POWERED UPPER LIMB ORTHOSIS ACTUATION SYSTEM BASED ON PNEUMATIC ARTIFICIAL MUSCLES

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[Received 16 October 2017. Accepted 04 December 2017]

ABSTRACT: The actuation system of a powered upper limb orthosis is studied in the work. To create natural safety in the mutual “man-robot” interaction, an actuation system based on pneumatic artificial muscles (PAM) is selected. Experimentally obtained force/contraction diagrams for bundles, consisting of different number of muscles are shown in the paper. The pooling force and the stiffness of the pneumatic actuators is assessed as a function of the number of muscles in the bundle and the supply pressure. Joint motion and torque is achieved by antagonistic actions through pulleys, driven by bundles of pneumatic muscles. Joint stiffness and joint torques are determined on condition of a power balance, as a function of the joint position, pressure, number of muscles and muscles

KEY WORDS: Upper limb orthosis, actuation system, pneumatic artificial muscles, experimental diagrams, stiffness, torques.

1. INTRODUCTION

In recent years, the increase of applications, related to interaction in virtual environments increases the importance of the exoskeletons used as Haptic device. The subject physically interacts with virtual objects, while the forces generated through the interactions are feedback to the user through the exoskeleton haptic device [1]. Powered upper limb orthosis can simulate forces at the hand or the arm, like the weight of an object held. This is achieved by providing feedback to the various joints of the arm: the shoulder, elbow, and wrist.

Many exoskeletons possessing very different mechanical structure and drive are presented in literature, with or without force feedback effect [1-4]. These devices have to meet the safety requirements in addition to the traditional requirements for performance. It is important to develop exoskeletons possessing naturally low impedance in order to achieve natural safety in the mutual “human-robot” interaction.

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Two basic approaches are known to reduce the device stiffness: the active and the passive approaches. Active compliance guarantees a wide range of compliance variations; however, it does not ensure a high level of safety due to low resolution or noise in the sensors, long calculation time and servo system instability. Passive compliance, being independent of servo-responses, is reasonable for the implementation of increased safety. Different approaches to implement passive compliance are well known. All of them require the use of a passive or intrinsic compliant element [5].

One of the most common approaches to implement natural compliance is the usage of pneumatic artificial muscles (PAM), [6-9]. The air muscles originally presented by McKibben in the late 1950s for prosthetic applications are now being seen as an effective solution to safety problems in robotic manipulators [6]. Compared to other actuation systems, high power/weight and power/volume ratios allow air muscles to be a good solution for lightweight actuation design [7]. Air muscle output impedance is low over a wide frequency range because of low inertia and inherent compliance from the compressible gas, reducing uncontrolled impact forces to potentially safe levels. This natural compliance, however, limits the actuation performance in terms of bandwidth (dynamic force response). Moreover, energy losses caused by the inner rubber core and friction between the outer threads produce a noticeable and problematic force/displacement hysteresis phenomenon.

An air muscle actuator on its own can only produce pulling forces. For use in robotics, therefore, further consideration is necessary in order to generate bidirectional torques at a joint [8]. Such torques can be provided by a biologically inspired antagonistic configuration, in which two air muscles would produce torque proportional to the difference of the applied pulling forces. Furthermore, the redundancy in actuation allows adjustment of the stiffness of the joint in an open loop manner by air muscle co-contraction [7]. The advantage of co-contraction instead of active stiffness control is noteworthy as it overcomes the closed loop gain limitations related to transmission delay and bandwidth.

A number of different approaches have been proposed in the literature in order to solve the air muscle limitations. Some strategies focus on air flow effects and air muscle physical structure, showing that reducing the dead volume in the muscle and carefully monitoring the air flow rate increases actuation bandwidth, increases system stiffness and reduces air consumption [10]. In addition to low dynamic force response, artificial muscle – based joint have restricted torque capacity and restricted range of motion due to the limited muscle contraction. Typically, torque capacity can be increased by utilizing a larger pulley [11]. Several methods have been proposed in literature to kinematical adjust spring force/torque, using a variable radius pulley.

Other approaches rely more upon improved control strategies. A hybrid actuation approach is proposed [12], which consists of a pair of PAMs coupled to a low-inertia
DC-motor in parallel. The macro torque component is primarily sustained by the muscles, while the ‘resultant torque error is compensated by the DC motor. This configuration improves the overall bandwidth, as the fast DC motor compensates for the slow dynamics of the muscles. In this control scheme, the DC motor supports the low density, high frequency part of the torque command, while the air muscle actuation provides high density, low frequency torque.

