DESIGN OF UPPER LIMB EXOSKELETON ACTUATED WITH PNEUMATIC ARTIFICIAL MUSCLES

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ABSTRACT. The aim of the work is to present the design of an active exoskeleton for upper limb assistance with five degrees of freedom. The upper limb exoskeleton is an active orthotic device which consists of two segments connected with hinge joints and two lightweight shaped bodies. Basic feature of the exoskeleton is the ability to rotate and support the shoulder and elbow joints by means of two or three pneumatic artificial muscles. These two joints have the specific range of motion that will assure the ability of the system to perform relatively complex manipulations. The upper limb exoskeleton is attached to the body exoskeleton by means of one spherical joint with three degrees of freedom. The general layout of the arm orthosis, design description and requirements are presented.

The mechanical assistive device is actuated by pneumatic artificial muscles (PAM) as power source for the system. Basic factors determining the length and the diameter of the actuators for each joint are presented. The device can be used for training/physiotherapy system in cases of the treatment of full or partial loss of function in the upper limb.

Keywords: Exoskeleton; upper limb; physiotherapy; training; pneumatic actuator

1. Introduction

An exoskeleton is active anthropomorphic mechanical device that is worn by an operator and fits closely to his body. Wearing in this way it should be controlled and moved in concert with the operator’s movements assisting his limbs. Powered exoskeletons, currently developed within research groups around the world, are focused on assisting human locomotion or to help lift heavy loads through wearable machines [1]. Several different suits for the upper extremities [2] and pneumatically powered exoskeletons have been created by research groups. Salford University Robotics team published results concerning the development of a 7-DoF exoskeleton aimed at the rehabilitation and training of an upper limb, motorized by pneumatic McKibben muscles [3].
Current industrial pneumatic artificial muscles are essentially derived from the McKibben model [4]. (see technical document of Festo Fluidic Muscle and SHADOW Air Muscle, Shadow Robot Group, http://www.shadow.org.uk). With its high power-to-weight and power-to-volume ratios, closely imitating the functions of the natural skeletal muscle, the McKibben muscle is the most adapted artificial muscle for motorizing “soft” and human-size robot arms. Tire manufacturer Bridgestone has shown the possibility of designing and controlling robot-arms entirely actuated by McKibben type artificial muscles called “rubbertuators” (i.e., rubber actuators) in which revolute joints are driven by two antagonistic muscles [5]. The soft nature of the pneumatic muscle actuators provides a clean, low cost actuation source with a high power/weight ratio and safety due to the inherent compliance. Several other groups had noted the potential of this form of actuation [6]. New applications were also identified particularly in the area of bio-robotics [7], and rehabilitation [8].

The paper presents the design and studies of a novel construction of an active exoskeleton for upper limb actuated by pneumatic artificial muscles. The assistance device will consist of two full orthoses for the left and right upper limb equipped with sensors and control system. Six pneumatic artificial muscles will assist motions of each limb. The prototype will be capable to perform rotation on each joint and 3 axis positioning using three pneumatic muscles. There is a possibility for different motions generated by different combinations of actuated muscles on reaching the pre-set position. While one muscle group contracts and rotates the joint in one direction, the other muscle group will elongate.

2. Methods

The design of active orthotic device is inspired by the biological musculoskeletal system of human upper and lower limbs, and mimics the muscle-tendon-ligament structure.

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. 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.

Based on the human model, over the last years several actuation solutions have been developed using pneumatic muscles working in tandem [9], [10]. Fig.1. shows some of these constructive variants.
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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.

Fig.1. Pneumatic muscle actuated rotation modules

This paper presents and studies a novel construction of a soft orthotic device, different from others by the fact that the three pneumatic actuators rotate together the shoulder joint constructive element and mimics the muscle-tendon architecture in a biological musculoskeletal system of a human upper limb.

In contrast to prior orthotic designs the device has multiple pneumatic artificial muscles that mimic not only the morphology but also the functionality of the real biological muscles in terms of its ability to control varied sagittal and mediolateral motions such as flexion/extension, abduction/adduction and lateral-medial rotation in the shoulder and flexion/extension, pronation/supination of the forearm.

