UPPER LIMB EXOSKELETON FOR MOTOR CONTROL

Arturo Forner-Cordero, aforner@usp.br
Andrey Bugarin Miranda, andrey.bugarin@gmail.com
Andre Yuji Yasutomi, yuji86@hotmail.com
Luis Filipe Rossi, luisf.rossi@gmail.com
Andre Luis Lima de Oliveira, and.snakes@gmail.com
Tarcisio Antonio Hess-Coelho, tarchess@usp.br

Biomechatronics Laboratory
Department of Mechatronics and Mechanical Systems Engineering
Polytechnic School, University of Sao Paulo
Av. Prof. Mello Moraes, 2231 - Cidade Universitária. 05508-030 - São Paulo-SP - Brasil

Abstract. *The goal of this work is the design and construction of an upper limb biomimetic exoskeleton actuating on the flexo-extension motion of the shoulder, elbow and wrist. There are several aspects to be considered in the design that involve, mechanical, electrical and control aspects. With respect to the mechanical part it is important to align the exoskeleton joints with the corresponding human joint centers in order to maintain kinematic compatibility. However, it must be taken into account that the axis of rotation of the human joints vary with time. Another relevant aspect in the design is the power transfer between the exoskeleton and the human body. This is done through the mechanical interface of the exoskeleton with the body segments. Therefore, it is necessary to place the higher pressure contact points on body locations that are able to support this load and it is needed to measure the interaction forces in order to control the forces applied on the subject. In this context it is very important the actuator choice. An ideal actuator would have a high power density, low consumption and reversibility. In this exoskeleton standard electrical DC motors with series elastic actuation are used. It is important to include different types of sensors in the exoskeleton design, these include force sensors and joint angle encoders to develop different control strategies, such as impedance control or interaction force suppression. In order to control the exoskeleton, it is used an embedded PC architecture along with a multichannel network with serial multidrop communication. This hierarchical architecture based on a central computer (PC-104) and local microcontrollers forming a network of sensors and actuators. In this way it is possible implement local control loops mimicking a hierarchical biomimetic control architecture. Therefore, the development of the motor control model will be based on physical (joint torques) and sensory (tendon vibration) perturbations of the upper limb reaching task, in order to register joint angles, interaction forces and EMG. The ultimate research focus of this work is the study of human motor control from an engineering perspective. The exoskeleton is a sophisticated experimental setup that will be used to study motor control of healthy volunteers and, at later stages, for the study of functional compensation of people with motor disabilities.*

Keywords: *Exoskeleton, Rehabilitation Robotics, Upper limb, Motor control, Biomimetics*

1. INTRODUCTION

Rehabilitation robotics is a multidisciplinary field of research that aims to develop suitable platforms to provide therapies for patients with neurological diseases. In this context, this work deals with the design and construction of an upper limb biomimetic exoskeleton actuating on the flexion/extension motion of the shoulder, elbow and wrist.

The paper starts with a brief review on the subject. Then, the concept design is presented, followed by the description of the exoskeleton main subsystems. Next, the preliminary results are shown and the conclusions are outlined.

2. REVIEW

Rehabilitation is a relevant concern in industrialized countries since the incidence of disability varies between 8% and 20% [1]. The causes of the disability rise are not due to a growth of occasional severe injuries but mainly because of the aging of the population.

In addition, cerebral vascular accidents (CVAs), often called “strokes”, became an important cause of disability affecting older people. They occur when the blood supply to the brain is interrupted either by a blood clot or internal bleeding. Due to this interruption, some parts of the brain do not receive fresh oxygenated blood and neurons in that region die. Depending on the region of neuronal death, control, sensory or cognitive functions may be lost or impaired [2].

Fortunately, the human neuromuscular system exhibits use-dependent plasticity, which means that use modifies the properties of neurons and muscles, including the pattern of their connectivity, and thus their function. Hence, the process of neuro-rehabilitation explores such plasticity in order to assist people relearn how to move following neuromuscular injuries or diseases. However, neuro-rehabilitation requires skilled therapists, including physical, occupational and speech therapists. This costly process is also time-consuming, involving daily, intensive movement practice over many weeks. On the other hand, robots could deliver at least the repetitive parts of movement therapy at lower cost than human therapists, allowing patients to receive more therapy. Consequently, rehabilitation robotics emerges as a research field seeking to develop robotic systems that help persons who have a disability with necessary activities, or that provide therapy for persons in order to improve their physical or cognitive function [1].

Basically, the research on rehabilitation robotics relies on the development of two distinct platforms. The first platform corresponds to a device, usually an open kinematic chain robot [3], which the patient interacts with by holding a stick attached to the robot end-effector. MIT-manus [4], MIME [5] and GENTLE/s [2] are remarkable examples of this approach. On the other hand, the second type of platform is the exoskeleton [1, 6, 7, 8]. Such device is actually worn by the patient, either attached to his/her upper limb or even the lower limb.

In nature, exoskeletons are found in most of invertebrate animals, namely, insects and crustaceans [9]. Support, protection and sensing constitute their basic functions [10]. Similarly, artificial exoskeletons have being developed not only for rehabilitation purposes but also for teleoperation [11], human performance augmentation [7] and virtual reality [12].

In general, exoskeletons are composed by a structural mechanism with joints and links, which is worn by the human. Hence, the whole kinematic structure usually performs either the same or even less than the number of independent motions provided by the human body. Perry et al. [13] as well as Kiguchi and Fukuda [7] developed exoskeletons for the upper limb with 7 and 4 degrees of freedom, respectively.

If the exoskeleton has a non-actuated mechanism with sensors placed to monitor the joint angular displacements, the main purpose is patient´s diagnosis. On the other hand, in exoskeletons where actuators are installed, the goal is to guide or to impose some resistance over the patient´s limb. In this case, the purpose is therapeutic.

In actuated exoskeletons, most of the employed actuators are electrical motors. However, Jeong et al. [14] employed only pneumatic actuators in their exoskeleton based on parallel mechanisms.

