Performance of a Pneumatic Muscle Actuated Rotation Module

Andrea Deaconescu, Tudor Deaconescu

***Abstract*— The utilization of pneumatic muscles in the actuation of robotized systems is still in its early stages, thus calling for further study of such constructive solutions. The need for light robotized systems with improved dynamics has led to the development of pneumatic muscles as a power source for the system. This type of actuator, which has also an excellent power/weight ratio, meets the need for safety, simplicity and lightness. Starting from the human model, the paper presents and discusses the performance of a standardizable rotation module, actuated by pneumatic muscles and adaptable on robotic systems designed for the aid of disabled persons. Rotation of a cylindrical joint by means of pneumatic muscles is achieved in a considerably similar way to that generated by human muscles, based on the agonist vs. antagonist principle, namely as one muscle contracts the other will relax.**

***Index Terms*— pneumatic muscles, rotation module.**

I. INTRODUCTION

Compressed air represents one of the most efficient means of actuation and automation of production systems. Known and applied already 2300 years ago in the structure of ancient Greek catapults, pneumatic actuations have evolved continuously, from the utilization of individual components to complex automation systems. These novel systems were developed by integrating classical pneumatic structures with mechanical and electronic elements, as well as with sensors.

Increasingly large scale utilization of compressed air in industrial applications is due to its advantages, like comfortable generation and storage, lack of flammability, minimum risk of explosion, minimum maintenance effort of pneumatic systems, etc. Another important advantage of compressed air is its being a clean, ecological working medium, lending itself to environmentally friendly processes, like those encountered in food, electronics or pharmaceutical industry [1].

Recent research on pneumatic actuation elements led to the conception of a membrane type actuation system, known as *pneumatic muscle* (Fig. 1).

Fig. 1 Pneumatic muscles

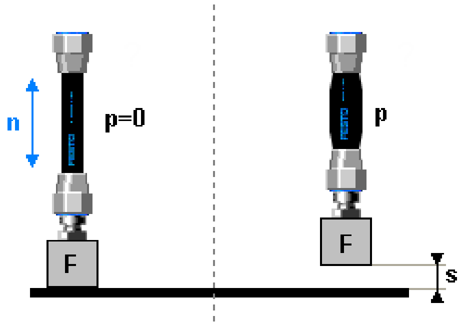

Fig. 2 Working principle of pneumatic muscles

The utilization of muscles in the construction of pneumatic actuation elements has known continued development, particularly in the field of industrial robots [2], [3]. A few examples illustrating this are the pneumatic arm developed by the American J.L. McKibben, the stepping robot built by AMS Osaka, Japan or the humanoid robot developed by the Festo Company in cooperation with the Technical University of Berlin, Germany.

Pneumatic muscles have been used for a number of years as actuators in robotic systems, usually in those that mimic human actions. They are most commonly used in systems designed to aid physically handicapped people [4], [5].

Air muscles consist of an inflatable tube, usually neoprene rubber that is constrained by a nylon mesh. When compressed air is passed into the muscle, which is blocked at one end, the tube inflates, but the action of the enclosing mesh forces the tube to shorten (Fig. 2). The resultant force is used as a linear actuator. The pulling force is at its maximum at the beginning of the contraction and drops with the stroke to zero.

The main advantages of pneumatic muscles are:
- low in price;
- high power to weight ratio;
- suitability for utilization in rough environments (e.g. sandy, wet conditions);

Manuscript received February 28, 2009. This work was supported by the Romanian National Council for Scientific Research in Higher Education (CNCSIS) through research contracts ID_184/2007 and ID_746/2008.

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- silent operation;
- no stick-slip effect;
- maintenance free, etc.

