CHAPTER 5

SHOULDER EXOSKELETON FOR REHABILITATION ACTUATED WITH SHAPE MEMORY ALLOY

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This paper presents the preliminary design of a rehabilitation exoskeleton for the shoulder joint with three degrees of freedom (DOF), actuated with Shape Memory Alloy (SMA) based actuators. Due to the actuation system, the proposed exoskeleton presents a light weight, low noise and everything in a simple design structure. The number of actuators and the preliminary designed was calculated after a biomechanical simulation of the human body with a specific category of patients.

1 Introduction

The upper limbs play an important role in daily life but neurological disorder and accidents such as stroke (cerebrovascular accident (CVA)) or spinal cord injury (SCI); significantly affect the normal rhythm of life, letting a partial or total trauma in the motor function with consequent medical and social care consuming a huge amount of healthcare resources. One part of these traumas can be recuperated through traditional rehabilitation therapy performed by therapists (each patient needing one or more therapists, resulting in elevated costs), and in the last decades through the rehabilitation robotic devices. It has been demonstrated that the use of the robot-aide in the rehabilitation therapy has a good result even better than the manual therapy in the patient motor function recuperation. Rehabilitation engineering has carried out a great effort in recent years in order to develop new technologies that should help to recover mobility of upper limbs. The technological advances in this area have been very remarkable. Among the most promising technologies, it is considered that therapies with robotic exoskeletons are very beneficial for the rehabilitation of patients that require repetitive treatments in order to teach movements that were previously lost (Pons, 2008).

The shoulder joint is the most dynamic and mobile joint in the human body. It consists of the glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic articulations and the muscular structures that act on them. These articulations give the possibility to a complex range of motion, measured in terms of flexion and extension in the sagital plane, abduction in the coronal plane, and internal-external rotation about the long axes of the humerus. For this reason, very few robotic devices have been designed so far for its rehabilitation. The vast majority of conventional robotic devices for shoulder rehabilitation have been based on rigid, heavy and uncomfortable electromechanical components (Maciejasz et al., 2014) (ORTE, 2016). Among their primary design goals, the new devices should consider patient comfort, low weight and cost reduction to allow a widespread use. It is necessary to investigate compact, lightweight, portable and affordable solutions that allow these tools to be accessible to general public. The mechanical structure of the device must take into account issues such the pain, security, comfort, noise, weight, autonomy and the possibility of portability. These aspects have a strong connection with the system of actuation, forcing to search solution in the no conventional actuators. The aim of the robotic exoskeleton presented in this paper is to provide more efficiently rehabilitation therapies for shoulder joint with a very light and noiseless exoskeleton. Here the focus will be on over-actuated low-cost systems. The main objectives are to build a shoulder exoskeleton fully actuated by SMA wires (Moreno, 2009), demonstrating that this technology is a viable alternative when investigating possible improvements of the existing devices in terms of weight, volume and cost (DeLaurentis, 2002), (Duering, 1999), (Morgan, 2004), (Pittacio, 2012). The mechanical design of the exoskeleton should allow the typical movements of the most common therapies in rehabilitation.

2 Mechanical design

This paper presents a rehabilitation exoskeleton for the shoulder joint with 3DOF, actuated with SMA for the right upper limb where the characteristic of patient are: male with 75Kg of weight and 1.75 m of height.

2.1 Biomechanical simulation

Nowadays, in the development of any robotic device the simulation tools play an important role due to their capacity to analyze the expected performance of the system designed prior to manufacture. To estimate the necessary torques in the articulations for a specific patient, simulation software Biomechanics of Bodies (BoB) was used. The software is capable to simulate the inverse dynamic behavior of the human body, receiving as input: the height, weight and motion of the patient, and giving as output, among other data, the torque of articulations (Wagner et al. 2013). In this case the simulation was configured with the next parameters: weight 75Kg, height 1.75m, a trajectory in the right shoulder joint between -45 and 120 degrees in flexion-extension and 0 and 120 degrees in abduction with a frequency of movement 0.25Hz. As it can results in the simulation, to complete the rehabilitation task in the shoulder articulation successfully it is necessary a torque no more than 12Nm (Fig. 1). This case assumes that the patient has definitively lost the motor function and all the force is made by the exoskeleton.

