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NEW EXOSKELETON ARM CONCEPT DESIGN AND ACTUATION FOR HAPTIC INTERACTION WITH VIRTUAL OBJECTS*

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Abstract. In the work presented in this paper the conceptual design and actuation of one new exoskeleton of the upper limb is presented. The device is designed for application where both motion tracking and force feedback are required, such as human interaction with virtual environment or rehabilitation tasks. The choice is presented of mechanical structure kinematical equivalent to the structure of the human arm. An actuation system is selected based on braided pneumatic muscle actuators. Antagonistic drive system for each joint is shown, using pulley and cable transmissions. Force/displacement diagrams are presented of two antagonistic acting muscles. Kinematics and dynamic estimations are performed of the system exoskeleton and upper limb. Selected parameters ensure in the antagonistic scheme joint torque regulation and human arm range of motion.
Key words: Human arm exoskeleton, pneumatic muscle actuators, virtual environments interaction, mechanical structure, antagonistic actuation, joint range of motion, joint torque.

1. Introduction

Exoskeleton is an externally wearable robot with joints and limbs corresponding to those in the human body. Exoskeleton transmits torques to human joints by means of actuators allocated in its mechanical structure. Exoskeletons are used for four basic functions by means of different control algorithms [1]: a)

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Rehabilitation – fit closely to his or her body, fulfils tasks of physical therapy in an active or passive working mode; b) Haptic device – the subject physically interacts with virtual objects, as the interaction forces are applied by the exoskeleton opposite the operator; c) Master device – for tele-communication robot control „master-slave" as the interaction forces are applied by the exoskeleton opposite the operator; d) Assistive device - human body amplifier, operator feels that the load is diminished, accepted by the exoskeleton.

The first modern exoskeleton arm was designed by Perceptual Robotics Laboratory (PERCRO) for replication of sensations of contacts and collisions [2]. This is a seven degree of freedom (7-DoF) ungrounded device, attached to operator's shoulder and torso. The operator holds onto the device with his/her palm. Hence, the device can only exert forces at the palm of the user. The authors of PERCRO have developed arm exoskeletons for haptic interaction with virtual environments L-Exos [3, 4]. This is a five-DoF exoskeleton with a wearable structure and anthropomorphic workspace that can cover the full range of motion of a human arm. It uses Direct Current (DC) motors with a cable transmission system for actuation. The forces are exerted at the palm of the user, too. A 9-DoF under-actuated exoskeleton arm using pneumatic actuators is developed by [5]. Their device allows for full reproduction of the human arm's workspace when operating the exoskeleton. An alternate arm exoskeleton developed at the Korea Institute of Science and Technology addresses the limited wear ability issues of previous designs by using parallel mechanisms and pneumatic actuators [6]. The wearable Salford arm addresses some of the issues and the limitations of earlier designs [7]. For example, nearly ninety percent of the human arm's workspace can be replicated with their device. Pneumatic muscle actuators (PMA) were selected to power the robot due to their high power-to-weight ratio and their natural compliance. Soft arm–exoskeleton was used in physiotherapy and training. Another design is presented [1] of a seven-DoF powered cable-driven arm exoskeleton for neuro-rehabilitation. Proximal placement of motors, distal placement of pulley reductions, and open mechanical human–machine interface are a few features that add to the performance and ease-of-use of the device. Additional characteristics include low inertias, high-stiffness links, and back drivable transmissions without backlash.

The objective of the work presented in this paper is to create a new concept project of a soft upper-limb force-feedback exoskeleton. The device to be used is an exoskeleton with a wearable structure and anthropomorphic workspace that can cover the full range of motion of a human arm. Device should enable an application of force within a wide range of human limb and reproduction of natural compliance. The device to be designed can be used for application where both motion tracking and force feedback are required, such as human interaction with virtual environments or rehabilitation tasks.

2. Mechanical structure

The exoskeleton mechanical structure as a wearable device must fulfil the following design requirements [7]: light with low mass/inertia; safety; comfort of wearing; anthropomorphic workspace arm, extensive range of motion, etc.