Once both the exoskeleton mechanism and the selected application are defined, various control algorithms were proposed [4, 13, 15]. EMG-based control is often used for control of the robotic systems since EMG signals of user's muscles directly reflect the user's motion intention [7]. In fact, incorporating muscle models (myoprocessor) and taking advantage of the electromechanical time delay in human neuromusculoskeletal physiology, the system can predict the operator's intention before the onset of movement and, consequently, integrate the patient and exoskeleton [13].

Moreover, when the levels of the muscle activity of the patient are little, the exoskeleton is controlled based on a wrist force sensor to avoid the operation failure [7]. On the other hand, when the user activates the muscles, the force sensor signals are ignored and the EMG-based control is applied.

However, the implementation of the EMG-based control is not easy to be accomplished due to some difficulties. Among them, we can mention: the activity level of each muscle and the way of using each muscle for a certain motion is different between persons; the real time motion prediction is not easy since many muscles are involved in a joint motion; and one muscle is not only concerned with one motion but also another kinds of motion [7].

Another different approach is the bio-inspiration for designing such assistive robotic devices [16]. Biological systems demonstrate impressive performances, for instance, adaptation, ability to learn and robustness to failure. Hence, physical or engineering models of biological systems might provide some guidelines about understanding biological behavior and, consequently, improve exoskeleton design [16].

3. CONCEPT DESIGN

In order to develop a suitable robotic platform for the upper limb therapeutic rehabilitation, we followed some fundamental directions:

- The exoskeleton must not impair the voluntary movements of the user. In this way, it will not interfere with the healthy motions.
- The platform should be able to guide the disabled limb through some basic motions. These basic motions will be defined according to requirements based on therapy movements and activities of daily living.
- The actuated mechanism should be light with low structural complexity.
- The whole platform has to be safe for both the patient and operator
- The device shape and the control strategy should be bio-inspired.

In addition, the conceptual design focused on the statement of the platform requirements and the development of two main subsystems: mechanical and control.

3.1 Requirements

The exoskeleton must work in cooperation with the human upper limb. Among the degrees of freedom available in a typical human upper limb, only three of them will be actuated. More specifically, there will be actuation at the flexion-extension movements of the shoulder, elbow and wrist. The other degrees of freedom (dof) will be designed with a passive stiffness. When sizing the mechanism components and the actuators, we have to consider the associated data of a user with a maximum of 100 Kg. For such individuals, the upper limb total mass is approximately 0.024 multiplied by the total body weight (2,4 kg). For safety reasons, the control must take into account the angular displacement range in each actuated joint. The whole platform should be built in such a way to allow mounting either on a fixed frame or on the user´s trunk. Moreover, another important requirement is backdriveability, which means that there should be some compliance between actuator shafts and the actuated joint.

3.2 Upper limb joint description

The upper limb ranges from the shoulder to the fingertips and it is commonly modeled with three segments: arm (formed by the humerus between shoulder and elbow joints), forearm (with the radius and ulna between elbow and wrist) and the hand. These segments are linked by three groups of joints: the shoulder, the elbow and the wrist. The bones that form the upper limb are the clavicle, which is joined to the trunk, the scapula, the humerus in the arm, the radius and ulna in the forearm, and the bones of the wrist and the hand: carpal bones, metacarpals and phalanges.

The motion of the upper limb has been thoroughly described from an anatomical perspective. However, the conventions in anatomy used to describe the motions or medical motion description are not directly applicable to describe technical motions. The reason is that the medical motion is based on a set of rules that could be ambiguous in some circumstances. For instance, flexion and extension movements are those that decrease or increase, respectively, the angle between two adjoining bones, such as bending the elbow, which decreases the angle between the humerus and the ulna. Abduction and adduction movements are the movements in that bring the limb away or towards, respectively, the mid-line of the body. For instance, abduction of both legs spreads the legs. In addition, there are rotation movements that are those occurring around the major axis of the limb.

The shoulder complex is composed by two joints, the acromio-clavicular and the gleno-humeral joint. Moreover, the steno-clavicular joint also contributes to shoulder motion. Nevertheless, most of the shoulder motion can be modeled with the gleno-humeral joint (range up to 90º of arm elevation). It is a ball and socket-type synovial joint formed by the hemispherical head of the humerus (upper arm) and the glenoid cavity of the scapula. This arrangement allows three degrees of freedom comprising the clavicle, scapula and humerus. The shoulder complex show a compromise between the mobility afforded by the ball and socket configuration and the stability provided by the muscles and ligaments and cover about a 65% of a sphere [16]. Considering the simplifications previously mentioned it is possible to approximate the shoulder joint with three dof's. These motions have been described as:

- Flexion-extension. That is the movement that ranges from 130º in flexion to 30º in extension.
- Abduction-adduction. The range of motion of the shoulder can attain up to 180º in abduction and 50º in adduction.
- Rotation. This is movement around the long axis of the humerus. Rotation can be medial (endorotation) with approximately 60º or lateral (exorotation) that can reach up to 90º.

The elbow joint links upper and lower arms. It is composed of three different joints (humero-ulnar, humero-radial and radio-ulnar). However, it can be assumed as a joint with two dof's:

- Flexion-extension. Elbow flexion is the approaching of the forearm and the upper arm, while extension is the opposite motion. In this case, the elbow functions as a hinge joint between the distal end of the humerus and the proximal ends of ulna and radius. The range of flexion-extension motion varies between full extension, (usually considered as 0º) and active maximal flexion that can reach up to 145º. However, for practical purposes most of the activities of daily life require a range of elbow flexo-extension between 30 and 130 degrees. As the elbow is usually modeled as a hinge joint an important consideration in the exoskeleton design is the orientation of the rotation axis of the hinge. It is slightly oblique, with the medial side below the lateral side, resulting in a 5 to 6 degrees of inclination with respect to the perpendicular to the longitudinal axis of the humerus crossing at the lateral epicondyle.
- Pronation-supination. This is the rotation around the long axis of the forearm and these motions are defined from a reference with the elbow flexed at 90 degrees and the hand parallel to the sagittal plane (a plane parallel to the median plane, which divides the body in two symmetric parts) with the palm of the hand inwards and the thumb upwards. Pronation is the rotation that brings the palm of the hand downwards and the thumb to a more medial position. Maximum rotation is 80 degrees. Supination is the rotation of the forearm so that the palm is upwards, and the maximum rotation is 85 degrees. The axis of rotation crosses the distal and proximal radio-ulnar joints.

