Design of a new 5 d.o.f. wire-based robot for rehabilitation

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Design of a new 5 d.o.f. wire-based robot for rehabilitation

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Abstract— **In the last three years, a wire-based robot called the NeReBot (NEuroREhabilitation roBOT) was developed at the Robotics Laboratory of the Department of Innovation in Mechanics and Management, University of Padua, Italy. NeReBot is a 3 degrees-of-freedom (d.o.f.) wire-based robot, designed for the treatment of patients with stroke-related paralyzed or paretic upper limb during the acute phase. Although first clinical tests showed encouraging results in terms of motor recovery and functional outcome, the robot presented some limitations.**

Hence a new wire-based robot, called the MariBot (MARIsa roBOT), was designed. The wire-drive philosophy, which makes the robot intrinsically safe, was maintained. Nevertheless, by changing the mechanical structure and adding two more d.o.f. the working space was enlarged significantly. Moreover, thanks to the improved mechanical design, MariBot results much lighter and less cumbersome than NeReBot. Finally, electronic hardware and control software were changed in order to improve man-machine interaction. In this paper, starting from the NeReBot experience, the design of MariBot is presented.

I. INTRODUCTION

Post-stroke rehabilitation therapies aim to make the patient develop new strategies in order to compensate the effects of a permanent disability. It has been proved that including a *robot-aided therapy* into current practice can increase the efficiency of therapists by alleviating the labor-intensive aspect of physical rehabilitation [1], [2]. In fact, each therapy can last longer and one single therapist can supervise more patients at the same time. However, robot-assisted neurorehabilitation goes well beyond the advantage of an increased productivity: different kind of motion strategies (such as passive, aid-assisted or active) can strongly affect the functional outcome of patients after brain injury [3]. Moreover, the increased intensity of standard physical treatment leads to significant results. Intensive treatment delivery is employed not only for upper limb rehabilitation: repetitive practice of hand and finger movements against loads resulted in greater improvements of motor performance and function scales than Bobath-based treatment [4].

Robotic prototypes employed for robot-aided neurological rehabilitation treatments have been improved to the point that they can operate in a reliable, safe and effective way. One of the most famous and successful examples of neurorehabilitation robot is the MIT-MANUS, which is a two degrees-of-freedom (d.o.f.) two-link serial robot designed to interact with the patient's upper limb. In this system, the patient forearm is fixed to the end-effector of the robot by means of a splint, which is guided by the planar motion of the end-effector [5]. A spatial working space is usually obtained by means of multi-d.o.f. serial robots. The ARM (Assisted Rehabilitation and Measurement) Guide, a four d.o.f. robotic device, is an example. It consists of a hand piece attached to an adjustable linear track [6]. Another example is the Wilmington Robotic Exoskeleton (WREX), a four d.o.f. power-assisted arm orthosis [7]. MIME is an even more complex system based on a 6 d.o.f. Puma robot arm, which is attached to the support of the upper limb on the paretic side of the patient. The robot moves the limb in simple predetermined trajectories by directly controlling the position and orientation of the forearm [8].

Although these examples proved to have good performances, the design of future rehabilitation machines must take into consideration the real healthcare environment where such robots operate. To this regard, robots should be easily transportable, especially when acute or sub-acute patients are treated. Moreover, they must be reliable and very user-friendly, as in most cases they are operated by non technical people (physicians and therapists). A third important issue consists in finding a trade off between low cost of the machine and functional outcome benefits. Finally, rehabilitation robots should not have an "industrial-like" appearance, which is not always well tolerated by the patients.

A possible solution to fulfill these requirements is the implementation of *wire-based robots*. Wire-based robots are light and intrinsically safe for patients and therapists thanks to the wire actuation. Several examples of wire-based robots for rehabilitation purposes can be found in the literature. Takahashi et al. presented an upper limb motion robot for disabled people [9]. SPIDAR-G is a 7 d.o.f. wire-based robot which allows the user to interact with virtual objects by manipulating two hemispherical grips [10]. More recently, the Gentle/s project proposed an interesting combination of wire-drive technology and serial robotic structures [11]. The same philosophy was employed for gait rehabilitation [12], [13]. These wire-based robots are usually cumbersome and cannot be transported inside a clinical environment nor they can be employed for domestic rehabilitation because of the complex structure they use to support the wires. For the same reason, they cannot deliver a proper assisted therapy to acute post-stroke patients laying on a bed.