The mechanical arm structure is to be used as the basis for the developed system that can have 5 DoF corresponding to the natural motion of the human arm from the shoulder to the elbow, but excluding the wrist and the hand. The structure of the human arm possesses 3 DoF in the shoulder (flexion/extension, abduction-adduction and lateral-medial rotation), 2 DoF at the elbow permitting flexion/extension and pronation-supination of the forearm, Fig. 1.

The device, which can be seen to function as a powered exoskeleton, usually is build up of a serial kinematics structure consisting of rotational joints kinematics equivalent to the structure of the human arm [2]. A closed loop chain structure is build up when the human arm is included to the exoskeleton, as it is clearly shown in Fig. 1.

For example, exoskeleton structure shown in Fig. 1a consists of five rotational joints [3]. The first two rotational joints are incident and mutually orthogonal in order to emulate the kinematics of a spherical joint with the same human shoulder rotation centre, which is supposed to be fixed in space.

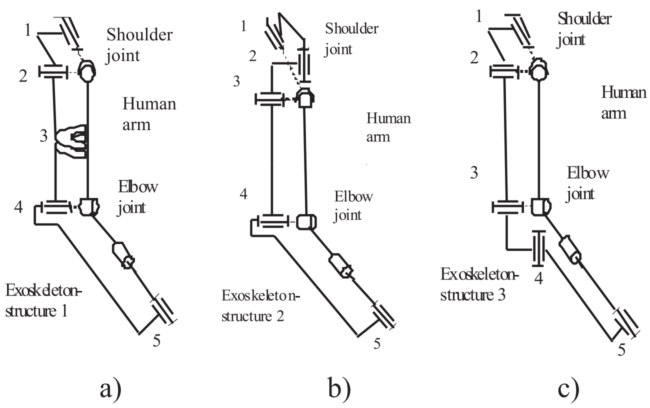

Fig. 1. Exoskeleton structures, kinematics equivalent of the human arm

The third joint is coincidental with the ideal axis of the upper arm, in order to emulate the kinematics of a spherical joint with the same centre of rotation as the human lateral-medial rotation. The circular guide could be developed for the implementation of this rotational joint. The fourth and fifth joints were assumed to be coincidental with the elbow joint and the forearm, respectively in order to allow the flexion/extension of the forearm and prono-supination of the wrist.

Other solutions are created to avoid the circular guide with a heavy and complicated construction. For example, structure of the exoskeleton, shown in Fig. 1 b consists of five rotational joints, too. The first three joints are incident and mutually orthogonal in order to emulate the kinematics of a spherical joint with the same centre of rotation of the human shoulder. The first joint possesses a horizontal axis of rotation, emulating the shoulder abduction-adduction motion. The next two joints emulate the effective motion of shoulder lateral-medial rotation and shoulder flexion/extension, without decoupling the motion in a way typical for structure in Fig. 1a.

In the next solution, the first two rotation joints are incident and mutually orthogonal in order to emulate the kinematics of a universal joint with the same centre of rotation of the human shoulder, (Fig. 1c). The third and the fourth joints are selected to be two rotational joints, incident and mutually orthogonal in order to emulate the kinematics of a universal joint with the same centre of rotation of the human elbow. The third and the fourth joints emulate the effective motion of the elbow flexion and human shoulder rotation without decoupling the motion in a way typical for structure in Fig. 1a. The fifth joint was assumed to be coincident with the forearm, in order to allow the prono-supination of the wrist. This joint is non-actuated.

Structure in Fig. 1c is chosen in order to manufacture a device that meets the requirements of a powered exoskeleton in which two equal type universal joints are used with 2 DoF and thus, circular guide and three axes joints are avoided. In this structure, the effective movement of the so selected four joints is equivalent of the human arm movement.

The exoskeleton structure will be constructed primarily by aluminium and composite materials, with high stress joint sections fabricated in steel. The total weight of the uncompensated orthosis should be less than 2 kg.