The wrist is a very complex multi-joint ensemble because it combines high mobility with heavy loads. It can be modeled with two degrees of freedom:

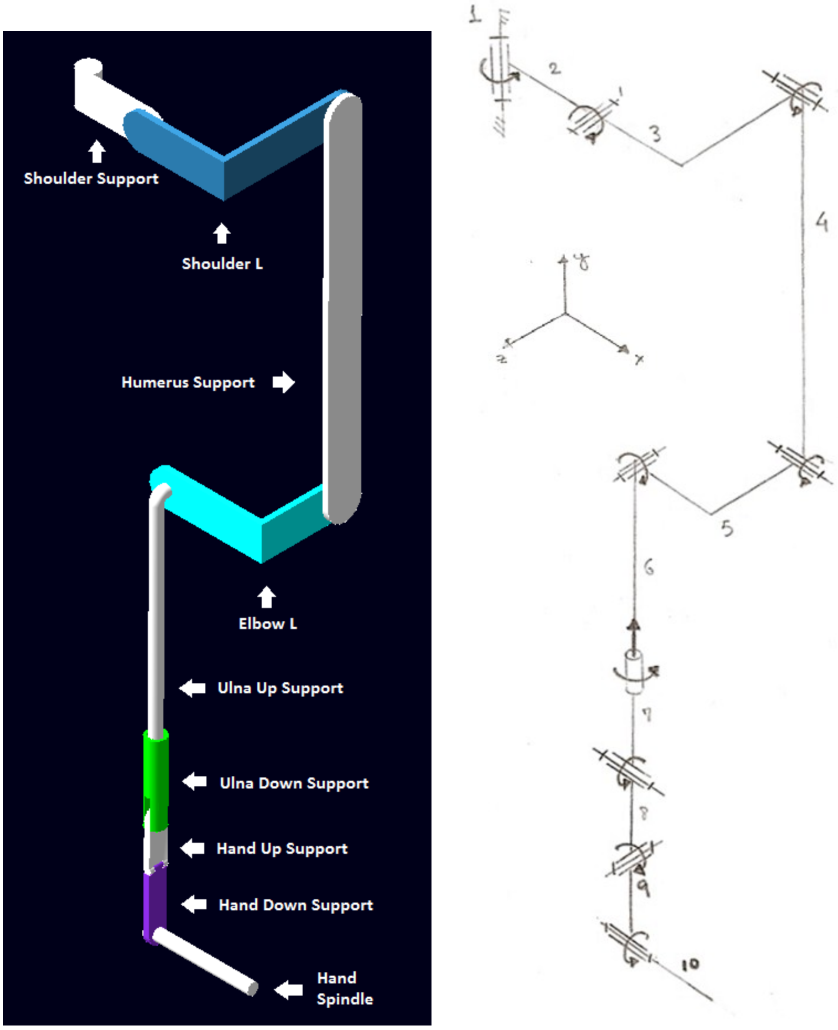
- Flexion-extension. Flexion of the wrist is the movement that approaches the palm of the hand to the forearm, while extension is the opposite. There are large inter-subject differences in the ranges of motion of the wrist but it can range from up to 90º in flexion to 80º in extension. It must be noted that wrist extension also involves some abduction (radial inclination).

- Abduction-adduction. This is the movement of the hand either towards the ulna (adduction) or towards the radius (abduction). Adduction reaches up to 30 degrees, while abduction is below 15 degrees. The wrist has to deal with heavy loads while requiring high mobility and precision [16].

3.3 Subsystems description

Regarding the mechanical subsystem, basically, it is composed of the links and the revolute joints of a 10-dof open kinematic chain mechanism. The direction of the joints rotation axes are selected in accordance with the available independent motions of the human upper limb. Section 4 describes, in more detail, the conceived structural mechanism, the associated models and the performed simulations.

The control subsystem includes the actuators, the sensors and the hardware chosen to provide the prescribed movements for the moving parts. It was decided to implement the hardware in a modular approach, which means that three identical modules will be used to power their correspondent joints. In addition, the controller will be based on a biomimetic hierarchical control strategy, meaning that there will be local and central decision levels. The control subsystem is briefly described in section 5.



(a) (b)

Figure 1. Exoskeleton structural mechanism: (a) CAD-model; (b) kinematic diagram

4. MECHANICAL SUBSYTEM

The upper limb exoskeleton is a 10-dof structural mechanism. Nevertheless, in this prototype only three degrees of freedom will be actuated independently. The other seven will be employed to allow some additional mobility to the user, without limiting any natural movement of his/her upper limb. In addition, the degrees of freedom are distributed along the exoskeleton as follows: three for the shoulder, two for the elbow, two for the forearm`s middle, two for the wrist and one for the hand. Figure 1 shows the exoskeleton CAD-model and its kinematic diagram.

The shoulder support`s revolute joint will be engaged in a vest worn by the user, located in the region of the Trapezius muscle in order to minimize the limitation of the shoulder movements. (Figure 2).