The aim of the present work is to propose a solution for actuation of the upper limb orthosis, based on pneumatic artificial muscles, which will provide force reflection on the human arm on the one hand and natural safety in the mutual interaction of the “human-robot” on the other. This solution has to be performed with the limitations of the pneumatic muscles mentioned above, by looking approach to overcome them.

2. CHARACTERISTIC OF PNEUMATIC ACTUATORS USED

To develop a powered upper limb orthosis, possessing natural safety in the mutual “man-robot” interaction, an actuation system, based on pneumatic artificial muscles (PAM) is selected [13]. One approach of using actuators with different numbers of PAM is developed to overcome air muscle limitations. For the development of this approach, the present work explores the actuation of a rotating joint from the structure of the orthosis, through artificial pneumatic muscles. Orthosis has 4 degrees of freedom and all joints have a similar actuation.

Self-made PAM are used, which allow greater control over the dimensions, the forces and the general performance. Each PAM consists of two layers: an inner one, representing rubber liner and outer one, representing braided nylon. Endcaps are allocated at both ends, to which the two layers are clamped by clips. A pipeline for supplying the pressurized air is located in one of the endcaps. The muscles possess a maximum diameter $D_0 = 0.016$ m and nominal length $L_n = 0.390$ m. The actuators have been created representing a bundle of several pneumatic muscles (Fig. 1). Muscles from the bundle are fed in parallel with air at a maximum pressure 600 kPa (6 bars). The supply pipeline is connected with two parallel arranged valves – one to supply the maximum pressure and the other one – for discharge to the atmosphere. All the muscles of the bundle are connected together mechanically at one and at the other end.

Fig. 1. Pneumatic muscle bundle.
Muscle bundle contraction is defined as the difference between their nominal value $L_n$ and the current value $L$:

$$C = L_n - L,$$  

(1)

Experiments were conducted under static load of the used PAM, as the number of muscles in a bundle and the magnitude of the supply pressure has been altered. At the pressure set, the contraction of muscles is measured from their nominal value $L_n$ to a minimum value $L_{\text{min}}$. The maximum contraction of the muscle bundle is the difference

$$C_{\text{max}} = L_n - L_{\text{min}}.$$  

(2)

Experiments have been carried out to assess the rate of muscle response at a different state of muscle contraction. Muscle contraction $C$ is represented as a percentage $c$ of the nominal muscle length $L_n$, determined by the outer braided layer

$$c = 100C / L_n.$$  

(3)

Experiments were performed with a muscle fixed at both ends with a set of different contractions, at pressure change of 0 to 500 kPa by switching on the supply valve for each contraction set. The change in muscle force $P$ is measured by a computer linked load cell sensor. The results are shown in Fig. 2 for a muscle with the following contraction sets $c$: 8%, 13%, 19%, 24%, 28% and 32%. As shown in the graph, the muscle reaches the effective force for the corresponding contraction for a different time.

![Fig. 2. Force response of muscle with different contractions $c$ (8% – 32%) at supply pressure of 500 kPa.](image-url)
Response time is lower in muscle with low contraction and higher in muscle with high contraction. The increase in force is a non-linear function of time with a drop in the beginning. When the contraction is about 24%, the force changes, but does not exceed its original size. When the contraction is 28%, 32% and so on, muscle feeding leads to a decrease in muscle strength.

Experimentally obtained force/contraction diagrams for the used bundles, consisting of 1, 2 and 3 muscles at constant supply pressure of 500 kPa, are shown in Fig. 3a) and at a pressure of 0 kPa in Fig. 3b). The experiments were carried out on a

![Fig. 3. Force/contraction characteristics of bundles of 1, 2 and 3 muscles with overload over the nominal length $L > L_n$: a) at a pressure of 500 kPa; b) at a pressure of 0 kPa.](image-url)
stand allowing a change in muscle contraction from 0 to 35%. The muscle force $P$ is recorded by a load cell sensor. The charts in Fig. 3 are captured at loading/unloading, and hysteresis is reported to 7.5%. The experiment was performed with an overload over the nominal length of the muscles $L > L_n$.

As shown in the graphs, at deformations larger than their nominal length, the muscle actuators have a big change in their characteristics. This is due to the fact that these are deformations of the nylon braid, which determines the strength of the muscle. For position and force control, the bundles of pneumatic muscle actuators will be used at deformations not exceeding their nominal length, where the hystere-

Fig. 4. Force/contraction of muscle bundles of 1, 2, …, 6 muscles at supply pressure of: a) 400 kPa and b) 0 kPa.
sis is smaller and the characteristic is closer to linear. For this reason, additional experiments were made in deformation up to their nominal lengths with bundles of 1 to 6 muscles, and the characteristic was reported under load. Experimentally obtained force/contraction diagrams at constant supply pressure of 400 kPa are shown in Fig. 4a) and at a pressure of 0 kPa in Fig. 4b).