3. Actuation system

The system developed here should possess the following advantages as a wearable robotic structure: excellent power/weight ratio with inherent safety, natural compliance, low cost, etc. The above advantages are due to the use of braided pneumatic muscle actuators (PMA) as power source for the system. These actuators provide a clean, low cost actuation source with a high power/weight ratio and safety due to the inherent compliance. Here, commercial PMA will be used, available from Festo [8]. Fluidic Muscle catalogue type DMSP-10 and DMSP-20 with press-fitted connections are suitable, with internal diameter 10 mm and 20 mm, respectively. The operating pressure is 800 kpa (8 bar), and 600 kpa (6 bar) for the two types of PMA. Forces at maximal permissible operating pressure are 1500 N and 630 N, respectively. The maximal permissible contraction of the pneumatic muscles DMSP is $h = 25\%$ of the nominal length Ln.

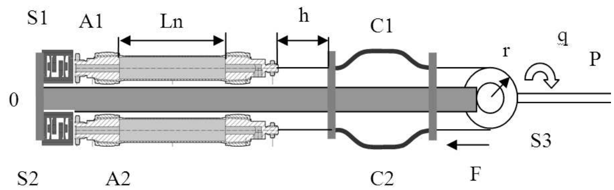

Fig. 2. Antagonistic scheme for providing joint motion/torque

Joint motion/torque on the exoskeleton arm is achieved by producing appropriate antagonistic torques through cables and pulleys driven by the pneumatic actuators. Two acting elements, A1 and A2, work together in an antagonistic scheme simulating a biceps-triceps system to provide the bidirectional motion/force (Fig. 2). Bowden cable transmissions C1 and C2 are used for the coupling between the muscles and the pulley P. The pulleys are fastened on the arm segments following joint shafts. All the actuators are mounted to the immovable base 0 by means of load cells S1 and S2 for measurement of the pulling force. High linearity sensors S3 are mounted in the joints to perform the position sensing in the joints.

All actuators are mounted on the body brace behind the operator's back. All actuators are coupled with the pulleys mounted on the arm and forearm by means of Bowden cable transmissions, as it is shown in Fig. 3.

Double sided drive without backlash is ensured, when both muscles work antagonistically in a single joint and also a possibility for stiffness joint variation is ensured. A disadvantage of this scheme is that the size of the useful contraction is limited by the contraction necessary for the preliminary muscle tensioning.

Force/displacement diagrams are shown in Fig. 4 of two single types

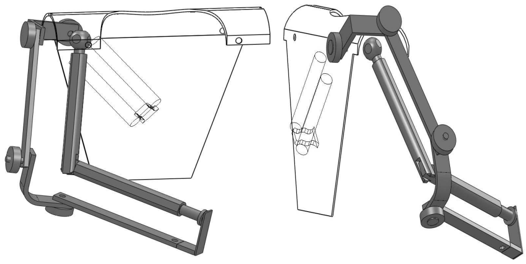

Fig. 3. Concept design of the exoskeleton arm

antagonistically acting PMA – type DMSP-20 [8]. The diagrams below illustrate the operating range of each muscle, depending on the operating pressure, shown on the right. Each line illustrates the force/displacement range at a certain muscle pressure. The intercept points of these lines correspond to the antagonistic balance of both muscles. The antagonistic balance force can be kept constant by pressure control of both muscles. The difference in contractions $h = h_{l2} - h_{l1} = h_{r1} - h_{r2}$, which can be used as a position control at a constant antagonistic force F_a by means of pressure variation, is shown in the same figure. The size of the antagonistic contraction h is increased at a lower value of the antagonistic force, and at a higher value of the antagonistic force this size diminishes and reaches 0 at a certain value of the force F_{a0}.

It is seen that, at equal values of the contractions in the two muscles $h_{l0} = h_{r0}$, the force control in the muscles is limited by a certain value of F_{a0}, with respect to regulation of the joint torques, presented in Fig. 4. The joint torque can be regulated by means of increasing one of the forces and diminishing the other, and vice verse. The variation range of the torque increases in one direction which causes torque diminishing in the other one, at difference in both muscle antagonists. For example, smaller force variation in one direction $F_1 < F_a$ and bigger force variation in the other muscle $F_r > F_a$ is achieved by means of pressure variation at a big contraction of one of the muscles $h_{l2} > h_{r2}$. The antagonistic force is zeroed and one of the muscles takes the corresponding loading above certain value of the outside joint loading. The position variation by means of pressure muscle variation is limited. The antagonistic force value can be increased by means of assembly definition of muscles in another antagonistic balance with a smaller useful contraction $h = h_{l2} - h_{l1} = h_{r1} - h_{r2}$.

