# Bio-inspired Rotation – Translation System for Rehabilitation Robots

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***Abstract*— Pneumatic muscles are bio-inspired actuation systems characterized by an adaptive compliant behaviour. The property of compliance deployed in the construction of robots underlies the development of human-friendly systems, capable of safe interaction with the human operator and/or user. The paper presents a compliant constructive solution based on pneumatic muscles designed for robotic manipulation systems used in rehabilitation activities of disabled persons. The discussion focuses on the construction and several performance related aspects of a bio-inspired rotation-translation system designed for manipulators mounted on the wheelchairs of locomotor disabled persons.**

***Index Terms*— pneumatic muscle, rotation-translation system.**

## I. Introduction

From an engineering perspective, the functional morphology of living organisms, represents a permanent inspiration for identifying high-tech innovative solutions. In this context over the last years a new branch of science has emerged and grown, namely bionics, combining skills and proficiency from biology, mathematics, medicine and engineering. Bionics draws upon biological intuition and engineering pragmatism in order to adapt projects from nature to the requirements of modern technology. Nature is thus the starting point for innovation, it offers clues for what is useful and should be deployed in a mechanism. Starting from such clues the engineer's task is to develop, test and improve the analyzed system.

As part of the objectives of current bionic research special attention is granted to the study of actuator elements. The study of such elements together with their control transmission processes represents an essential part of bionics. In this context humans, mammals, birds and fish represent the source of inspiration for developing various motion generating systems, with immediate utility, for example, in robotics.

Numerous categories of robots are destined for operation in the immediate vicinity of humans. In order to be able to operate close to humans or to interact with these, a first requirement to be met by the new generations of robots is safe functioning. This entails preventing undesired collisions between the robot and humans, or in the worst case, the minimizing of the effects of such collisions. Reliability means the display of a compliant behaviour of the robot, or, in other words, the possibility of continuous control of its stiffness.

Human-friendly robots characterized by variable stiffness entail a structure including compliant actuators. Variable stiffness actuators (VSAs) or adjustable compliant actuators are being designed and implemented because of their ability to minimize large forces due to shocks, to safely interact with the user, and their ability to store and release energy in passive elastic elements [1].

Bio-inspired actuation systems, like pneumatic muscles, meet such requirements, due to their adaptive compliant behaviour, materialized by the possibility of continuous stiffness variation.

Compliant behaviour, however, has its disadvantages, as it limits the robot's performance because it reduces control bandwidth, due to structural resonance [2].

Compliant execution elements can be divided into two categories: *active* compliant actuators where a controller of a stiff actuator mimics the behaviour of a spring and *passive* compliant actuators, respectively, the latter including a compliant element capable of storing and/or releasing energy [3]. Passive compliant actuators are not designed for applications requiring high positioning accuracy, like for example, pick and place type activities. They are preferred in novel robots where safe human- robot interaction is required or in applications where energy efficiency must be increased by adapting the actuator's resonance frequency. As both positioning accuracy and collision safety are important requirements, a robotic system should exhibit very low stiffness when subjected to a collision force greater than the one causing human injury, but maintain very high stiffness otherwise [4].

The paper discusses a technical solution meeting both these requirements and presents a pneumatic muscle actuated rotation – translation system applicable in robotics. These actuators are regarded as bio-inspired elements of passive compliant type. An important step in the development is identifying the properties and performance that the artificial system is expected to achieve.

Manuscript received May 4, 2010.

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## II. Construction of the Rotation-Translation System

Many applications require increased robot stiffness, what entails the utilization of electro-mechanical actuation systems. In such applications, where compliant behaviour is only secondary, the utilized electric motors offer a reduced force-to-weight ratio, as far as 16/1. For this reason, generation of large forces calls for the utilization of either high power electric motors or of reducing gears with high transmission ratios. In both situations the resulting structures are of large dimensions and high weight, what will cause high inertia forces with negative impact on the dynamic behaviour of the robot.

Considering these aspects, the utilization of pneumatic muscles in the construction of robots becomes of interest, as in comparison to electric motors, pneumatic muscles offer a clearly superior force-to-weight ratio (as far as 100/1), thus allowing the construction of small and light robots with favourable dynamic behaviour. In addition, air compressibility endows the robotic system with compliance, rendering unnecessary a further elastic element. [4].

The utilization of pneumatic muscles, or, in other words of so-called compliant elements with specifically adjustable compliances offers the possibility to transmit motions just by structural deformations.