As seen from the graphs, the increase in the muscle number leads to an increase in the bundle stiffness. At zero pressure, the muscles show elastic properties, determined by inner rubber liner. Braided pneumatic muscle behaves like a pressure-dependent variable compliance spring. For a definition of the used PAM, as a nonlinear quadratic spring, a simplified static model [6] can be used, which is described in [9] by the following equation:

\[ P = K_{\text{gas}} p L (L - L_{\text{min}}), \]

where \( P \) is the force of the muscles, \( K_{\text{gas}} \) is a muscle geometry dependent coefficient, \( p \) is the supply pressure.

As a result of experiments conducted under static load on the used PAM, in which the number of muscles in a bundle and the magnitude of the supply pressure were altered, it was obtained that at zero pressure the muscles show elastic properties determined by inner rubber liner. Taking into account this property of the muscles and according to (1) and (2), the equation (4) is transformed as follows:

\[ P = (k_0 + k_1 p)(L_n - C)(C_{\text{max}} - C). \]

Above, \( k_0 \) and \( k_1 \) are empirically derived coefficients. In the process of approximation, the following relations of the coefficients \( k_0 \) and \( k_1 \) have been determined in accordance to the number \( \text{mus} \) of bundle muscles.

\[ k_0 = -39 + 321 \text{ mus}, \quad k_1 = -21 + 4.41 \text{mus}. \]

Approximated characteristics are composed for bundles of different muscle number \( \text{mus} = 1, 2, 3, 4, 5 \) and 6, at pressure \( p = 100, 200, 300 \) and 400 kPa. Approximated characteristics at a supply pressure of 400 kPa and a supply pressure of 0 kPa, are shown in Fig. 4a) and Fig. 4b), where they are compared with experimentally obtained characteristics. Unlike other PAM models, the proposed static model takes into account more parameters, such as: the number of muscles in the bundle, the current contraction and the maximum contraction, as well as the nominal length of the used muscles and the pressure. The muscle force at zero pressure is also taken into account. By accepting that the supply pressure is kept at a constant value, the stiffness of the muscle bundle can be determined as a derivative of the muscle force.
(5) over muscle contractions, or

\[
k = \frac{\partial P}{\partial C} = (k_0 + k_1 p)(2C - (L_n + C_{\text{max}})) .
\]

The stiffness according to (7), (5) and (6) is a linear function of the pressure, the contraction and the number of the pneumatic muscles in the bundle.

3. Actuation System, Joint Torques and Joint Stiffness Control

Joint motion and torque on the exoskeleton joints is achieved by antagonistic actions through pulleys, driven by bundles of pneumatic muscles (see Fig. 5 a). Two bundles – “a” and “b” – work together in an antagonistic scheme, simulating a biceps-triceps system, to provide the bidirectional motion/force.

When the muscle bundles “a” and “b” move the joint in an antagonistic scheme (Fig. 5 b), the current contractions \( C_a \) and \( C_b \) of each bundle in the joint are determined by the position \( q \) of the driven joint. Muscles are slung over the pulley at the joint, so their contractions depend on the radius of the pulley \( r \).

\[
C_a = r(q_{\text{max}} - q) ,
\]

\[
C_b = r(q - q_{\text{min}}) .
\]

In each joint position, the sum of contractions (8) and (9) represents the sum of pre-tensioning of the two muscle bundles

\[
C_q = r\Delta q_{\text{max}} = r(q_{\text{max}} - q_{\text{min}}) .
\]

Fig. 5. Joint actuation through pneumatic muscle actuators: a) antagonistic actions of bundles of pneumatic muscles; b) antagonistic scheme for joint motion and torque.

To generate the maximum forces, the muscles are attached to operate with minimum contraction; i.e., in one end position of the joint \( q_{\text{max}} \), one bundle has zero contraction, and at the other end position of the joint \( q_{\text{min}} \), the other has zero contraction. In any position \( q \) of the joint, the contractions of the two muscle bundles are

\[
C_a = r(q_{\text{max}} - q) ,
\]

\[
C_b = r(q - q_{\text{min}}) .
\]
Then, according to (4), (5), (8) and (9), the forces of joint muscle bundles “a” and “b” are

\begin{align*}
P_a &= (k_{a0} + k_{a1}p_a)(L_n - r(q_{\text{max}} - q))(C_{\text{max}} - r(q_{\text{max}} - q)), \\
P_b &= (k_{b0} + k_{b1}p_b)(L_n - r(q - q_{\text{min}}))(C_{\text{max}} - r(q - q_{\text{min}})).
\end{align*}