4. Antagonistic muscles parameter selection

Two factors determine the length and the diameter of the muscle ac-

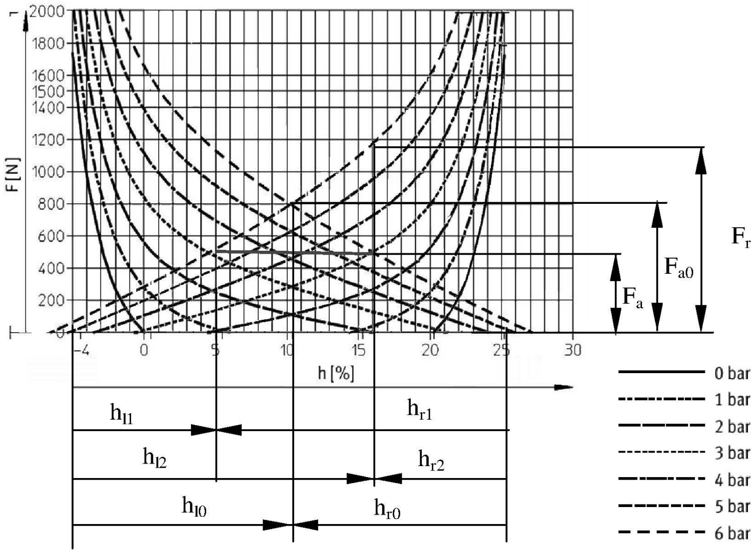

Fig. 4. Force/displacement diagrams of two antagonistically acting PMA type DMSP-20

tuators. The first is the torque required at that joint and the second is the range of the joint motion. Additional factor that determines the length and the diameter of the muscle actuators is the pulley radius r. System kinematics and dynamic evaluations including exoskeleton and upper arm are carried out. Model of the mechanical system upper limb – exoskeleton is build up according to the kinematics scheme shown in Fig. 1c. Software package SOLID DYNAMICS is used for kinematics and dynamic evaluations.

The closed loop kinematics structure includes 9 rotation joints and possesses 4 DoF. Input data for evaluation of the system kinematics are the motion parameters in the four joints of the exoskeleton q1, q2, q3 and q4, corresponding to the four basic motions of the upper limb: Shoulder abduction/adduction, Shoulder flexion/extension, Elbow flexion and Shoulder medial rotation/lateral rotation. Sinusoidal functions of angle variations in these joints are presented. Different laws for system motion exoskeleton-upper limb are investigated. One exemplary realization of exoskeleton is shown in Fig. 5a.

The mass geometric parameters of the system upper limb-exoskeleton are defined. The segments length of the upper limb is dependent on the height of the individual [9]. The exoskeleton will be constructed for usage by a 'typical adult'. For a human possessing height of H = 1.70 m, the values of the elements of the upper limb are derived: Upper arm length – 0.316 m; Forearm length

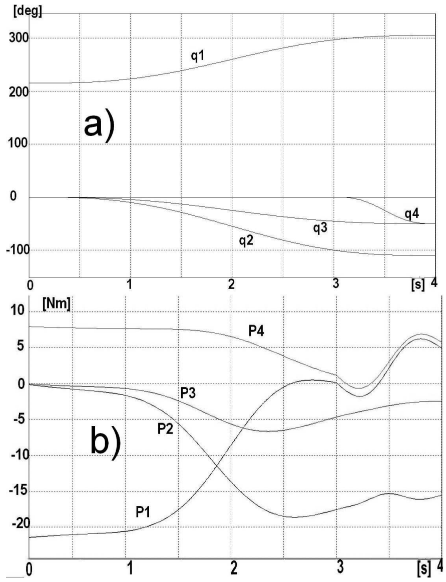

Fig. 5. Joints' motion laws and resulting torques of the exoskeleton

– 0.248 m; Hand length – 0.184 m and the positions of their mass centers are specified, too.