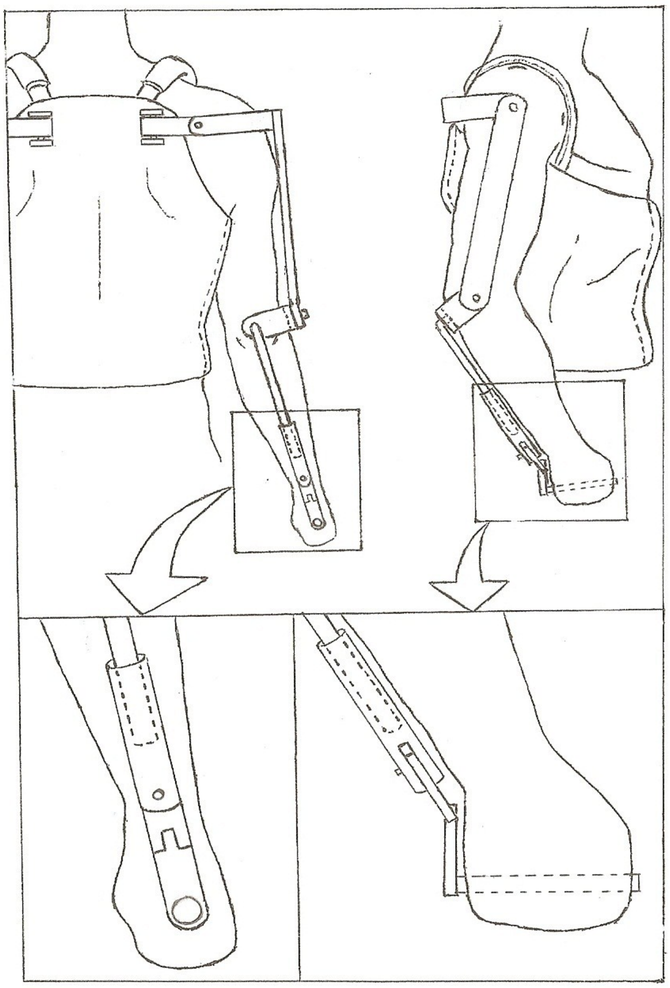


Figure 2. Back and side views of the user wearing the exoskeleton

The two degrees of freedom in the middle of the forearm (cilindrical joint) were added in order to avoid that the fixation of the exoskeleton to the forearm would slip during elbow flexion, extension, pronation and supination, providing the user more comfort while using the exoskeleton.

Also with the purpose of providing comfort to the user, a degree of freedom in the hand was added, in order to provide a rotation of the hand spindle during the flexion and extension of the elbow.

Regarding the exoskeleton computational model, it was built in the software INVENTOR (Autodesk, Inc). However, as soon as the simulations of the exoskeleton behavior became crucial for the development of the project, the model was converted to run under the simulation program ADAMS (MSC software, Corp). All parts will be made from aluminum with the purpose of reducing the exoskeleton mass. Simulations were performed to test if aluminum would be able to bear the loads without suffering too large deformations.

The three actuated degrees of freedom in the exoskeleton will provide the shoulder, elbow and wrist flexion and extension motions. Figure 3 shows the motions of the human shoulder, elbow and wrist, along with the exoskeleton.

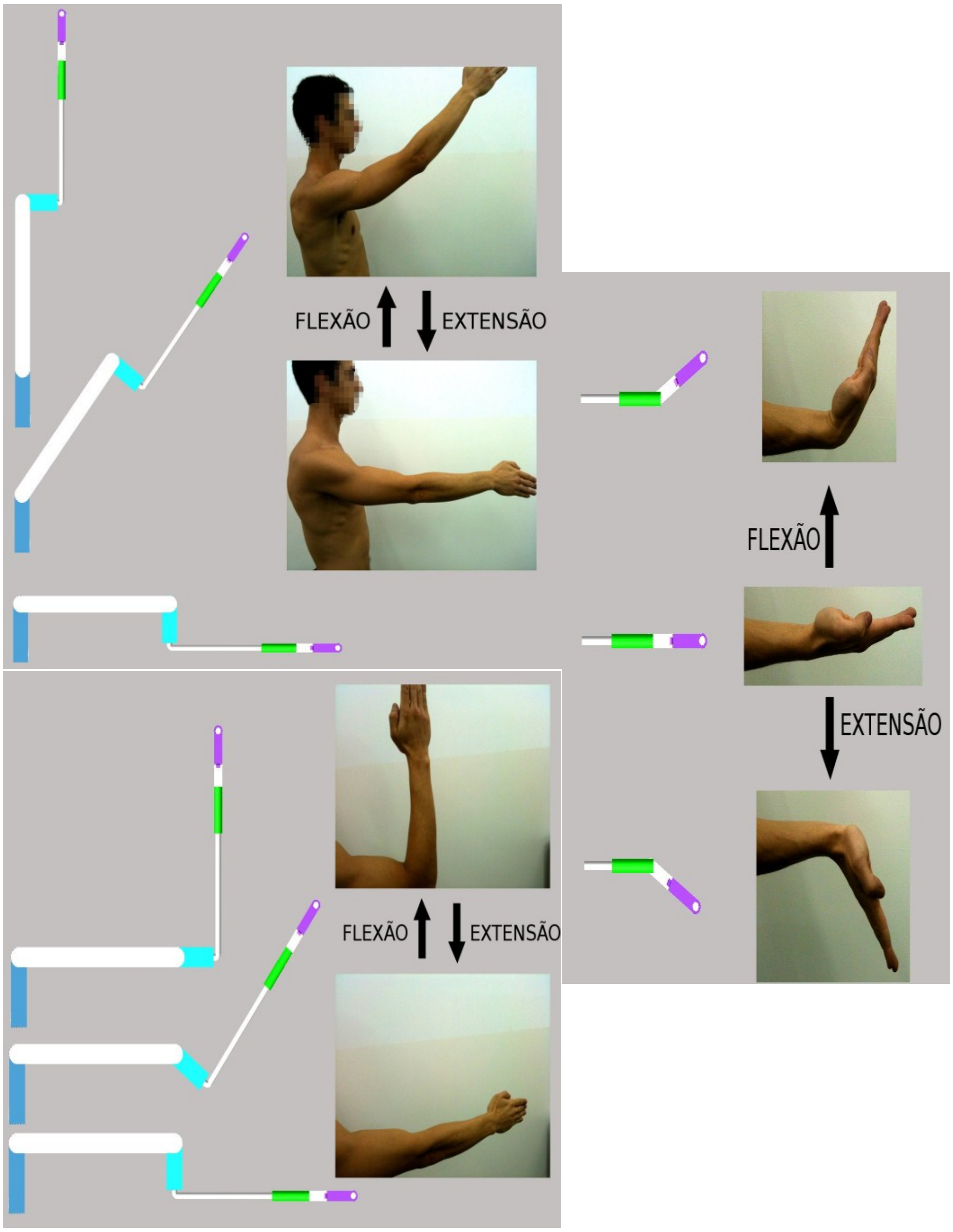


Figure 3. Three configurations of the exoskeleton during the flexion/extension of the shoulder, elbow and wrist. In detail, the conventions for the flexion/extension motions of the human shoulder, elbow and wrist.