The pneumatic muscle is a system based on a contracting membrane, that under the action of compressed air increases its diameter while decreasing its length. Thus the pneumatic muscle carries out a certain stroke, depending on level of the fed pressure. The operational behaviour of such a system is similar to human muscles, as shown in Fig. 1.

Pneumatic muscles are operational elements that have started to replace pneumatic cylinders in certain applications. Compared to pneumatic cylinders, the muscles are about eight times lighter, while generating an about ten times greater force, for identical interior diameters.

Pneumatic muscle actuated robots entail an extremely light construction of increased flexibility, while meeting the safety requirements for equipment deployed in the immediate vicinity oh humans or in narrow spaces [5…9].

The pneumatic muscle actuated rotation-translation system presented in Fig. 2 is part of a robotic arm mounted on a wheelchair. In view of their applicability, wheelchair mounted manipulators have the highest degree of flexibility. They are deployed for the gripping of objects randomly located in space, for opening and closing doors, drawers, taps or for simple manipulation tasks like pouring drink into a glass and raising that glass to the drinker's mouth.


Fig. 1 Working principle of pneumatic muscles

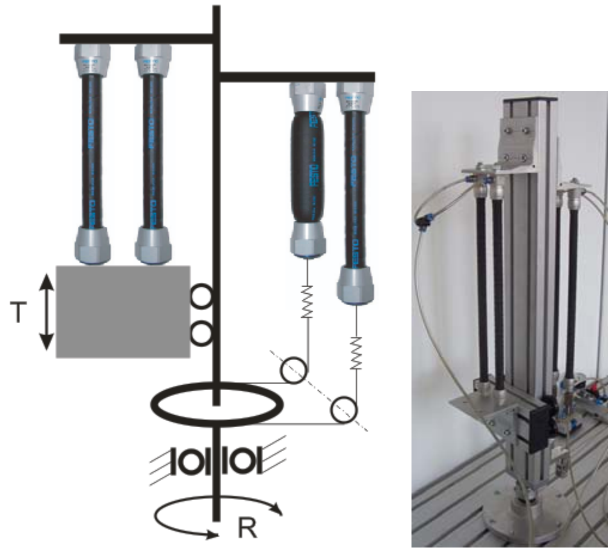


Fig. 2 Pneumatic muscle actuated rotation-translation system

The rotation-translation system is actuated by two pairs of pneumatic muscles. The first pair with the function of generating the rotation is based on the principle of antagonistic actuation, while the second pair of muscles with the function of generating the translation motion are actuated synchronously (agonistic actuation).

The generation of rotation is based on an innovative solution, that differs from others by the two actuators (pneumatic muscles) rotating together with the actuated element. The role of the two muscles is to generate a ± 45º rotation, and to ensure the balance of any intermediary position of the actuated system. The rotation of the entire robotic system is quite similar to motion generated by human muscles, as being based on the same agonist-antagonist system illustrated in Fig. 3.

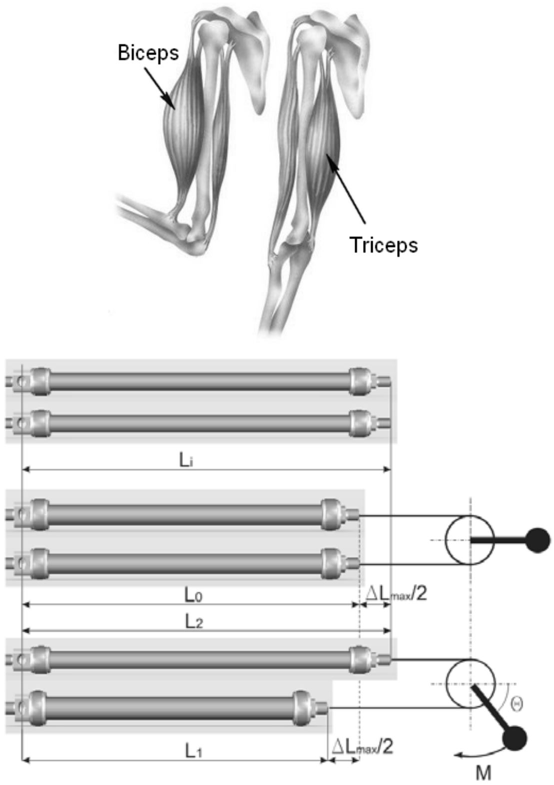


Fig. 3 Working principle of the rotation module

ISBN: 978-988-17012-0-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Two flexible steel cables are affixed to the free ends of the two pneumatic muscles. The cables are then passed through the groove of a reel of 2R = 38 mm diameter, and rigidly fixed at the opposite ends.