The segments of the upper limb are modelled by means of simple bodies, as shown in Fig. 3, as their masses are equalized with those of the limb. The limb segments' masses are derived according to the weight of the individual [10]. The following values for the masses of the upper limb elements are derived for an individual with weight 70 kg: Upper arm – 1.89 kg; Forearm – 1.12 kg and Hand – 0.46 kg. The total mass of the upper arm is 3.47 kg. The projected exoskeleton elements are manufactured of aluminium, as the program calculates the entire weight of the exoskeleton of 1.55 kg, without some additional elements such as shells, soft connections, and others.

The exoskeleton joint torques deviation is derived P1, P2, P3 and P4 as a result of the carried out simulations, corresponding to the input coordinates q1, q2, q3 and q4. The torques are evaluated for the cases: a) when the system is loaded only by exoskeleton masses; b) masses of the exoskeleton are estimated and those of the arm: c) except masses of the exoskeleton and those of the arm, the loading of the end effector of 1 kg is assessed, additionally. The torques variation for the last case c) are shown in Fig. 5b and the deviation boundaries for the cited above three cases are presented in Table 1.

According to the performed assessment, the built up exoskeleton can

Table 1. Deviation of the exoskeleton joint torques at different loads

	a) [Nm]	b) [Nm]	c) [Nm]
Shoulder abduction/ adduction- P1	−6.9; 0	−14.2; 2.2	−21.1; 6.1
Shoulder flexion/ extension – P2	0; −6.8	0; −13.1	0; −18.4
Elbow flexion – P3	0; −1.3	0; −3.2	0; −6.8
Shoulder medial rotation/ lateral rotation-P4	1.2; −0.2	2.8; −0.1	7.6; −0.4

be designed in order to ensure torque control at unidirectional joint loading for Shoulder joint to the values $P_{sh} = 6.9$, 14.2, 22 Nm, and for Elbow joint to the values $P_{el} = 1.3$, 3.2, 8.0 Nm. One single value can be selected of pulley radius for example $r = 0.0315$ m, out of constructive considerations. The necessary force of each muscle, which separately to ensure unidirectional loading torques in the shoulder joint can be calculated using the next equality: $F_{sh} = P_{sh}/r$ or $F_{sh} = 219$, 451, 698 Nm, and for the elbow joint $F_{el} = P_{el}/r$, $F_{el} = 41$, 102, 254 Nm. At antagonistic action of both muscles, the same force value should be reached by the muscle antagonist in order to keep up a constant position in the joint at variation or zeroing of the loading.

The maximal antagonistic force, at which both muscles have equal contractions (Fig. 4) must be equal to the shoulder joint of $F_{00} = 698$ Nm and for the elbow joint $F_{00} = 254$ Nm. Thus, by means of relaxation of one of the muscles, the other one takes the occurred joint loading. Antagonistic interaction exists also at the difference in the contractions of both muscles, as the useful loading is ensured by the difference of both muscle forces. The deviation diagrams of the muscle forces in the shoulder joint with Fluidic Muscle DMSP-20 are shown in Fig. 6, ensuring the calculated torques.

The defined in this way useful loading in each joint allows definition of the variation range of the joint position. In the shoulder joint, as shown in Fig. 6, when the value of the load is $F_{sh} = 698$ N, each muscle contraction can be changed to $h = 15\%$. In lower load values possible contraction of the muscles is increased, while in a load $F_{sh} = 219$ N, possible contraction is $h = 24\%$. To determine the length of the muscles can be assumed under a load, joint angle to achieve progress at $q = 115$ deg. Maximum stroke of each muscle is $H = qr\pi/180 = 0.063$ m, when the radius of the wheel is $r = 0.0315$ m. Nominal length of the muscle is $Ln = H/15\% = 0.42$ m. When the load is effected only by the exoskeleton weight ($F_{sh} = 219$ N), possible contraction is $h = 24\%$, and can be achieved progress in the joint $q = 24\%\ Ln = 183°$.