5. CONTROL SUBSYSTEM

As described before, a modular, distributed and hierarchical approach was implemented. Basically, the control subsystem is composed of a Central Processor, a Communication Network and Nodes. The Nodes are responsible for the local distributed processing and for the interface with the sensors and actuators. A very simplified scheme of the subsystem can be seen in Figure 4.

5.1 Central Processor

In order to achieve processing performance and strict timing control, the Central Processor should be a high-end digital signal processor with a float-point unit, running a lightweight real-time operating system. However, for academic and research purposes, it is more suitable to employ a standard PC computer with a very compact size, because that would allow the use of third-part programs, as Matlab/Simulink (The Mathworks, Inc), and a friendly programming environment that facilitates the implementation and modification of different control architectures. Therefore, a computer with a PC/104+ form factor and an Intel ®Atom™ processor was chosen to be the Central Processor. To guarantee third-part tools compatibility and minimum real-time behavior, a Linux with a real-time patch is used as the operating system.

5.2 Communication Network

The physical layer of the communication interface between the Central Processor and the Nodes was chosen to be the M-LVDS(TIA/EIA-899), a multidrop differential-signal standard. Its multidrop capability enables a reduction of the number of cables crossing the joints, improving the system's reliability without compromising the noise immunity due to the differential signaling. Finally, the SN65MLVD206 was chosen ti implement the transceiver. Once this state-of-art transceiver allows a maximum 200Mbps baud rate, well above the current requirements of the exoskeleton.

For the data-link layer is used a standard asynchronous communication with one start bit, one stop bit, 8 bits of data and one bit to differentiate address from data bytes. In order to deal with all the data-link layer overhead (address filtering, cyclic redundancy check, etc…), a Network Interface for each node was implemented on a FPGA. As for the Central Processor, a Network Controller was implemented on a FPGA, that is responsible for dealing with the data-link layer, bus arbitration, data flow controlling and to work as a bridge between PC/104+ PCI Bus and the M-LVDS Bus.

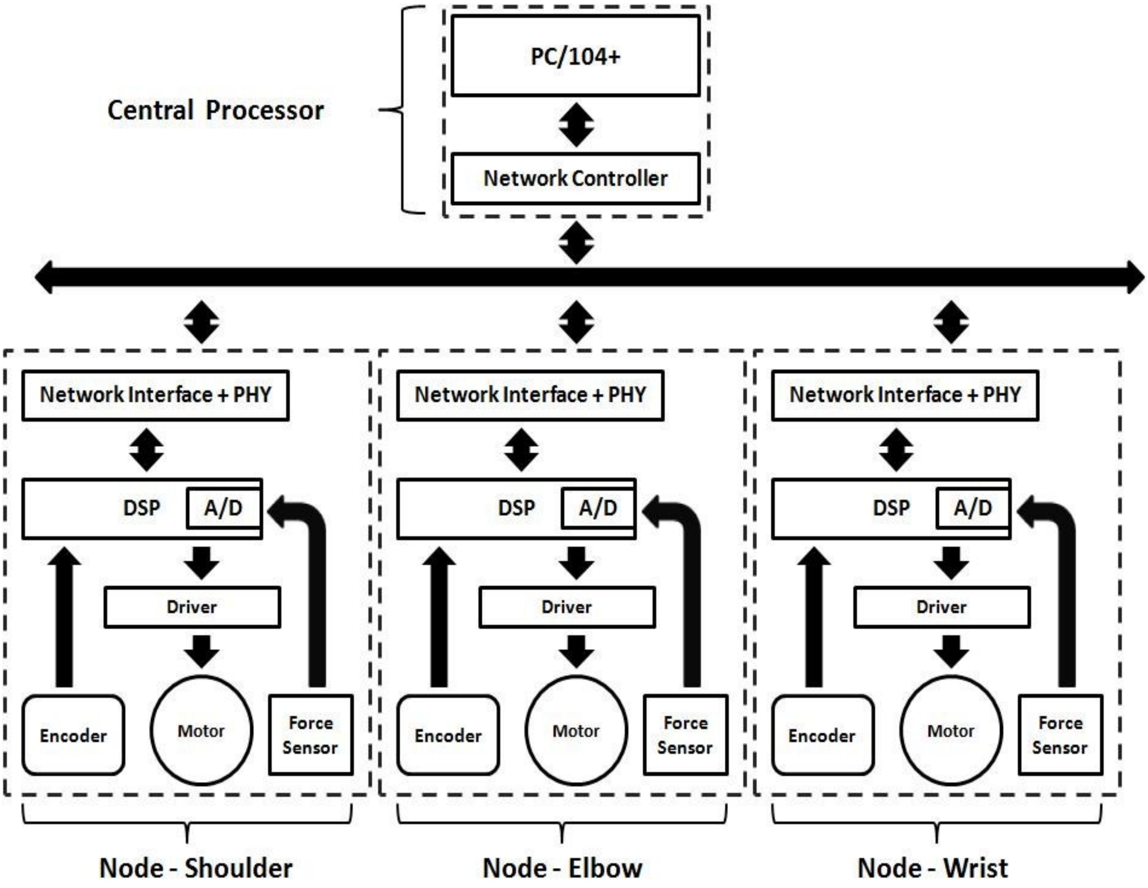


Figure 4. General architecture of the control subsystem

5.3 Nodes

All tree nodes are composed by the same hardware: an actuator (DC motor) coupled with an encoder and the appropriate analog front-end for driving it, force sensors with the appropriate signal conditioning, a DSP and a Network Interface with a M-LVDS transceiver. For the DSP, the TMS32028335 was chosen due to the availability of sixteen PWM channels, two quadrature encoder interface, sixteen Analog to Digital Converter channels, a Floating-Point Unit and a maximum of 150MHz processing frequency [17]. All of these features make it very suitable to control the DC motors (both brushed and brushless) and to run the bio-inspired routines which demand floating-point math operations. Finally, all other available peripherals make it useful and reusable in future projects.