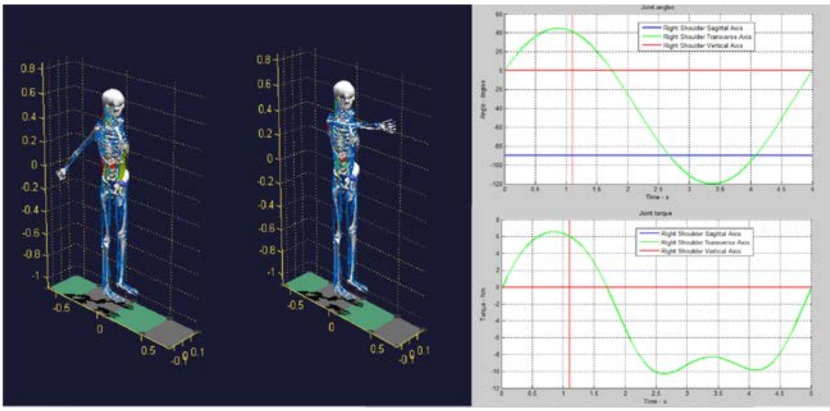

Fig. 1. In the left part the Biomechanics of Bodies simulator configured in the flexion-extension of the shoulder joint. In the right part the input trajectory and the results of simulation, the necessary torque in the shoulder joint.

2.2 SMA based actuators

The first result of the viability of the SMA actuator for soft wearable robots was presented in the past publication (Villoslada et al., 2014). Considering 12Nm the necessary torque in the shoulder exoskeleton joint and ranging the parameters such as: radio of pulley to pas from a translation motion to rotary motion, the diameter of the SMA wire, the SMA composition (NiTi and in composition with other alloys) a simulation program (see Fig. 3) capable to calculate the number of actuators and the length of this was done. In function of these results an optimal configuration for 165 degrees of angular motion (45 degrees in extension and 120 degrees in flexion) was chosen: 8 SMA wires with a length of 2.2 m and a radio of pulley of 30 mm. For the abduction-adduction motion was necessary 145 degrees (120 degrees abduction and 15 degrees adduction) resulting: 8 SMA wires with a length of 2m and a radio of pulley of 20 mm. The better alloy in this case is SmartFlex® with the diameter of 500mm. Moreover, the SMA wires were introduced in the Bowden cable that in addition of the fixed structure (one of the extremity of the SMA is crimp in the extremity of Bowden) have effect of heat dissipation. The election of the number of was done taking into account the additional weight of the exoskeleton and a possible additional weight in the hand, the total torque generated by the exoskeleton surpassing the 12 Nm.

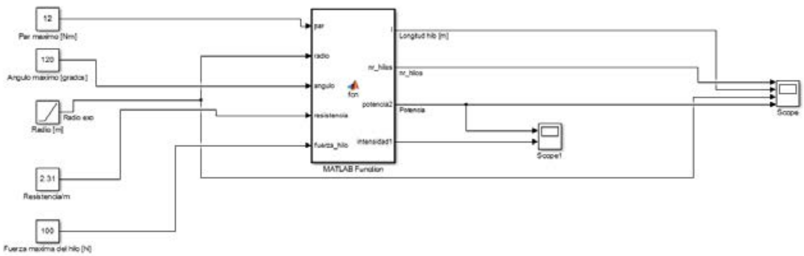

Fig. 2. Matlab/Simulink program for calculate the optimal actuator characteristics in function of the exoskeleton pulley

2.3 Exoskeleton design

In function of the biomechanics analysis and the chosen actuators an exoskeleton designed are proposed (Fig. 3). This is made of simple parts how give the possibility to easy assembly and adjustable them in function of the patient. In addition was designed such a low cost system give the possibility to build them with a 3D printer. The design of the exoskeleton shows three DOF. The first DOF (2 of Fig. 3) give the possibility to abduction – adduction movement, 4 give the possibility of flexion-extension movement and 7 permit a passive scapulohumeral movement necessary in abduction movement.

