. 2. The ability to work both in supine position as seating position that pneumatic rehabilitation robotic system presented on Sect. 3 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. On the other hand, seeing the study of workspace available

Table 2 Pneumatic rehabilitation robots for upper limbs: actuators and control system

System	Actuator	Control	Brief description
iPam	Antifriction cylinders	Future impedance control, cooperative control scheme admittance control	Passive gravity compensating
RUPERT	Pneumatic muscles	PID + ILC with self-tuning and fuzzy techniques	Double effect muscles
PNEU-WREX	Cylinders	Two control levels	Passive gravity compensating
		1-Torque/position control	Dead zone compensator for pneumatic systems
		2-Pressure control of chambers	
SRE	Pneumatic muscles	Position, torque, and impedance control	Adaptive root locus
UMH RehabRob	Pneumatic swivel modules	Low level: pressure control of chambers	Proportional pressure valves
		High level: torque/position future impedance control	Two control levels

devices in development today, most have exoskeleton configuration and focus on ADL. As a result, these robots do not allow their use in the early stages of rehabilitation because they are designed for later stages where the patient is required seating configuration. It is noticeable that the pressure in each chamber of the rehabilitation system developed at UMH is controlled by a single pressure valve. In this way, it is possible to control directly the torque exerted by each joint. In addition, after a power failure of the valves or an emergency situation, they return to the exhaust position, depressurizing the chambers, and preventing unwanted torques in the joint. Another important feature is the used of space not used by the therapist to position the robotics arms, so the therapist and the robot can work together. Taking advantage of unoccupied space, usually above the patient, the robot can provide a great workspace. The robot learns how the patient has to move, so a flexible system is achieved and shortening the preparation time in the pre-sessions. On the other hand, the virtual environment of the pneumatic swivel modules robot offers motivation to the patient during the therapy by visual and audio reinforcement. At the end of each exercise, the robot provides pictures and music to relax the patient, increasing the outcomes of therapy. The pneumatic swivel modules robot offers the possibility to work actively, moving the patients arm, or passively, providing resistance to movement of the patient according to the phase of therapy that the patient is.

5 Conclusions

We reviewed the most remarkable pneumatic rehabilitation robots for upper-extremity robot-assisted therapy. Even more, a new pneumatic robotic device 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 ADL has been presented as case study. We can conclude that pneumatic technology can potentially meet the requirements of rehabilitation robots because they have a high power-to-weight ratio, are mechanically compliant because of the inherent compliance of air, and are force controllable. Even though a considerable amount of work has been carry out in this field, there are some issues that are still open, i.e., control algorithms, development of new pneumatic actuators, extensive clinical tests, etc.

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