6. PRELIMINARY RESULTS

This section introduces the methodology followed to select the appropriate DC motors to power the three active joints, shoulder, elbow and wrist in the prescribed motions (flexion and extension).

6.1 Determination of the peak torques

In order to build an exoskeleton capable to drive the human upper limb, it was necessary to determine the required torque and power in each joint, shoulder, elbow and wrist for the actuated dof, in this case flexion and extension.

For this purpose, it was performed a search in the literature that did not yield conclusive results because the available data showed a large dispersion of values, probably due to inter-subject differences and to different experimental methodologies. Therefore, it was decided to carry out some experiments to obtain the reference values for the torque and power at each joint. The tests consisted of performing between 5 and 10 repetitions of concentric (in the direction of the muscle contraction) and eccentric (against muscle contraction) isokinetic, with constant force, movements. It was used the CYBEX Evaluation machine (CSMI Solutions) from the Vita Institute (São Paulo, Brazil). This machine can reach up to 678 Nm torques (concentric and eccentric) and velocities up to 500º/s in concentric test and 300º/s in eccentric test. Two male young subjects participated in the study (23 years, 73±1 Kg, 1,81±1 m). They performed concentric shoulder tests at 30º/s, 60º/s, 90º/s, 150º/s and 180º/s and elbow concentric tests at 30º/s, 60º/s, 180º/s and eccentric tests at 60º/s and 180º/s. Table 1 shows the results for the dominant side (right).

Table 1. Experimental results for isokinetic concentric and eccentric tests in upper limb joints for dominant side

Joint	30º/s		60º/s		90º/s		150º/s		180º/s	
	Peak Torque(1)	Average Power(2)	Peak Torque	Average Power	Peak Torque	Average Power	Peak Torque	Average Power	Peak Torque	Average Power
Shoulder Flexion(3)	61	15.3	61	33.8	62	45.6	46	51.5	38	53.4
Shoulder Extension(3)	74	29.3	77	56.8	66	78.3	59	98.6	56	112.5
Elbow Flexion(3)	31	10.6	25	17.1	-	-	-	-	20	31.1
Elbow Extension(3)	33	11.8	27	19.5	-	-	-	-	20	32.9
Elbow Flexion(4)	-	-	34	24.9	-	-	-	-	37	58.8
Elbow Extension(4)	-	-	35	24.8	-	-	-	-	34	65.7

(1) : in Nm (2) : in Watts (3) : concentric motion (4) : eccentric motion

6.2 Determination of the peak torques considering only the exoskeleton inertias

The methodology to determine the peak torques by taking into account the effects of the exoskeleton inertia was based on performing dynamic analysis based on simulations run with the software ADAMS (MSC Software Corp).

The eccentric motion was selected due to the fact that this movement is more severe than the concentric. The results are shown in Figures 5 and 6 for flexion and extension, respectively with an angular velocity of 60 degrees per second and in Figures 7 and 8 for flexion and extension in an angular velocity of 180 degrees per second.

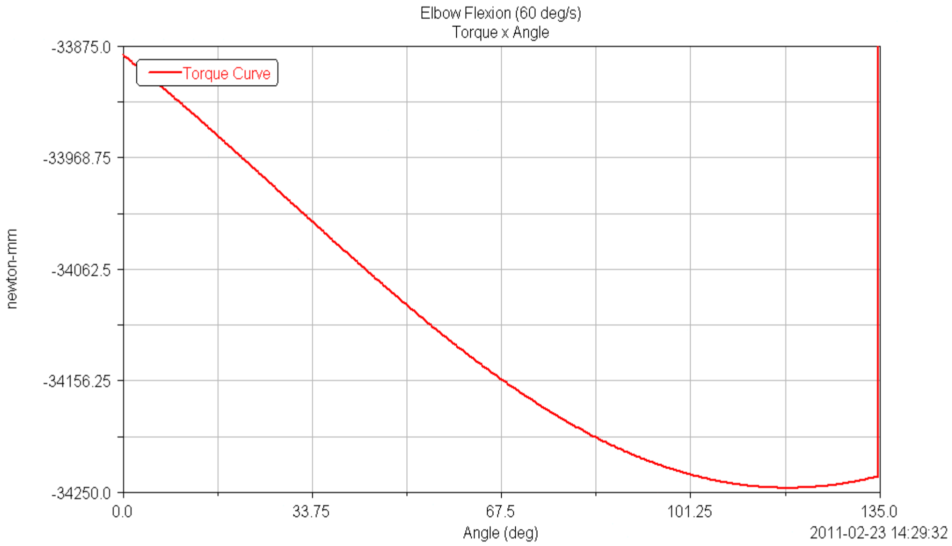


Figure 5. Elbow flexion torque as a function of joint angle at a speed of 60 deg/s

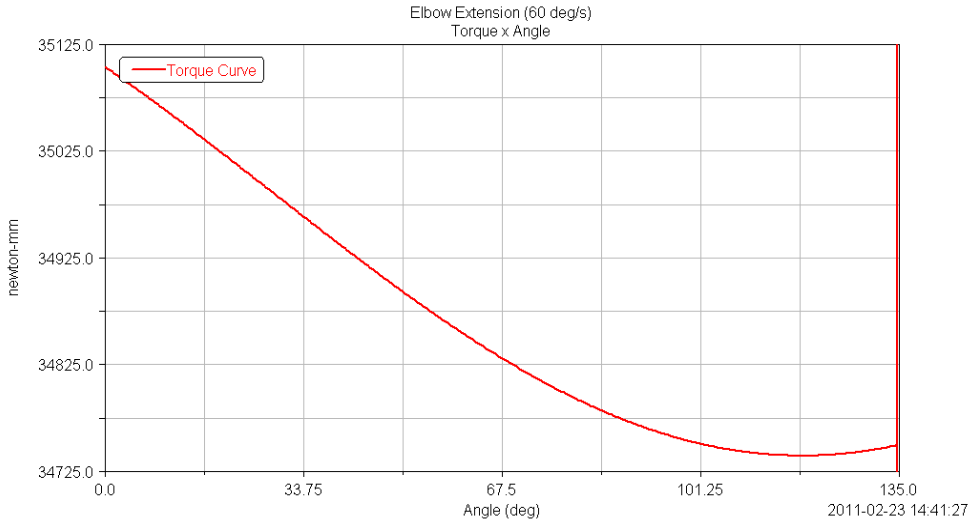


Figure 6. Elbow extension torque as a function of joint angle at a speed of 60 deg/s