3. Mechanical Structure of the Exoskeleton Arm

The fundamental principle in designing the exoskeleton joints is to align the rotational axis of the exoskeleton with the anatomical rotation axes.

The human arm has three complex articulations: shoulder, elbow and wrist. Our prototype, being dedicated to the shoulder and elbow, covers three shoulder degrees of freedom (abduction/adduction, flexion/extension and internal/external rotation) and one elbow DOF (flexion/extension) with additional forearm DOF (pronation-supination).

The construction of the arm exoskeleton is achieved by rotation of two modules, combined with pneumatic muscles and allows five degrees of freedom. The diagram on Fig.2 ensures one degree of freedom for the elbow (flexion-extension) obtained by one pair of pneumatic muscles. Fig.3 presents shoulder joint with three degrees of freedom (abduction-adduction, flexion-extension, internal-external rotation) obtained by three pneumatic muscles.
Fig. 2. Diagram of elbow joint with one DOF (flexion-extension) obtained by one pair of antagonistic pneumatic muscles.

Fig. 3. Diagram of shoulder joint with 3 DOF (abduction-adduction, flexion-extension, internal-external rotation) obtained by three pneumatic muscles.

The major difference with respect to previous works is that the shoulder joint is driven by agonist PAM attached anterior to the thorax exoskeleton module, the antagonist PAM attached posterior to the module and one medial PAM to ensure the balance of a certain intermediary position of the actuated system.

The exoskeleton arm is actuated by six PAM that transmit the appropriate torque to each joint utilizing a cable-based transmission system. Four force/torque sensors are located at all interface elements between the human arm and exoskeleton as well as between the exoskeleton and external load, measuring all forces and torques acting and reacting between the human arm, the external load, and the exoskeleton.
4. Actuator Attachments

The exoskeleton arm is actuated by six PAM that transmit the appropriate torque to each joint utilizing a cable-based transmission system. The primary advantage of using cable drive transmissions lies in their ability to transmit loads over long distances without the friction or backlash. An I-beam cross section shape was used for all the links allowing bilateral cable routing, as well as high structural stiffness and appropriate strength.

Fig. 4 Block diagram of the shoulder joint actuators

The compact actuator structure allows for integration close to their respective powered joints. Since most of the joints required a range of rotation in excess of 90°, double groove pulleys can be employed.

The shoulder joint is actuated with three actuators (shoulder, anterior and posterior PAM) mounted across the shoulder, at the front of the body brace and behind the operator’s back. The three shoulder degrees of freedom are generated with the following muscles combinations:

- **shoulder medial/lateral rotation** actuators (anterior and posterior PAM) are fixed at the front and behind of the human trunk support section. The forces are transmitted through cables the direction of which is controlled by small idler pulleys on the shoulder level;
- **shoulder abduction** actuator is directly coupled across the shoulder while the **adduction** is activated through the cables of anterior and posterior PAM;
- **shoulder flexion/extension** actuator is a combination of anterior and abduction PAM and correspondingly anterior and posterior PAM.

The **elbow flexion/extension actuators** (two actuators) are mounted on the upper arm. The force difference between the agonist and the antagonist muscle generates a positive or negative torque/motion at the joints.
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The forearm pronation/supination is realised by means of the flexion actuator and an additional actuator mounted in front of the forearm parallel to the flexion actuator.

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. 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. The hinge joint is attached laterally of the orthosis coinciding with the elbow joint, thus allowing rotation in both directions.

5. Actuation System

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 $q$, 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

$$L_2 = L_0 + \Delta L.$$  

Similar is the operating principle of the shoulder joint. The three muscles form different combinations for different DOFs and act as antagonists.

$$p_n = p_{0n} - \Delta p_n, \quad L_n = L_{0n} + \Delta L_n \quad (n=1...3)$$  

$$ (F_{PM1} - F_{PM2}) r = mgl \sin q,$$

where $q$ is the angle of the joint, $F_{PM1}$ is the force of the agonist muscle group, and $F_{PM2}$ is that of the antagonist muscle group, $l$ is the distance between the ages of the joint and the centre of the mass of the arm segment.