With the aim of overcoming these problems, two prototypes of wire-based robots for upper limb rehabilitation have been designed at the Robotics Laboratory of the

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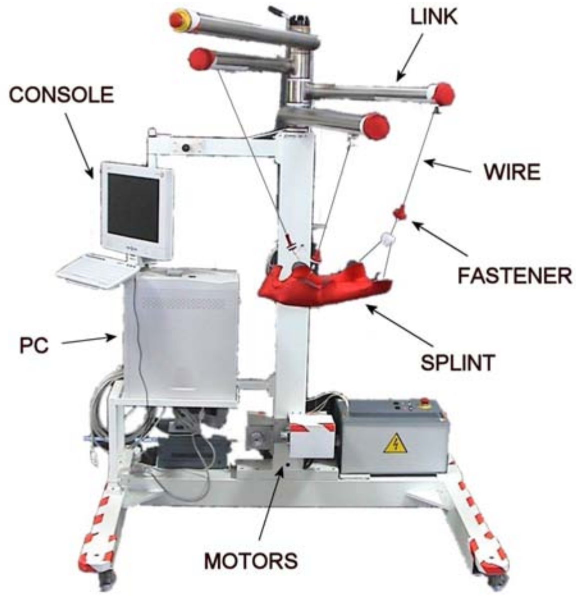

Fig. 1. The NeReBot 3 d.o.f. rehabilitation robot. Three wires are used to move the splint; each wire passes through a manually adjustable link and is pulled by a brushless motor located at the column base. The topmost link can be used to sustain the shoulder by means of a non-driven cable.

Department of Innovation in Mechanics and Management (DIMEG), University of Padua, Italy. The first one, called the NeReBot (NEuroREhabilitation roBOT [14]), was presented at *ICORR2003* and is currently undergoing clinical trials, whereas the second one, called the MariBot (MARIsa roBOT), has just been designed and came up as an evolution of the first prototype. The next section includes a brief description of NeReBot, highlighting the major problems arisen during first clinical tests. The third section, which is the core of the paper, presents the main features of MariBot as well as design details.

II. The NeReBot Experience

The NeReBot is shown in figure 1. The principle is very simple: once the forearm of the patient is fastened onto the splint, the machine can produce sensorimotor stimulation on the upper limb by pulling three Nylon wires (see figure 2). Each wire is connected to the splint by means of a magnetic fastener and is directly driven by a brushless motor located at the base of the robot. A manually adjustable mechanical structure is used to support the wires: each wire passes through a hollow aluminium link which is connected to the main column by means of a rotational joint. Before beginning the therapy, the therapist can set and fix the angular position of each link and the linear position of wire entry points along the links, according to the specific needs of the patient and/or of the exercise.

The NeReBot is programmed to perform repetitive passive movements of the upper limb, and can be used to treat patients both sitting on a chair and laying on a bed. Each exercise is recorded by manually moving the patient's forearm: once a certain position is reached, by pressing a button the therapist makes the control system store motor angular positions (*learning phase*). Hence, the machine interpolates acquired data obtaining cubic-spline joint trajectories which produce a very comfortable motion for the patient (*therapy*).

The control system runs on a desktop PC based hardware, provided with a Quanser PCI MultiQ terminal board for signal I/O. The control software implements both the motion control (a separate PID position control for each motor) and a graphical user interface, used for parameters setting and patient visual feedback. Each motor is equipped with a $1000ppr$ incremental encoder, whereas wire maximum winding speed is set to $100mm/s$.

First clinical trials of the NeReBot gave very encouraging results [15], [16]. Twenty patients with post-stroke hemiparesis or hemiplegia received standard multidisciplinary rehabilitation and were randomly assigned either to early robotic training (*robotic group*, for 25 sessions of about 1 hour per day) within the first week after stroke, or exposed to the robotic device without training (*control group*). Outcomes were assessed by the same masked raters, before treatment began and at 60 days after the stroke. The robotic group demonstrated significant improvement in motor and functional outcome compared to the control group. All treated patients had favorable impressions of robotic treatment, without receiving the unpleasant feeling of being restrained by a machine. There were no side effects.