The analysis of Figures 5 and 6 indicates that, with an angular velocity of 60 deg/s, the peak torques reached values of 34.25 Nm (flexion) and 35.10 Nm (extension). Considering the Figures 7 and 8 it can be concluded that, with a angular velocity of 180 deg/s, the peak torques reached 37.25 Nm (flexion) and 34.12 Nm (extension).

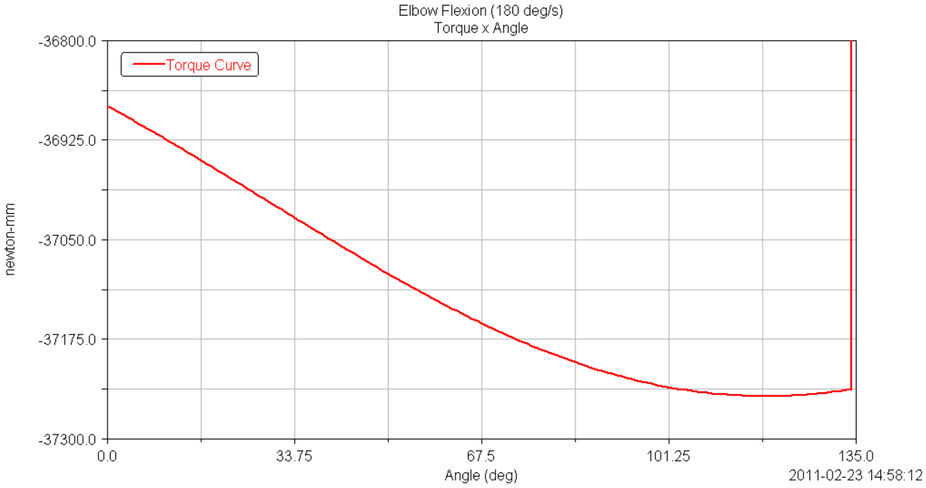


Figure 7. Elbow flexion torque as a function of joint angle at a speed of 180 deg/s

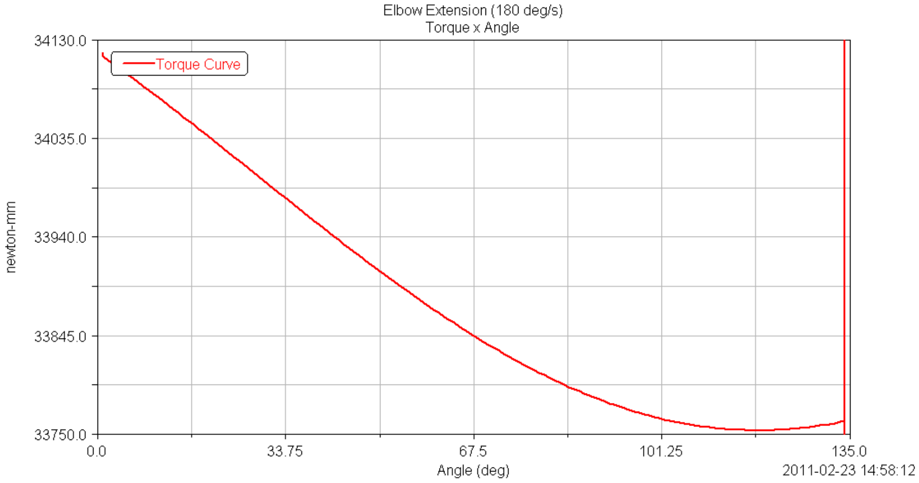


Figure 8. Elbow extension torque as a function of joint angle at a speed of 190 deg/s

Taking into account the peak torques obtained by the simulations and the results obtained by the experiments, it was possible to specify an operation point to our exoskeleton and to size the appropriate DC motor for each joint. All selected motors are brushless DC motors (MAXON flat EC series). For the shoulder, considering that the maximum joint angular speed is 90º/s a 90 watts motor was chosen. For the elbow joint, a lower power is required, so a 60 watts motor was selected. Finally, for the writs it was estimated that a 30 watt motor was sufficient.

6.3 Built prototypes

In earlier studies, it has been developed three prototypes to evaluate some exoskeleton's features as teleoperation, fixation, control and bio-inspired mechanical architecture.

A muscle-inspired mechanical architecture was also built with low cost materials to study the advantages and disadvantages of this topology. The prototype consisted of an elbow joint actuated by a DC motor moving a bar that emulates a muscle. As it was not possible to control directly the bar's length, a linear screw, coupled with a motor reduction spindle, moved the 'muscle' attached at the humerus, providing the angular movement. Figure 9 shows the physical construction. Further studies could emulate various muscle fibers exploring the possibility to use multiples bars and motors to distribute the power source as occurs in our limbs.

Figure 9. Low-cost prototypes developed by AB Miranda to study different aspects in the construction of the exoskeleton.

In order to explore the different possibilities in the design of the fixation of exoskeleton to the arm, it was developed a prototype with parallel and series chain as shown in Fig. 9. The parallel part is responsible for axial rotations (e.g. forearm pronation and supination) and the series part is responsible for perpendicular rotations (e.g. elbow extension and flexion). In this way, user could easily fix the exoskeleton to the arm and forearm.

Currently a real scale prototype with one actuated dof in elbow is being used to test the control strategies, options to implement the fixation to the arm, sensors, hardware and human-robot interaction.

