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On the design of an exoskeleton for neurorehabilitation: design rules and preliminary prototype

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***Abstract* — The neurorehabilitation robotics is a promising research field that allows improvements of the therapy effects. Some interesting systems for the neurorehabilitation of the upper limb are based on standard robotic arms and their applicability and effectiveness are based on the presence of patient's residual motor control synergy. On the other side, the exoskeletons overcome the single joint control allowing the full control of the arm kinematics. This paper presents the first results obtained at ARTS lab for the development of an exoskeleton for upper limb, starting from one of its building block that is a stand-alone active orthesis for functional assessment of the human wrist. We are addressing the design with a biomechatronic approach, based on an extensive analysis of the state-of-the-art. The design rules of sensorized wrist orthesis for functional assessment of the wrist and its first prototype are presented.**

Keywords—**Neurorehabilitation, Exoskeleton, Robotic system, Upper limb, Wrist**

I. INTRODUCTION

This paper presents the concepts for designing and developing a sensorized orthesis for functional assessment of the human wrist. It is the first building block of a more complex exoskeleton system intended for rehabilitation and augmentation of the human upper limb. The development of the system has started from an analysis of usefulness of robotic system in neurorehabilitation field and from related state-of-the-art analysis. According to the requirements of functional augmentation, we have defined the architecture of an exoskeleton system for robot-mediated functional restoration and augmentation of the upper limb (see Fig. 1).

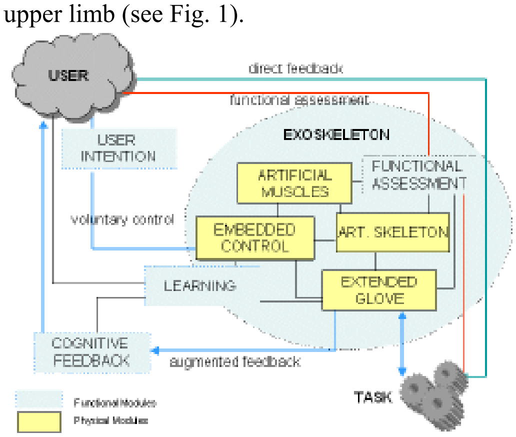

Fig. 1. Architecture of the system for robot-mediated functional restoration and augmentation of the upper limb.

This paper presents part of the work in progress for developing the system described in Fig. 1, with particular reference to the development of the mechanism and the functional assessment module of the wrist subsystem. The module for functional assessment is fundamental in order to provide a continuous quantitative monitoring of the human limb performance while the system is worn and operated by the user. The Section II presents a synthesis of the results of the state-of-the-art analysis of the neurorehabilitation robotics. The design requirements have been described in Section III and the first prototype has been presented in the last section.

II. STATE-OF-THE-ART ANALYSIS

Use of robotic technology in the neurorehabilitation allows improvements of the therapy benefits [1]. Robotic systems are intended to mediate neurorehabilitation therapies that are based on brain plasticity for recovery of motor functions. Classical neurorehabilitation therapies are provided by highly skilled medical personnel. Depending on impairment level, each patient needs at least one or more therapists. This implies an high social cost and may result fatigue for the physiotherapists. In addition, functional assessment of the patient during the therapy depends on subjective evaluation of the physiotherapists thus resulting in a difficult analysis of the rehabilitation process on the same patient and among different patients.

The application of robotic technology, due its peculiar characteristics, provides real improvements in terms of:

- repeatability and accuracy of the therapy,
- disability evaluation,
- objective estimation of patient improvements.

The use of robotic systems allow new scenarios, i.e. for implementing rehabilitation therapies at distance and/or at home [2], [3].

Arm and hand impairment involves important limitation for an independent and active life so our attention has been focused on systems used in upper limb neurorehabilitation. Standard robotic systems and medical devices can be used to perform the rehabilitation task [4],[5]. The end effector of the robotic arm is also the human machine interface and the human arm closes the kinematic chain for achieving the rehabilitation therapy. This approach is not usable for controlling the single arm joints so it is useful in case of presence of residual motor control synergies.

The use of rehabilitation exoskeletons allows the position control of whole upper limb. Due to the extension of human-machine interface to the whole arm the exoskeleton must replicates the human arm kinematic. Such rehabilitation exoskeletons have to support/substitute therapists to operate according to a passive/active assisted/active resistive control mode, and, finally, to evaluate patient progress and/or therapy effects. The application of exoskeletons in rehabilitation field aims to reduce rehabilitation system mass, increase power/weight ratio, ensure subject safety, compliance, simple fitting and removal.

Several arm exoskeletons have been developed for upper limb rehabilitation [6],[7],[8]. In general, these exoskeletons require an external support because they need energy supply (electrical or pneumatic) and weight too much for being sustained by the users. A solution has been proposed by Kobayashi et al. who developed a muscle suit for upper body that provides muscular support to disabled people and manual workers [9]. The Armour suit is actuated by McKibben pMAs and the control system is based on differential pressure measured between the armour type suit and the subject. The suit is light weight and its size is easily adaptable to the user.