The following equation describes the dynamic behaviour of the exoskeleton.

$$M(q)\ddot{q} + V(q, \dot{q}) + F(q) + G(q) + J^T F_R = \tau_{\text{joint}} \quad (7)$$

where
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$q$ is the joint variable $n$-vector

$\tau_{\text{joint}}$ is the joint $n$-vector of the generalized torques

$M(q)$ is the inertia matrix

$V(q, \dot{q})$ is the coriolis/centripetal vector

$F(q)$ is the friction vector

$G(q)$ is the gravity vector

$F_r$ is the force that the arm generates at the end-tip

$J^T$ is the transpose Jacobian of the manipulator

6. Requirements for System Performance

Commercial form of the braided actuator is available from Festo. The pneumatic muscle actuators are constructed as a two-layered cylinder, Fig. 5. The detailed construction, operation, and mathematical analysis of these actuators can be found in [11]. The structure of the muscles gives the actuator a number of desirable characteristics [12]. The manufacturer provides greater control over the dimensions, forces and general performance of the pneumatic muscles allowing them to be tailored for this application. Within each actuator a pressure sensor has been incorporated to monitor the internal state of the muscle. The complete unit can safely withstand pressures up to 700KPA (7 bar), although 400kpa (4 bar) is the operating pressure for this system.

The developed rotation module for the elbow joint 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 about 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 ± 45°.

In practical application the real motion is going under different force constraints. The system analysis has to be done for the functions describing the structure’s dynamics. Several important features should be taken into account during the design of the system.

The arm exoskeleton places kinematic constraints on the human arm. It is desirable that the exoskeleton does not compromise the natural arm motion and workspace of the operator. The device should also have torque capabilities to match and enhance human abilities. Table 1 show the range of motion and torque capabilities of the human arm for reference.

Table 1. Workspace and torque limits of human arm

<table>
<thead>
<tr>
<th>Joint</th>
<th>Range of motion (°)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Flexion/extension</td>
<td>180/60</td>
</tr>
<tr>
<td>Adduction/abduction</td>
<td>48/134</td>
<td>27-50</td>
</tr>
<tr>
<td>Medial/ Lateral Rotation</td>
<td>97/34</td>
<td>6-20</td>
</tr>
<tr>
<td>Elbow</td>
<td>Flexion/extension</td>
<td>142/0</td>
</tr>
<tr>
<td>Supination/pronation</td>
<td>90/77</td>
<td>5</td>
</tr>
</tbody>
</table>

The muscles that are to be used for the system of the exoskeleton have a diameter of 2cm to 4cm with a length varying from 15cm to 45cm. The factors that determine the length and the diameter of the actuator are range of motion and the required torque at each joint.

7. Discussion

The device will consist of two full orthoses for the left and right upper limb equipped with specially adapted actuators, sensors and control system. The system will have the ability to perform relatively complex manipulations (to perform flexion/extension, abduction/adduction, lifting weights, doing different exercises etc.).

Pneumatic actuators have exceptionally high power and force to weight/volume ratios >1kW/kg. The actual achievable contraction is dependent on the construction and loading but is typical 30%-35% of the dilated length - this is comparable with the contraction achievable with natural muscle. Being pneumatic in nature the muscles are highly flexible, soft in contact and have excellent safety
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potential. This gives a soft actuator option, which is again comparable with natural muscle.

Force and position control using antagonistic pairs for compliance regulation is possible. To achieve this, the device control architecture employs joint position/torque control for the execution of the conventional human manipulation.

8. Conclusions

The aim of this work is the development and design of an active orthosis for upper limbs (exoskeleton for arm motion). The basic features of the orthosis segments are the lightweight shaped bodies with the ability to rotate and support the joints of the shoulder and elbow by three pneumatic artificial muscles.

A five DOF model of the human arm was presented including two segments (upper arm and lower arm) connected to each other and the human trunk section with a frictionless ball-and-socket shoulder joint and two-axis elbow. These two joints have the specific range of motion that will assure the ability of the system to perform relatively complex manipulations.

REFERENCES