II. STRUCTURE OF A ROBOTIC SYSTEM ACTUATED BY PNEUMATIC MUSCLES

Research conducted over the last few years at the Transilvania University of Braşov, Romania has highlighted the advantages of pneumatic muscle utilization in robotics. An example of such utilization is presented in this paper, namely a robotic manipulation system deployable in rehabilitation activities of disabled persons. The construction of the manipulation system is achieved by standardizable rotation and translation modules, that combined allow the development of robots with several degrees of freedom [6], [7]. Pneumatic muscle actuated robots involve an extremely light construction, increased flexibility and meet safety requirements for equipment operating in the proximity of humans or in narrow spaces.

Fig. 3 presents the structure of the robotic system actuated by pneumatic muscles. The diagram ensures two degrees of freedom (rotation – translation), both obtained by two pairs of pneumatic muscles.

Further analysis focuses on the achievement of the rotation R1, as well as on the performance obtained by such an actuation system.

III. PNEUMATIC MUSCLE BASED ROTATION SYSTEM

The achievement of rotation of a cylindrical joint by means of pneumatic muscles is considerably similar to that generated by human muscles, based on the agonist vs. antagonist principle [8]- [11].

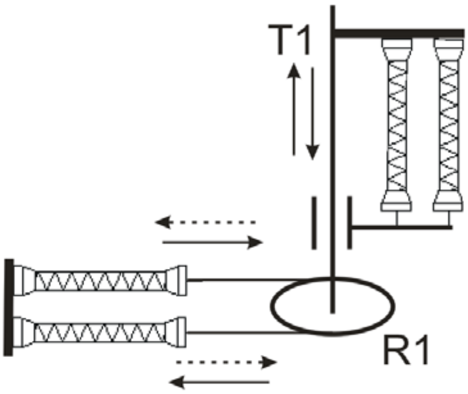

Fig. 3 Kinematic diagram of the robotic system

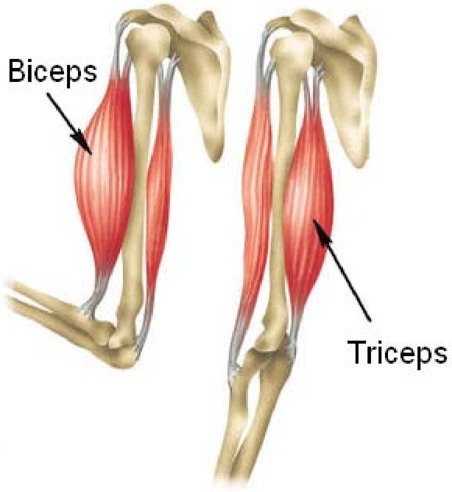

Fig. 4 Human arm

For every muscle or group of muscles that generates movement of a certain part of the body, there is another muscle or group of muscles which generates an opposite movement. Such muscles, causing opposite movements, are called antagonistic muscles. They make the smooth co-ordination of movement possible. As the one muscle contracts, the other (which is able to generate an opposite movement) will relax, and vice versa.

To illustrate the operation of antagonistic muscles the muscles in the human arm are considered as shown in Fig. 4. At the front of the arm is the biceps muscle which is spindle-shaped. The tapering ends are attached firmly to the periosteum of the skeleton by means of strong tendons. The upper end of the biceps muscle is attached to the scapula by means of 2 tendons. These points of attachment are called the origin of the biceps as they are fixed, i.e. they do not move as the muscle contracts. The lower end of the biceps is attached to the radius of the forearm. The radius is moved upwards as the biceps contracts.

The muscle antagonistic to the biceps is called the triceps. It is situated at the back of the arm, just behind the humerus. The origin of the triceps consists of 3 tendons. One is attached to the scapula and the other two are situated at the back of the humerus.

When a muscle is stimulated it contracts and becomes shorter and thicker thus moving the bone to which it is attached. When it is relaxed, the muscle becomes longer and thinner. The shape changes, but not the volume. To understand how movement is brought about, it needs to be pointed out that muscles can do work only by pulling as they contract. A muscle is unable to do work by pushing as it elongates. The arm is flexed by the contraction of the biceps muscle. The triceps muscle relaxes as the biceps contracts and the arm bends at the elbow.