During the first lab and clinical trials, however, some limitations of the NeReBot came up:

- the robot is *heavy and cumbersome*: transportation and storage are time-consuming and not always easy;
- the *working space* is not always satisfactory for therapists: some horizontal movements of the upper limb cannot be performed properly;
- the pre-tratment *manual set up* of the machine structure is not always performed by therapists in the best way, and the final result is operator-dependent;
- the *hardware/software* configuration does not fulfill the requirements of a hard real-time control system.

In order to overcome these problems, a more complex robot, called the MariBot, was designed.

Fig. 2. The NeReBot during first clinical tests. In this trial, patient's right forearm is fastened onto the splint to receive sensorimotor stimulation.

III. MariBot: A New 5 d.o.f. Wire-Based Robot

The MariBot is depicted in figure 3. The wire driven philosophy, which makes the robot intrinsically safe and well tolerated by the patient, was maintained. However, the mechanical structure was modified by introducing a two d.o.f. serial robotic arm, which is used to move the wire entry points in the horizontal plane during therapy, according to patient's movements. As a result, the working space is much larger with respect to the NeReBot and covers nearly every movement of the upper limb. Moreover, no manual set up of the machine is required before treatment.

The robotic arm is mounted on a commercial patient handling machine (the Marisa by Arjo Ltd.), whose column is an SKF motorized linear module. In this way, the height of the arm can be adjusted very quickly by the therapist (this is a manual, time-consuming procedure with the NeReBot). Moreover, thanks to the design of the Marisa, the new robot results much lighter than the NeReBot and less cumbersome. Also, the MariBot can be easily placed aside a bed or a wheelchair to treat the patient. Nonetheless, the robotic arm could be mounted on different equipment or even on a wall, according to the needs of a specific application.

In order to reduce the robotic arm weight, three gearmotors are employed to drive the wires, instead of using a direct drive pulley-motor system. The main drawback of this choice is that wire tension cannot be estimated properly by simply monitoring motor current, as is for a direct-drive system working in quasi-static conditions (this is the case of NeReBot). In fact, gearmotor friction cannot be neglected.

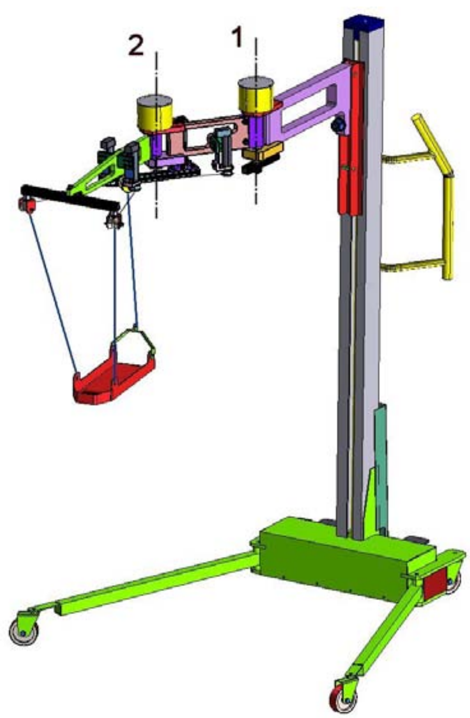

Fig. 3. The MariBot 5 d.o.f. rehabilitation robot. The robot is based on a patient handling machine (the Marisa by Arjo Ltd.), to whom a 2 d.o.f. robotic arm is linked, holding three gearmotors which are used to drive the wires. The two axes of the rotational joints are shown.

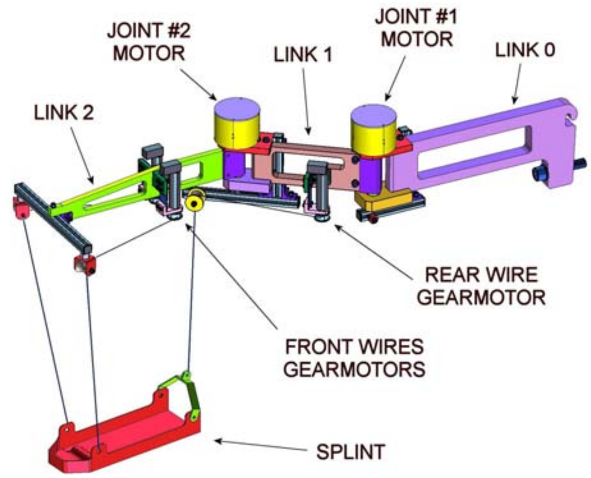

Fig. 4. MariBot arm close-up. The arm is composed of three links: *link 0*, which is to be mounted on the column, *link 1*, to whom the rear wire is attached, and *link 2*, to whom the front wires are attached.