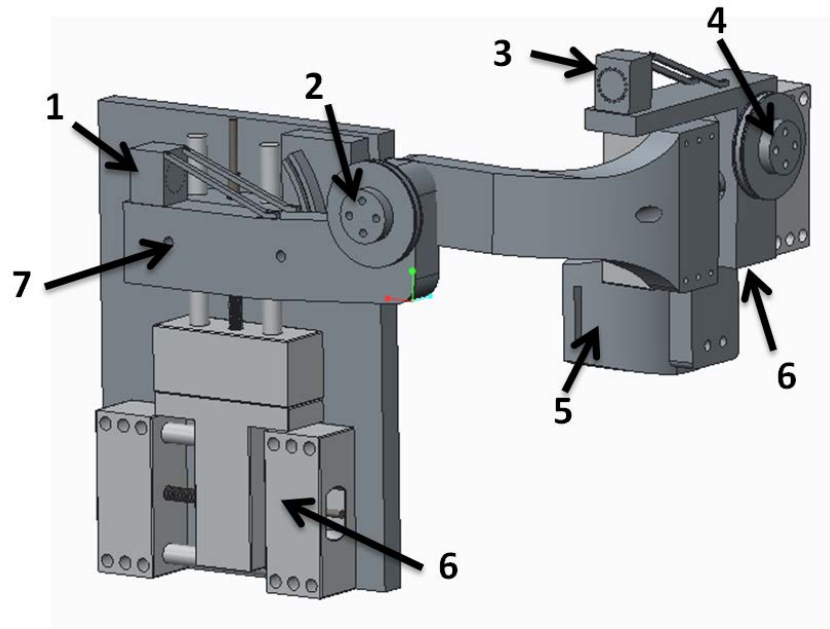

Fig. 3. SMA actuated exoskeleton: 1, 3 – fixed points for Bowden cable termination, 2, 4- pulley to switch from linear movement to rotary motion, 5 – attached point with the arm, 6 – configurable system in function of the patient, 7- passive DOF for scapula movement.

Based in the parameters such as: mobility, comfort, safety and easiness to put it on patient, the proposed design of the exoskeleton compared with the actually solution present a significantly evolution. The main advantages are given by the SMA based actuators that drastically reduce the weight of the structure, less than 2.5Kg, and in the same time with a very low noise - due to the lack of gears and motors in the mechanism. For the comfort all intern part in contact with the patient was covered with a very soft hypoallergenic material.

3 Controls

3.1 Control strategy

The main difficulty when controlling SMA based materials is the hysteresis, which appears in the phase of transition (Martín, 2014). It introduces in the system nonlinear behaviors which make difficult the controls algorithms for this type of actuator. Moreover in this structure the problem become more complicated when controlling for actuators mounted in parallel. In this work a four-term bilinear PID controller was used. The performance of this type of regulator used in control of SMA based single actuators was presented in (Villoslada et al., 2015).

3.2 Control hardware architecture

The control hardware architecture equipment was based IEC 61508, IEC 60601, SIL 4 according to the security criterion of the medical equipment (Fig. 4). This was based in a NRF51822 Bluetooth with a 32-bit ARM® Cortex™ M0 CPU ideally for soft devices (Flores, 2012). With the electronics, the control hardware architecture is capable to manage 8 controllers for 8 distinct actuators. In the case for the shoulder articulation only needing 2 controllers.

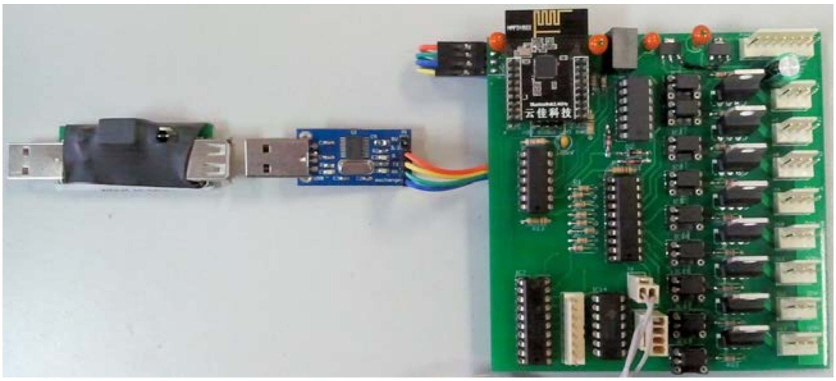

Fig. 4. Control hardware architecture.

4 Conclusions

In this paper it was presented the preliminary design for a wearable shoulder exoskeleton actuated with SMA based actuators (without motors) which permit to reduce drastically the weight of the exoskeleton (less than 2.5kg) and achieve a quiet operation characteristic that increase the comfort of the system.

The preliminary design of exoskeleton was built as a low cost and easy to use rehabilitation device, which can be made with a 3D printer, with a low cost electronics and actuators, which can be adjustable depending on the patients.

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