This constructive schematic allows the generation, by antagonistic inflation/deflation of the two muscles, of rotation in one or the other direction of the entire mechanical structure, thus also of two pneumatic actuators. The bearing of the entire system is located at its lower end, thus allowing its rotation in either direction.

The contraction ratio of a muscle $\varepsilon$ is defined by (1):

$$\varepsilon = \frac{L_i - L}{L_i} = \frac{\Delta L}{L_i} \quad (1)$$

where $L_i$ is the initial length of the muscle, at a pressure equal to zero, and $L$ – is the length of the muscle inflated at a random pressure $p$.

The maximum contraction ratio $\varepsilon_{max}$ is:

$$\varepsilon_{\max} = \frac{\Delta L_{\max}}{L_i} \quad (2)$$

where $\Delta L_{max}$ is the maximum stroke carried out by the free end of a muscle, when charged at maximum pressure.

The force developed by a pneumatic muscle can be computed by (3):

$$F = F_{\max} \cdot (1 - \frac{\varepsilon}{\varepsilon_{\max}}) \quad (3)$$

It can be noticed that for $\varepsilon = \varepsilon_{max}$, the force developed by the muscle is $F = 0$.

In order for the rotation to be possible, the first step is the pre-charging of the two muscles with air at a pressure $p_0$ equal to ½ of the maximum working pressure. Upon pre-charging, the pneumatic actuators will have contracted to length $L_0$, at a contraction ratio for each of $\varepsilon_0$, computed by (4):

$$\varepsilon_0 = \frac{\frac{\Delta L_{\max}}{2}}{L_i} = \frac{\Delta L_{\max}}{2 \cdot L_i} \quad (4)$$

Fig. 4 presents the constructive solution adopted for compensating the displacement of the two muscles upon their pre-charging (inflation at pressure $p_0$). The system is based on allowing the axles of the two cable reels to gliding in a guide, while the support of the reels is strained by means of compression springs. When the pre-charging of the pneumatic muscles is achieved, the horizontal axles of the two reels are simultaneously lifted by half the maximum possible stroke of each muscle. Upon releasing the air from the muscles, the compression springs cause the reels to return to their resting position.

When a rotation by an angle $\theta$ is desired, one of the muscles will be fed additional compressed air, up to pressure of $p_1 = p_0 + \Delta p$, while the second muscle will be deflated to a pressure $p_2 = p_0 - \Delta p$.

Fig. 4 Compensating for muscle shortening by $\Delta L_{max}/2$

By feeding the two muscles different pressures, their lengths will be modified in relation to their initial state as follows: the muscle inflated to pressure $p_1$ will shorten to a length $L_1 = L_0 - \Delta L_{max}/2$, while the second muscle will expand to a length $L_2 = L_0 + \Delta L_{max}/2$.

Upon rotating the joint by angle $\theta_{max}$, the contractions of the two muscle become:

$$\varepsilon_1 = \varepsilon_0 + \frac{R \cdot \theta_{\max}}{L_i} = \frac{\Delta L_{\max}}{L_i} \quad (5)$$

$$\varepsilon_2 = \varepsilon_0 - \frac{R \cdot \theta_{\max}}{L_i} = 0 \quad (6)$$

where $R$ is the radius of the reel guiding the cable connecting the free ends of the two pneumatic muscles.

The forces developed by the two muscles are determined by (7) and (8):

$$F_1 = F_{\max} \cdot (1 - \frac{\varepsilon_1}{\varepsilon_{\max}}) = 0 \quad (7)$$

$$F_2 = F_{\max} \cdot (1 - \frac{\varepsilon_2}{\varepsilon_{\max}}) = F_{\max} \quad (8)$$

while the generated torque will be:

$$M = R \cdot (F_1 - F_2) = R \cdot F_{\max} \quad (9)$$

Air compressibility renders the pneumatic muscles compliant. Compliance $C$ can be expressed as the inverse of stiffness, $K$ [10]:

$$C^{-1} = K = \frac{dF}{dL} \quad (10)$$

As the magnitude of the force depends on that of the feeding pressure of the two muscles, it follows that compliance can be adapted by controlling the pressure.

The construction of the translation module includes as its two main elements a pair of pneumatic muscles operated synchronously by the feeding of compressed air. Upon being fed compressed air the muscles shorten their initial (resting) length by $\delta L$, thus causing the displacement of a vertical slide, guided by two pairs of rollers..