For this reason, the gearmotors are mounted on the links by means of three deformable elements equipped with strain gauges, which provide a measure of wire tension in the range of $0-50N$. Anyway, no direct measure of the force exerted on patient's arm can be obtained. This is the major drawback due to the choice of using only three wires to drive the splint, but we are developing an algorithm to estimate the force exerted on the splint.

During the learning phase, the gearmotors produce a constant wire tension, while joint motors are switched off. Thus, the robotic arm adjusts its configuration according to the therapist-induced movements of patient's upper limb. These sets of joint rotations are recorded together with gearmotors angular positions, allowing the control system to reproduce the motion of both the wires and the mechanical structure during therapy.

A. Mechanical Design

The two d.o.f. robotic arm is depicted in figure 4. As it shows, front wires entry points and gearmotors are attached to link 2, whereas rear wire entry point and gearmotor are mounted on link 1. Different configurations of the entry points have been evaluated (e.g. with all gearmotors and entry points fixed on link 2), but the one of figure 4 proved itself to be the best in terms of motors size reduction.

Since the robotic arm must move freely during the learning phase, joint motors are directly keyed on joint pins. Bayside-Motion frameless brushless motors have been chosen, which are very light ($0.7kg$) and provide high continuous torque (nearly $2Nm$). When the therapist puts the forearm of the patient (i.e. the splint) in a learning position, the robotic arm, driven by wire tensions, reaches an equilibrium point at which joint torques are null (please consider that joint motors are switched off in this phase). By storing and interpolating these joint rotations, the control system is able to plan joint trajectories which require minimum joint torques (less than $0.4Nm$ per joint for a completely passive patient).

Also gearmotors size has been minimized, by choosing proper link dimensions. The wire tensions required to sustain the upper limb of the patient at a given position depend on robotic arm parameters, i.e. link lengths and wire entry points position in the link reference frames. In fact, these parameters affect the equilibrium configuration reached by the robotic arm and hence wire orientation with respect to the limb. Thus, we simulated several therapies with different sets of link parameters, obtaining their optimum values in terms of gearmotor torque reduction (the torque required is in the range $50 - 300Nmm$).

Link shape has been chosen, performing finite element analysis, in order to minimize arm weight without hampering torsional stiffness. As a result, the robotic arm should weight nearly $15kg$ with Ergal7075 aluminum alloy links. The main structure weights nearly $70kg$.

B. Control System Architecture

The control system is based on PC104 hardware, including a Pentium based motherboard, two multifunction I/O boards and a small LCD/keyboard user interface. The control software is currently under implementation using C++ language, and will run in a VxWorks Real-Time Operating System environment. A HTTP server will be executed on the same hardware, to let external users connect and retrieve all therapy data during and after treatment. In this way, not only remote monitoring but also therapist console and patient visual feedback software will run on separate hardware as Java applets, without increasing the workload of the real-time hardware.

The control system will be able to control the position/torque of each joint and the length/tension of each wire. By combining these control actions, both passive and active exercises will be implemented.

IV. CONCLUSIONS AND FUTURE WORKS

This work presented the ongoing evolution of the wire-based robotic approach to the rehabilitation treatment of post-stroke patients. Our main challenge was to deliver the therapy starting from a very early stage, right after the stroke event. For this purpose, a first 3 d.o.f. wire-based robot was conceived, realized and tested in clinical environment. To the best of the author's knowledge, NeReBot is the first robot capable of delivering an early robot-aided post-stroke therapy. The study revealed statistically significant benefits of robotic therapy in persons with stroke-related paralyzed or paretic upper limb. In these patients, an early robotic approach may usefully complement other treatments by reducing motor impairment during both the acute and the chronic phases of stroke recovery.

In order to improve the effectiveness of the robot-aided therapy and eliminate the limitations raised by the use of NeReBot, a new 5 d.o.f. wire-based robot was designed. With respect to NeReBot, the MaRibot will be lighter, less cumbersome, capable of a larger working space and provided with an embedded hard real-time control system.

A key issue in future work will be the implementation of a software with enhanced robot-patient interaction capabilities, in order to deliver a more effective assisted/active therapy.

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