7. CONCLUSIONS

This work has presented the tasks performed to design and build an upper limb exoskeleton oriented to test the control of the arm. Next to the bibliography search, several experiments and simulations have been carried out and a model of the controller has been designed. The preliminary prototypes have been used to evaluate the different constructive solutions. Currently a real scale prototype with one actuated dof in elbow is under construction.

8. ACKNOWLEDGMENTS

This work is supported by the Fundação de Amparo a Pesquisa do Estado de Sao Paulo (FAPESP) project “Estudo do Controle Motor do Membro Superior. Fase 1 - Desenvolvimento de um exoesqueleto robótico biomimético” (Process2010/17181-0). We thank Professors Lucas Moscato and Marcos Duarte from the University of São Paulo and the Vita Institute for the experimental facilities provided.

9. REFERENCES

[1] Machiel Van der Loos, H. F.; Reinkensmeyer, D. J. Rehabilitation and healthy care robotics In : Siciliano, B.; Khatib, O. (Ed.). Handbook of Robotics. Berlin-Heidelberg: Springer, 2008, p. 1229-1231.

[2] Loureiro, R.; Amirabdollahian, F.; Topping, M.; Driessen, B.; Harwin, W. Upper Limb Robot Mediated Stroke Therapy—GENTLE/s Approach. Autonomous Robots , v.15, p.35–51, 2003

[3] Tsai, L. W. The mechanics of serial and parallel manipulators. New York: John Wiley & Sons, 1999. 505 p.

[4] Krebs, H. I; Hogan, N.; Aisen, M. L.; Volpe, B. T. Robot-Aided Neurorehabilitation. IEEE Trans Rehabil Eng. , v. 6, n. 1, p. 75–87, 1998.

[5] Burgar, C.G.; Lum, P.S.; Shor, P.C.; Machiel Van der Loos, H.F. Development of robots for rehabilitation therapy : The Palo Alto VA/Stanford experience. Journal of Rehabilitation Research and Development , v. 37, n. 6, p. 663-673, 2000

[6] Cattin, E.; Roccella, S.; Vitiello, N.; Sardellitti, I.; Artemiadis, P. K.; Vacalebria, P.; Vecchi, F.; Carrozza, M. C.; Kyriapoulos , K. J.; Dario, P. Design and Development of a Novel Robotic Platform for Neuro-Robotics Applications: the NEURobotics ARM (NEURARM). Advanced Robotics, v. 22, n. 1, p. 3–37, 2008

[7] Kiguchi, K.; Fukuda, T. Upper-Limb Exoskeletons for Physically Weak Persons, In: Kommu, S. S. (Ed.), Rehabilitation Robotics, Vienna Itech: Education and Publishing, 2007, p. 287-299.

[8] Rocon, E.; Ruiz, A. F.; Pons, J. L. Wearable upper limb robots. In: Pons, J. L. (Ed.). Wearable Robots: Biomechatronic Exoskeletons. Chichester: John Wiley and Sons, 2008, p. 235-278.

[9] Cashore, K. Exoskeleton. Scott Foresman Science 3.2. Glenview : Pearson Education, 2006

[10] Yang, C. J. ; Zhang, J.-F. ; Chen, Y. ; Dong, Y.-M. ; Zhang, Y. A review of exoskeleton-type systems and their key technologies. J. Mechanical Engineering Science, v. 222, p. 1599-1612, 2008

[11] Jacobsen, S.C.; Olivier, M.; Smith, F.M.; Knutti, D.F.; Johnson, R.T.; Colvin, G.E.; Scroggin, W.B. Research Robots for Applications in AI, Teleoperation and Entertainment. The International Journal of Robotics Research, v. 23 n. 4-5, p. 319-330, 2004.

[12] Gupta, A. and O'Malley, M.K. Robotic Exoskeletons for Upper Extremity rehabilitation. In: Kommu, S. S. (Ed.), Rehabilitation Robotics, Vienna Itech: Education and Publishing, 2007, p. 371-396.

[13] Perry, J. C.; Rosen, J.; Burns, S. Upper-Limb Powered Exoskeleton Design. Transactions on Mechatronics, v. 12, n. 4, p. 408-417, 2007.

[14] Jeong, Y.; Lee, Y.; Kim, K.; Hong, Y.-S.; Park, J.-O. A 7-DOF Wearable Robotic Arm Using Pneumatic Actuators. In: INTERNATIONAL SYMPOSIUM ON ROBOTICS, 32., 2001, Seoul, Proceedings, 2001. p. 388-393.

[15] Hogan, N. Impedance control: An approach to manipulation: Part I, Part II, Part III. J. Dynam. Syst., Measurement, Contr.—Trans. ASME , v. 107, p. 1–24, 1985.

[16] Forner-Cordero, A.; Pons, J. L.; Turowska, E. A.; Schiele A. Chapter 3. Kinematics and dynamics of wearable robots. In: Pons, J. L. (Ed.). Wearable Robots: Biomechatronic Exoskeletons. Chichester: John Wiley and Sons, 2008, p. 235-278.

[17] Texas Instruments. TMS320F28335, TMS320F28334, TMS320F38332, TMS320F28235, TMS320F28234, TMS320F28232 Digital Signal Controllers (DSCs) Data Manual, June 2007 – Revised March 2010.

[18] Hill A.V. (1953) The mechanics of active muscle *Proc Roy Soc Lond (Biol),* 141: 104-117

[19] Ruiz A.F., Rocon E., Forner-Cordero A. (2009) Exoskeleton-Based Robotic Platform Applied in Biomechanical Modelling of the Human Upper Limb. Appl Bionics Biomechanics 6(2): 205-16.

[20] Williamson, MM. (1995) Series Elastic Actuators. PhD Thesis. MIT

[21] Hogan, N. (1984). Adaptive Control of Mechanical Impedance by Coactivation of Antagonist Muscles, IEEE Transactions on Automatic Control 29, 681–690.

10. RESPONSIBILITY NOTICE

The following text, properly adapted to the number of authors, must be included in the last section of the paper:
The author(s) is (are) the only responsible for the printed material included in this paper.