Among the different joints of the upper limb that must be naturally coupled with the exoskeleton system, the wrist is particularly challenging because of its complex kinematics and functional anatomy. For example, the first 3 DoFs wrist MIT-MANUS module mounted at the end of the MANUS manipulator is composed of a differential mechanism used to select wrist radial/ulnar deviation or flexion/extension and of a five bares linkage module used to obtain wrist pronation/supination motion. The second MIT-MANUS wrist rehabilitation module uses a differential mechanism for obtaining wrist abduction/adduction and flexion/extension motions and a curved slider for the wrist pronation/supination motion [10].

III. Design requirements

The main points required to design an exoskeleton for human neurorehabilitation are essentially two:

1) the measurement of the movement;
2) the actuation, both active and resistive respectively (the system should exert a force to the subject's limb to provide some movement and should oppose an impedance to the subject's active motion).

The kinematic data collected to determine the movement (position, velocity and acceleration of different limbs) can be used in order to evaluate the range of motion (ROM) and for feedback controlling the actuation system. To measure the movements, the exoskeleton has to modify its configuration in order to follow the natural motion: this implies that kinematics differences between the external mechanism, such as the exoskeleton, and the internal natural one, such as the human "endoskeleton", should be taken into account to extract the anthropometric data from the measurement of the mechanism movement.

Concerning the external mechanism, it must perform: a) a movement following the human motion; b) an independent measurement of different DoFs on the same joint.

The equation describing the natural movement versus the exoskeleton motion may hardly be analytically determined because of the uncertainties about the position of the anatomical axis of rotation. For this reason, a calibration process is needed.

It is necessary to avoid crosstalk that is to obtain the measurement of two or more different DoFs separately and independently. Crosstalk occurs when movement in one anatomical plane causes a false signal in the other anatomical plane [12] (as said above it occurs when two or more movements are measured at the same time). Specifically referring to the wrist, the radial/ulnar (R/U) deviation component can be also recorded during the flexion/extension (F/E) movements and vice versa. Crosstalk can also occur for reasons related to the placement of the system, when the exoskeleton axes are not collinear with the anatomical axes (external).

Other factors that affect the measurement regards the positioning of the exoskeleton. It characterizes the stability of the references and the precision and the repeatability of the measurements.

The stability of the exoskeleton placement depends on the mobility of soft tissues with respect to the bones on which the coordinate frame for relating the measurement is fixed [12]. The error derived can be reduced by an appropriate fastening considering that an acceptable level of comfort must be ensured.

The precision of the alignment with anatomical reference and motion axes, e.g. the forearm axis and the F/E and R/U axis for the wrist, and the repeatability of the exoskeleton placement depend on the possibility of determining the references with respect to natural and easily determinable (external) spot, e.g. ulnar and radial condyles, and on a structure which can easily refers to them for the placement. As said before the precision of the alignment influence the crosstalk (external).

Concerning the actuation, the first and most important requirement is the safety of the subject who wears the exoskeleton.

The mismatch between the exo- and endo- kinematics introduces a (problem) relatively to the respect of the joint functionality. In fact the two kinematics must coexist without interfering with each other. They must be congruent. An abnormal load on the subject can derive from an interference between the two kinematics so when such situation is detected the system must stop (or go backward until the force normalizes). The motion of the exoskeleton must be limited inside the subject's ROM. Mechanical movement stops must be considered as well. The ROM can be measured at the beginning of the wearing process, by asking the subject to perform a movement as wider as possible. Then security controls must be performed: a) on the maximum ROM; b) on the maximum load admitted.

Considerations upon the way the forces are applied are also necessary. First of all the forces applied on the natural joint due to the action of the exoskeleton must be estimated, because the load must not exceed the natural ones. Also the direction and the application point are important to know the torque load on each joint. As a general rule, it is recommended to obtain the highest torque with the lowest force.

Another important issue is the behaviour of the exoskeleton with respect to a disturbance like an unpredictable force suddenly applied to the exoskeleton, e.g. an involuntary contraction in patients with spasticity. The control of the exoskeleton must provide an appropriate compliant behavior for the subject safety. As a consequence, the system must be backdrivable [11]. The backdriveability is defined as a low intrinsic endpoint mechanical impedance [11], or simply as the ability to move a device by pushing on its linkages [3]. It allows the patient to move relatively freely when the actuators are not powered (advisable for the measurement of the movements). For rehabilitation application an impedance-based control is required to exert an appropriate force to the patient limbs, given the unpredictability of their dynamic response [11].

In summary, the main factors involved in the design of an exoskeleton for rehabilitation are:

General issues:

- comfort;

Kinematics issues:

- kinematics relations between the endo- and exoskeleton;
- errors due to internal crosstalk;
- positioning system and anatomical landmarks choice;

Actuators issues:

- safety stop at maximum ROM and at maximum load applied (sustained by the wrist);
- point and direction of forces applied;
- back-driveability;
- impedance control.