Concludingly, short strong contractions are required for a biological muscle to do work. Research has shown that by a contraction of 10% of its length the human muscle is capable of producing the work required for a certain task.

Based on the human model, over the last years several actuation solutions have been developed using pneumatic muscles working in tandem. Fig. 5 shows some such constructive variants.

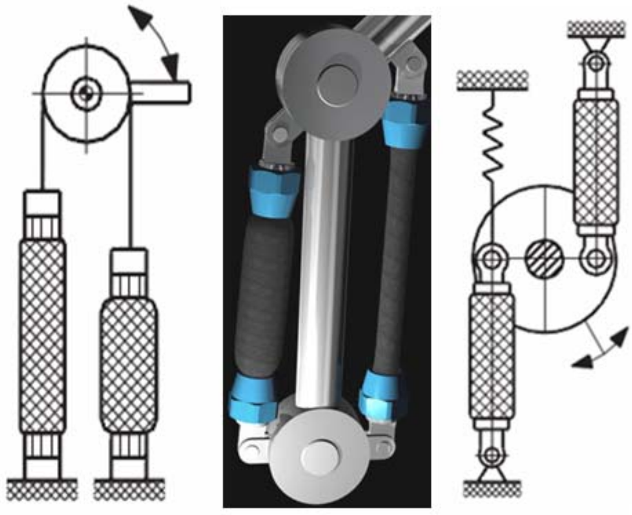

Fig. 5 Pneumatic muscle actuated rotation modules

It can be noticed that in each of the presented cases rotation is obtained by means of two pneumatic muscles actuated antagonistically; while one muscle contracts or inflates, the other relaxes or deflates.

The paper presents and studies a novel construction of a rotation module, different from others by the fact that the two actuators rotate together with the driven constructive element. The two pneumatic muscles are actuated antagonistically such as to cause a ± 45º rotation and to ensure the balance of a certain intermediary position of the actuated system (Fig. 6).

The upper ends of the two muscles are rigidly fixed, while free ends are attached to flexible steel cables wound through the groove of a pulley of diameter $2r = 38$ mm.

By alternating or antagonistic inflation/contraction and deflation/relaxation of the two muscles this constructive diagram allows the generation of rotation in one or the other direction of the entire mechanical assembly, thus also of the two pneumatic actuators. The bearing for the entire system is at its inferior part, thus allowing rotation in both directions.

For rotation to be possible the first step is to pre-load the two muscles by feeding a pressure p_0 that is half of the maximum working pressure. Upon pre-loading the length of both pneumatic actuators will be L_0;

In order to achieve a rotation by a certain angle α, one of the muscles will be fed additional compressed air until pressure reaches value $p_1 = p_0 + \Delta p$, while the second muscle will be relaxed to a pressure $p_2 = p_0 - \Delta p$. By feeding different pressures to the two muscles, their respective lengths will be modified as follows: the muscle inflated at pressure p_1 will shorten to a length $L_1 = L_0 - \Delta L$, while the second muscle will elongate to a length la $L_2 = L_0 + \Delta L$.

The developed rotation module uses a pair of pneumatic muscles of 10 mm interior diameters and initial (relaxed) length of $L = 300$ mm. Knowing that the value of the maximum required actuation force is 80 N and considering a 4 bar working pressure, manufacturer diagrams read a corresponding 10% contraction of the muscle. Under these conditions the maximum rotation angle of the mobile assembly will vary between ± 45º.

Fig. 7 shows the construction of the pneumatic muscle actuated rotation module, while its pneumatic actuation diagram is featured in Fig. 8.