According to (7), (5), (8) and (9), the stiffness of muscle bundles a and b are

\begin{align*}
k_a &= (k_{a0} + k_{a1}p_a)(2r(q_{\text{max}} - q) - (L_n + C_{\text{max}})), \\
k_b &= (k_{b0} + k_{b1}p_b)(2r(q - q_{\text{min}}) - (L_n + C_{\text{max}})).
\end{align*}

The joint stiffness can be defined as a derivative of joint torque with respect to joint position

\begin{equation}
K_q = \frac{\partial Q}{\partial q}.
\end{equation}

The generated torque in the rotation joint is

\begin{equation}
Q = [-r; r]P,
\end{equation}

where

\begin{equation}
P = [P_a; P_b]^T
\end{equation}
is the vector of the driving forces in the actuators (11) and (12) and r is the pulley radius. If the muscle contractions (8) and (9) are unified in the matrix

\begin{equation}
C = [C_a; C_b]^T,
\end{equation}

after substituting equations (16), (17) and (18) into (15), it follows that:

\begin{equation}
K_q = [-r; r] \frac{\partial P}{\partial C} \frac{\partial C}{\partial q}.
\end{equation}

The derivative of the muscle forces about muscle contractions gives the stiffness of the selected muscle bundles (13) and (14), incorporated in the matrix

\begin{equation}
\frac{\partial P}{\partial C} = \begin{bmatrix} k_a & 0 \\ 0 & k_b \end{bmatrix}.
\end{equation}

The derivative of the muscle contractions (8) and (9), about the joint position, represents a vector with constant components

\begin{equation}
\frac{\partial C}{\partial q} = [-r; r]^T.
\end{equation}
After substitution into (19), it follows that:

\[ K_q = r^2[k_a + k_b]. \]

Joint stiffness \( K_q \) (eq. (22)) is determined by the stiffness of muscle bundles \( k_a \) and \( k_b \) (eqs. (13) and (14)). When both muscle bundles are different, the joint stiffness depends on the joint position, as well as on the pressure, number of muscles and pre-tensioning of muscle bundles (10). The stiffness in the joint is realized in the condition of the antagonist equilibrium of forces (11) and (12) of the two muscle bundles. The antagonistic balance in each joint is achieved by generating control torques (16) in each joint, according to the equality

\[ Q = (P_b - P_a)r = Q_b - Q_a. \]

According to (11) and (12), the joint torques are a function of the joint position, as well as a function of the pressure, number of muscles and pre-tensioning of muscle bundles. An experiment is conducted to illustrate the change of the torque in the joint, under the influence of bundles antagonists \( a \) and \( b \), respectively consisting of \( \text{mus}_a = 3 \) and \( \text{mus}_b = 7 \) muscles. When the pulley radius is \( r = 0.0315 \) m and the joint stroke is \( (q_{\text{max}} - q_{\text{min}}) = 120^\circ \) according to (10), the pre-tensioning of the two muscle bundles is 0.066 m or 16.9%.

The variation of the joint torque according to (23) as a function of the torques created by the forces \( Q_a, Q_b \) of the actuators antagonists at different pressures \( p_a, p_b \) from 0 to 600 kPa is shown in Fig. 6a). Shaded area of the chart shows the muscles work area, corresponding to the sum of pre-tensioning of the two bundles (10) expressed as a percentage of the nominal muscle length \( L_n \), \( c_q = 100C_q/L_n = 16.9\% \) at joint move \( q_{\text{max}} - q_{\text{min}} = 120^\circ \). This area corresponds to a joint torque obtained at a pressure of muscle bundles \( p_a = 600 \) kPa and \( p_b \) between 0 and 600 kPa. Changing the pressure of the two muscle actuators changes the torque in the joint.

The joint stiffness according to (13), (14) and (22) is positionally dependent and is determined by the pressure, the number of muscles in the antagonist bundles and the muscles pretensioning. Figure 6 (b) shows the change in muscle stiffness as well as stiffness in the joint at the bundles antagonists \( a \) and \( b \) consisting of \( \text{mus}_a = 3 \) and \( \text{mus}_b = 7 \) muscles. The experiment is performed at a pressure of 600 kPa and a joint move \( q_{\text{max}} - q_{\text{min}} = 120^\circ \). As can be seen from the graph, the value of the joint stiffness is limited by the number of muscles in the bundles and the allowable pressure in them.