Fig. 5 presents the actuation diagram of the rotation-translation system, based on three proportional pressure regulators PR. Two of these ($PR_{R1}$ and $PR_{R2}$) have the function of controlling the rotation, while the third one, $PR_T$ is responsible for feeding the two muscles achieving the translation.

The electrical diagram presented in Fig. 5 shows that the asynchronous displacement of the two muscles responsible for the rotation is controlled by a double potentiometer, that antagonistically commands the opening of the two proportional pressure regulators.

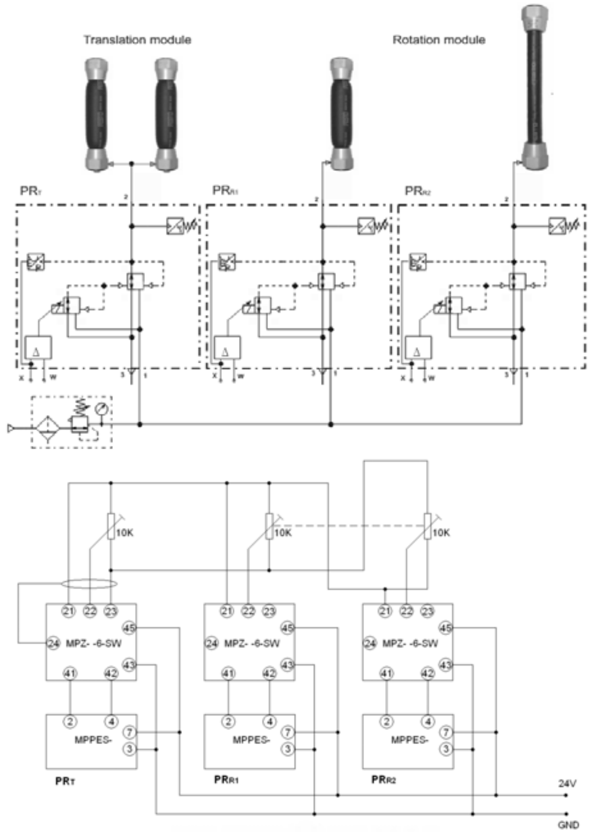


Fig. 5 Actuation diagram of the rotation-translation system

## III. System Performance

Experimental research conducted on the rotation-translation system was directed towards determining the time related evolution of the feeding pressure of the two pairs of muscles. For this three pressure transducers were placed on the test rig. One was responsible for determining the pressure of two muscles generating the translation motion, while the other two transducers measure the pressure in the two muscles responsible for the rotation. Fig. 6 presents the location on the test rig of the proportional pressure regulators and of the three pressure transducers.

Fig. 7 shows the curves obtained by feeding the rotation – translation system compressed air at a pressure of 6 bar. In the case of rotation, the two muscles were initially fed air at half the maximum working pressure ($p_0 \approx 3$ bar).

Fig. 6 Location of the proportional pressure regulators and the pressure transducers

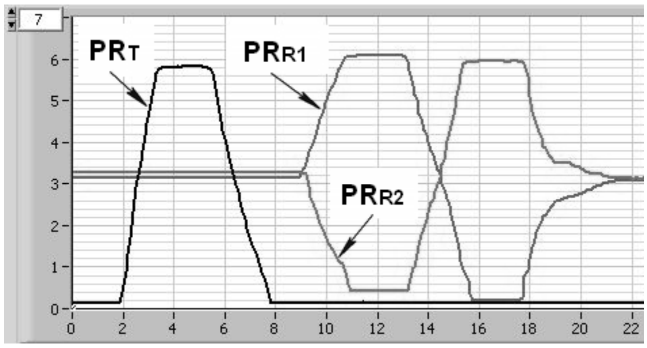


Fig. 7. Variation curves of pressure vs. time

It then can be noticed that one of the muscles is additionally fed air (the $PR_{R1}$ curve), while the other muscle is deflated (the $PR_{R2}$ curve) and vice-versa. The curve denoted by $PR_T$ describes the evolution of the feeding pressure of the muscles responsible for the translation motion.

## IV. Conclusion

The paper presents and discusses a novel variant of a bio-inspired rotation-translation system , actuated by pneumatic muscles. Such a solution lends itself particularly to developing robotic manipulation systems for rehabilitation activities of physically disabled persons. The solution of pneumatic actuation was selected due to the compliance characteristic to these actuators.

Ensuring the driving of systems by pneumatic muscles proves that these actuators, yet insufficiently known and deployed, offer numerous advantages related to dynamic behaviour as well as to involved costs.

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ISBN: 978-988-17012-0-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)