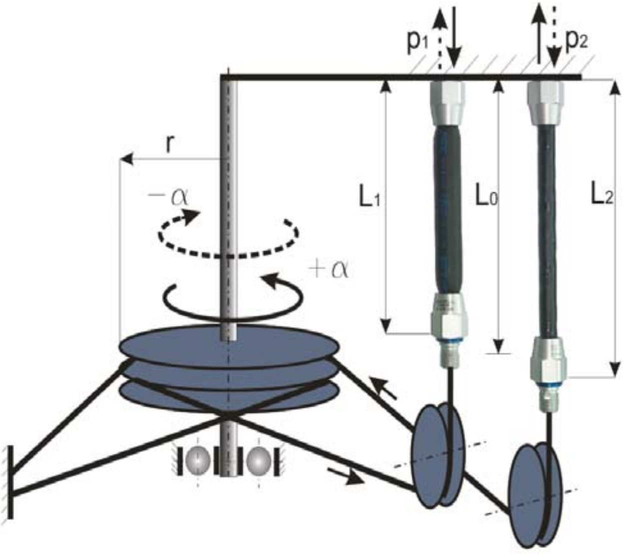

Fig. 6 Presented rotation module

Fig. 7 Construction of the rotation module

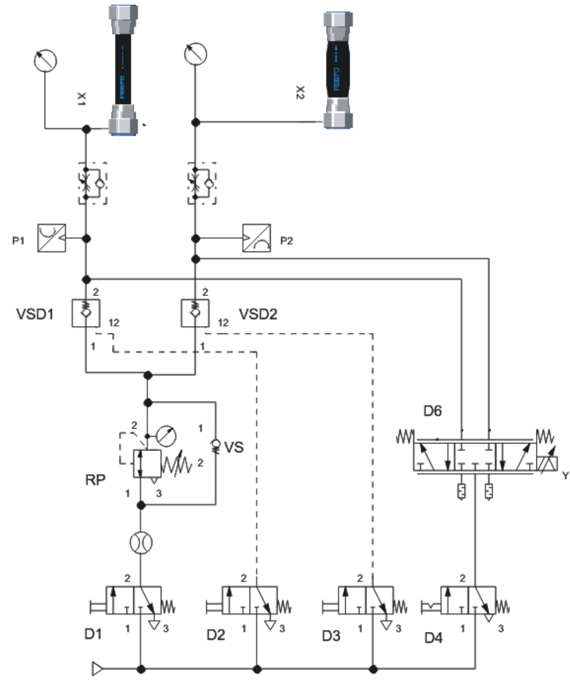

Fig. 8 Pneumatic actuation diagram of the rotation module

The role of the main components of the pneumatic diagram is the following:

- distributor D1 is responsible for pre-loading (pre-compressing) of the two muscles at a pressure p_0 amounting to ½ of the maximum working pressure. The level of the pre-loading pressure is adjusted by means of pressure regulator valve RP.
- distributors D2 and D3 are responsible for relaxing the pneumatic muscles when the robotic system is switched off.
- Via command button D4 compressed air is fed to distributor D6, thus initiating rotation. The antagonistic control of the two pneumatic muscles needed for rotation is achieved by means of a 5/3-way directional valve (D6), a PID-controller and a displacement encoder.

The rotation speed of the mobile assembly is achieved by means of two one-way flow control valves, located in the proximity of the pneumatic muscles.

Measurement of the feeding pressure levels for each muscle, as well as of the value and evolution of the air flow consumed by the system is achieved by two pressure sensors with indicators (P1 and P2) and of a flow rate sensor with display, all connected to the computer by an EasyPort DA interface.

IV. SYSTEM PERFORMANCE

Research conducted on the experimental model was aimed at analyzing the evolution of the pressure required for the activation of the two pneumatic muscles, the evolution of the consumed airflow, as well as at determining the response times of the muscles in contraction/inflating and relaxation/deflating, respectively. Measurements were carried out by loading the muscles with compressed air at the maximum pressure of 4.2 bar, the evolution of pressure versus time being recorded by means of the two pressure sensors with indicators (P1 and P2). At the same time the evolution of the air flow rate feeding the two muscles was monitored. Fig. 9 shows the diagrams corresponding to pressure and feed flow rate variation for two cycles.