At the elbow joint in a similar manner to the Fluidic Muscle DMSP-10,

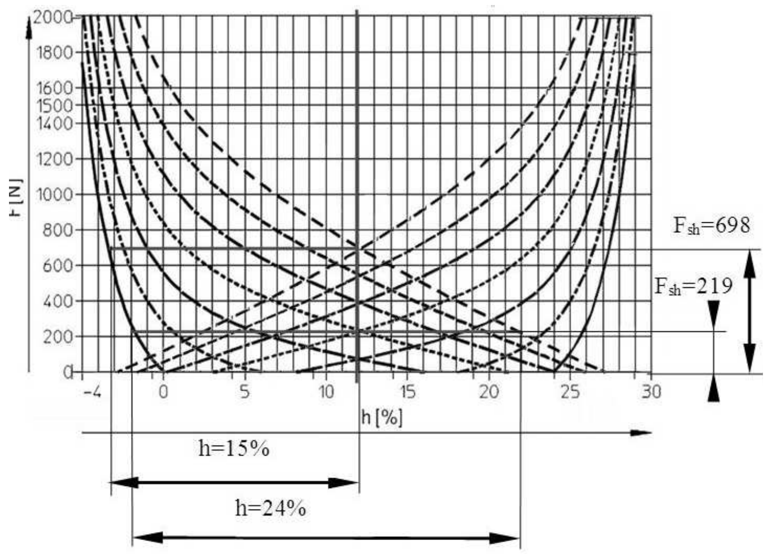

Fig. 6. Force/displacement diagrams at the desired antagonistic interaction in the shoulder joint with PMA DMSP-20

when the load value is $F_{el} = 254$N, each muscle contraction can be changed to h = 14.5%, and when the load is $F_{el} = 41$ N, contraction can be changed to h = 23.5%. Similarly, to determine the length of the muscles under a load, can be accepted joint angle to achieve progress at q = 90 deg. Maximum stroke of each muscle is H = 0.049 m in the same radius of the wheel r = 0.0315 m. The nominal length of the muscle is Ln = H/14.5% = 0.341 m. When the load is effected only by the exoskeleton weight ($F_{sh} = 41$ N), can be achieved progress in the joint q = 24% Ln = 146°.

It is assumed a uniform actuation for abduction/adduction and flexion/extension in the shoulder joint, as well as flexion and medial/lateral rotation in the elbow joint. The results are summarized in Table 2, wherein the torques and the range of exoskeleton joint motions are presented at different loads. Typical human isometric joints strength and typical range of the human arm joints are shown in Table 2, too [7].

5. Conclusions and future work

In this work, the conceptual design and actuation of a new exoskeleton of the upper limb is presented. The choice of several solutions of a mechanical structure is shown, kinematics equivalent to the structure of the human arm.

Table 2. Torques and range of motions in the exoskeleton joints at different loads

	Human isometric joints strength [Nm]	Torques of the exoskeleton by different loads P [Nm]	Typical ROMs of the human arm [deg]	ROMs of the exoskeleton by different loads q [deg]
Shoulder abduction/adducton	110	6.9–21.1	182	115–183
Shoulder flexion/ extension	125	6.9–21.1	249	110–176
Elbow flexion	72.5	1.3–8.0	142	90–146
Shoulder medial/ lateral rotation		1.3–8.0	131	90–146

An actuation system is selected based on braided pneumatic muscle actuators and antagonistic drive scheme for each joint is shown, using pulley and Bowden cable transmissions. Force/displacement diagrams are presented of two antagonistic acting muscles and the possibilities are analyzed for torque regulation in the joint and in the joint position by means of pressure variation.

Kinematics and dynamic assessments are performed of the system exoskeleton-upper limb, and based on them are chosen parameters of the pneumatic muscles: diameter and nominal length. These parameters ensure in the antagonistic scheme torque regulation in the joint up till definite boundaries and the joint range of motion that can cover the range of motion of a human arm. The performed kinematics and dynamic evaluations must be refined after adjustment of the design of all the details, as the final force characteristics must be derived and the motion dimensions, as well.

A mechanical model must be built up thereafter, suitable for the system control. A control algorithm must be derived, which allows the usage of the device for application, where both motion tracking and force feedback are required.

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