The actuation of the orthosis joints with PAM bundles in antagonistic scheme allows both control of the joint torques and parallel control of the joint stiffness.
In the first case, to obtain maximum moment in the joint, it is appropriate for one actuator to be passive (with zero pressure) and the second to be active (with controllable pressure). When changing the direction of the torque, the actuators change their roles. Figure 7 shows a block diagram of the joint torque control. The pressures of the active muscle actuators are calculated according to equations (11), (12) and (23), to achieve the required joint force command Q, while the pressures of the passive muscles is 0. The last one is represented by the function

\[ p = f(Q, q). \]

![Fig. 6. Moving joint with antagonist bundles consisting of \( \text{musa} = 3 \) and \( \text{musb} = 7 \) muscles: a) joint torque as a function of torques \( Q_a, Q_b \) at different pressures \( p_a, p_b \) from 0 to 600 kPa.; (b) the two muscle stiffnesses \( k_a, k_b \) and the summary joint stiffness \( K_q \) at a pressure of the two bundles of 600 kPa.](image)

![Fig. 7. Block diagram of the joint torque control.](image)
Pressures in the muscle bundles $p_a$ and $p_b$ are monitored by pressure sensors mounted to each muscle bundle. When the torque and stiffness of the joint are controlled simultaneously, the pressure $p_a$ for actuator antagonists is set to achieve the desired stiffness in the joint. For this purpose, an optimization procedure has been developed [14], which finds the pressures $p_a$ according to equations (13), (14) and (22). In this procedure, the pressure $p_b$ for the actuators’ agonists is calculated, using equations (23), (11) and (12) to achieve the required joint force command $Q$.

4. Joint System Control

The control of the exoskeleton system is built up as a Distributed Control Scheme (DCS). The exoskeleton consists of several Micro-controller Units (MCUs) which communicate with the Master controller through standard Two Wire Interface (i2c) communication protocol and perform the following tasks for each joint: actuation, sensing, signal processing and control. The master controller can be used as an interface between the PC and the valve controllers that coordinates all the valve control units and feeds them with self-generated data, based on the exoskeleton’s operating mode.

MCUs are connected to the sensors and actuators by a control loop, consisting of a pressure sensor, controller, and control valves. Each MCU runs at 16 MHz and can control up to 8 PAMs (8 inlets + 8 outlets) with the joint torque control scheme illustrated in Fig. 7. Joint muscle pair is controlled by a local micro-controller (Atmega 2560). In each joint, 4 pneumatic valves (type on/off, 3 Port Solenoid Valve, series V114, SMC Automation) are used for joint actuation.

Positional and pressure measurements are transmitted to the controller, through the aid of a signal conditioning input/output (I/O) device. Control algorithm and program application are build up, according to control schemes in Fig. 7, using C++ program code.

5. Conclusion

A solution for actuation of upper limb orthosis, based on pneumatic artificial muscles (PAM) is presented in the work, which provides force reflection on the human arm on the one hand and natural safety in the mutual interaction “human-robot” on the other. To overcome the limitations of the existing muscles, one approach of using actuators with a different number of PAMs is studied.

Experimentally obtained characteristics of actuators, consisting of different number of muscles are shown in the paper. It is reported, that muscle actuators have a strong change in their characteristics at deformations larger than their nominal length. To control the force, bundles of PAM are used at deformation to their nominal length where the hysteresis is smaller and the characteristic is closer to the linear one. For
replication of PAM based actuators as a nonlinear spring, quadratic functions of muscle contraction are used. The force and the stiffness of the pneumatic actuators are assessed as a function of the number of muscles in the bundle and the supply pressure. Approximated characteristics are composed for bundles of different muscle number, where they are compared with experimentally obtained characteristics. Unlike other PAM models, the proposed static model takes into account more parameters such as: the number of muscles in the bundle and the muscle force at zero pressure.

Joint motion and torque on the exoskeleton arm is achieved by antagonistic actions through pulleys, driven by bundles of pneumatic muscles. An approach is presented for the joint control by antagonistic interaction of bundles with different numbers of pneumatic muscles. Joint stiffness and joint torques are determined on condition of a power balance, as a function of the joint position, pressure, number of muscles and muscles’ pretensioning. The actuation of the upper limb orthotics with bundles from different number of muscles in an antagonistic scheme allows both joints torque control and parallel joint stiffness control. The range of torque and the range of stiffness in the joint are regulated by selecting an appropriate number of muscles in the antagonist actuators.

ACKNOWLEDGEMENTS
This work was funded by the Bulgarian Science Found, Call: 2016, through Project AWERON – DN 07/9, to which the authors would like to express their deepest gratitude.

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