The upper graph displays the evolution of feeding pressure of the two muscles, with continuous and dotted lines, respectively. Initially, the two muscles are fed simultaneously to a pressure amounting half its maximum working value ($p_0 \approx 2$ bar). During actual operation it can be observed that while one of the muscles is loaded additionally with compressed air, the other one is relaxed, and vice versa.

In relation to the airflow, impulse growths can be noticed corresponding to the switching of the system from one state to another, namely when left or right rotation is initiated.

Starting from the graph in Fig. 10, illustrating a pre-loading – loading sequence of a pneumatic muscle, the duration of these events can be determined. Thus, the pre-loading of the muscles requires about 1.25 seconds, while their loading to 4.2 bar requires 0.6 seconds.

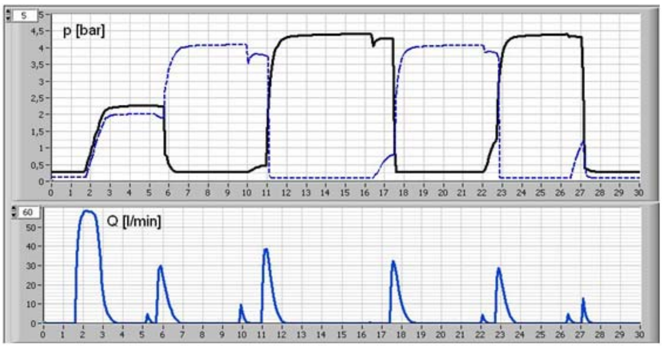

Fig. 9 Pressure and airflow evolution versus time

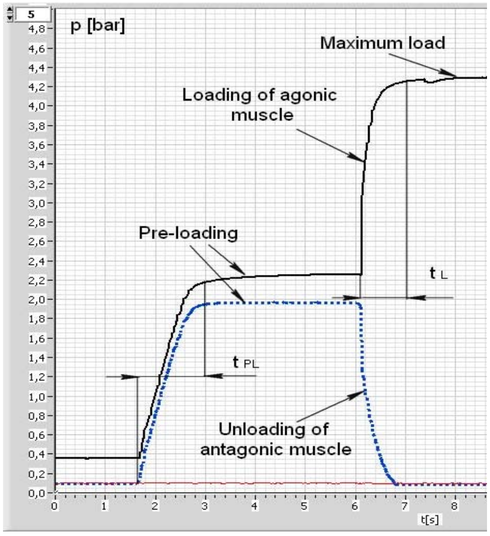

Fig. 10 Determining pre-loading and loading times

It is evident that the durations of pre-loading – loading of the two muscles can be reduced by feeding at a higher air flow rate, adjustable by means of the two one-way flow control valves. Experimentally, however, it could be observed that a smooth, shock free operation of the entire system is obtained for the time values mentioned above.

V. CONCLUSIONS

The paper presents the mechanical structure and the actuation system of a rotation module developed for robotic manipulation systems useful in rehabilitation activities of disabled persons. Driving the module by means of pneumatic muscles demonstrates that these actuators, still insufficiently known and used offer numerous advantages from the viewpoints of both dynamic behaviour and involved costs.

Emphasis is placed on the use of pneumatic muscle actuators with particularly favourable power to weight ratios; due to their highly flexible and soft nature they are beneficial in applications where a powered device is in close proximity to a user. In addition, antagonistic action allows direct compliance control, its advantages being increased safety and human friendly “soft” interaction. From the viewpoint of compliance control the developed device is not dissimilar to the characteristics of manipulation conducted by humans.

A detailed knowledge of pneumatic muscle actuators will allow their future replacing single drive cylinders in an increasing number of applications.

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