IV. WRIST EXOSKELETON PROTOTYPE

A first design of an exoskeleton has been addressed in order to develop a device which can perform the measurement of the wrist movements without internal crosstalk error. A simplified kinematics wrist model has been used, although the fact that the differences between the model and the anatomical way of performing the movement could be a source of crosstalk. The axes of motion of the wrist (of F/E and of R/U) have been considered orthogonal and intersecting in a single point inside the capitate bones, determined by external anatomical landmarks as reported in [13].

The exoskeleton mechanism is based on two cables passing through two guides placed laterally on a chain like mechanism and they are fixed on the same point on the hand splint (see Fig. 2). During the F/E the displacements of the cables are symmetric while during the R/U they are antisymmetric. Thus it is possible to determine the F/E angle by extracting the mean value from the two measured displacements and the R/U angle from the differential value. The chain must keep fixed the distance between the two cables over the wrist: in this way, during a combined movements, the measurement of the differential value and, consequently, of the R/U angle, does not result affected by the cables winding around the curved surface of the wrist.

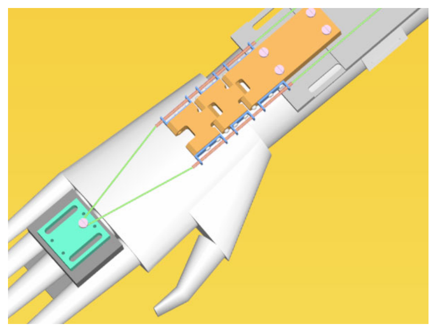

Fig. 2. Exoskeleton 3D CAD model.

Although a calibration procedure is required, an analytical description, even if approximated could be useful for the results analysis. For the F/E movement, a linear relationship between the symmetric displacement and the F/E angle (φ) can be used:

$$\Delta l_{symmetric} = k \cdot \varphi$$

with k = constant, function of the wrist height and of the set up of the device.

Concerning the R/U deviation, as shown in Fig. 3a), the equation which correlates the displacement Δl of a single cable and the R/U angle is not linear, but can be considered linear inside the physiological range of motion (-30° ÷ 15°, radial deviation positive). An investigation has been conducted about the dependency of Δl in respect with the parameters h and r, where h is the distance of the cable from the forearm axis, and r, or better its differential value, it is proportional to the symmetric displacement.

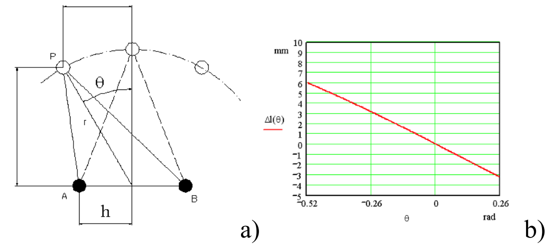

Fig. 3. a) Kinematic scheme of the R/U movement, b) $\Delta l(\vartheta)$ function in the ROM.

$$l(\vartheta) = \sqrt{(r \cdot \cos(\vartheta))^2 + (h - r \cdot \sin(\vartheta))^2}$$

$$\Delta l(\vartheta) = l(\vartheta) - \sqrt{r^2 + h^2}$$

As shown in fig. 4a) the displacement Δl, is as bigger as higher is the value of h, so it has to be magnified as possible but taking into account the width of the distal forearm, because it must not be exceeded.

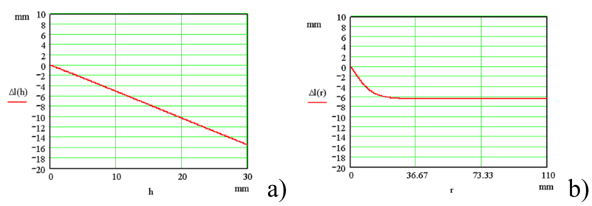

Fig. 4. a) $\Delta l(h)$ function, b) $\Delta l(r)$ function.

For what regards r, the graph in Fig. 4b) shows that Δl results independent from r, over a certain value of it. This statement affirms the theoretical absence of internal crosstalk.

A prototype of the exoskeleton has been built and a first set of trial has been performed (see Fig. 5).

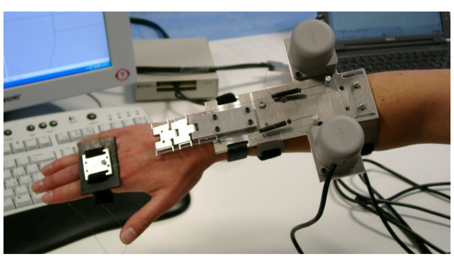

Fig. 5. Wrist exoskeleton prototype.

CONCLUSION

First results, presented in [14], show a good behavior with respect to the internal crosstalk, but the exoskeleton is still affected by errors due to the external crosstalk (consequence of the skin mobility and the misalignment between natural and reference axis). Future works will be focused on the design of a better placement system and then the analysis of the actuation will follow.

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