Extended Abstract: Flexible actuators for biomedical engineering and robotics

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Abstract — **This paper describes results of research projects developed at the University of L'Aquila by the research group of the authors, in the field of biomedical engineering and robotics. The research projects concern the development of innovative actuators, such as pneumatic muscles and Soft Pneumatic Actuators (SPAs), the development of a variable stiffness grasper and, finally, the development of a soft finger for the collaborative robotics. The main aspects of these research projects are described in the paper, highlighting the technologies used such as the finite element analysis.**

I. Introduction

The authors have been engaged for several years in the development of innovative non-traditional actuators. In this paper, some of the research conducted on non-traditional pneumatic actuators, interesting, for example for safety reasons, when the movements must take place avoiding that the moving parts constitute a danger to the user, will be illustrated. This is the case in the medical sector of assistive and rehabilitation devices, for example an active orthosis, in which the patient interfaces directly with the device that has an autonomous movement capacity, or in the field of the collaborative robotics where the robot and the user share the same workspace. These actuators are made of an elastomeric material and are pneumatically powered. Different solutions are proposed for deformation: an element of appropriate shape made only of soft material or the combination of an element in soft material with a reinforcement of adequate internal stiffness.

In the following, the term SPAs (Soft Pneumatic Actuators) will be used for these non-traditional pneumatic actuators. The SPAs here shown are made of silicone rubber or natural lattice, due to their high deformability and simplicity of processing, inside which one or more chambers are obtained to contain the compressed air. The power-to-weight ratio is higher than traditional actuators, since they are very light materials. These actuators require, for their realization, the development of a technological set-up.

This paper shows some original development of SPAs, including applications to biomedical engineering and robotics, and of pneumatic muscle actuators, that are made by elastomeric materials too. For both types of pneumatic muscle here showed, McKibben and Straight Fibres, the air inlet causes a radial expansion followed by an axial contraction of the heads and that allows to perform an external traction work. The research activity that led to the design and prototype realization of a remote-controlled surgical grasper, and of its Variable-Stiffness Actuation (VSA) system, is also shown. The robotics for the NOTES, also called Natural Orifice Transluminal Endoscopic Robotic Surgery (NOTERS), requires specific and customized solutions, such as a snail-like robot and the implementation of the variable-stiffness actuation (VSA). A finger that kinematically mirrors the shape of an object to be grasped is also presented.

II. Materials and Methods

It is very complex to identify analytical correlations, assigned a geometry, between the deformation, the developed force and the pressure within the actuator chamber, when the material used for soft pneumatic actuators and pneumatic muscles is an elastomer. This material has a non-linear constitutive law, as well as the behaviour of the air, being a compressible fluid. Therefore, for the design of the actuators it is very used the numerical modelling by the finite elements method and, in some cases for pneumatic muscles, the dimensional analysis, which allowed to build a design graph based on three dimensionless parameters, which contain the quantities which influence the behaviour of the actuator.

The finite element model of the Braided pneumatic muscle developed by the authors has been experimentally validated. The model developed is non-linear and based on real muscle parameters. It is proposed to predict the muscle behaviour and to be used as a reliable design tool. Several prototypes have been made of this muscle and have been applied in research projects for the development of orthoses. In Figure 1, a-b-c, an

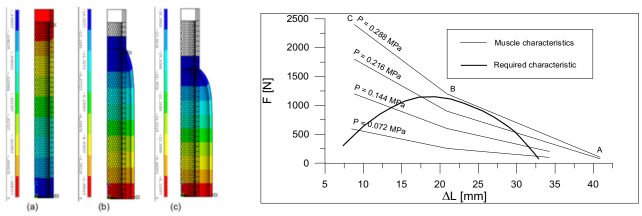

Fig. 1: Numerical results of an isotonic test simulation with the Braided pneumatic muscle model: (a) rest muscle, (b) during shortening, (c) at maximum inflation speed (side view). Graph obtained by connecting the design curve of the Straight Fibres pneumatic muscle together with the curve desired by the designer (d).

example of numerical results of an isotonic test simulation, based on the model proposed, is shown. A research work was carried out also for Straight Fibres pneumatic muscles and in Figure 1.d an example of a characteristic graph obtained with the design curve is shown together with the curve required by the designer (traction force F vs. shortening ΔL) for a biomedical application.

III. Results

Actuators and active orthoses

The types of pneumatic actuators here presented belong to two different families: pneumatic muscles and soft pneumatic actuators (SPAs). The former have been the subject of research activities and find space in some industrial applications, as they are available on the automation components market; the latter are not present on the market, but are often designed ad hoc and integrated into commonly used devices such as blood pressure measurement systems and other medical devices, car seats, massage chairs.

The Straight Fibres pneumatic muscle, Figure 2a, is made of a silicone cylindrical chamber in the wall of which a cage consisting of 40 kevlar threads, arranged longitudinally and held in position by two end rings, of which one is buried the inside of the silicone and the other is connected to the head that presents the air supply/discharge pipe. The pneumatic and mechanical seal is ensured by means of clamping systems with the tube at the heads. To limit the radial deformation of the muscle, metal circumferential rings are arranged externally of the cylindrical chamber. The pneumatic muscle of the McKibben (Braided) type, Figure 2b, is formed by a cylindrical chamber made of elastomeric material, a sheath consisting of a rhomboidal mesh that externally covers the chamber and two heads which have the function of isolating the chamber, block the sheath on the outside of the chamber and allow the anchorage of the muscle to the device. On one of the two heads the air supply/discharge hole is made. The sheath is of the braided type and has a cylindrical shape: the wires, in polyamide, are placed side by side in number of six and wound to form 42 spirals that create rhomboidal meshes.

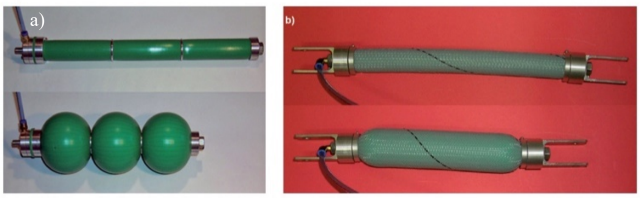

Fig. 2: Prototypes of pneumatic muscles developed: straight fibres, a), and braided, b), also known as McKibben muscle.

By sending air into the chamber, it causes an increase in volume, so that the outer surface of it comes into contact with the outer sheath; the muscle contracts due to the high axial stiffness of the wires forming the sheath.

Medical devices

The research project on a surgical grasper has been carried out. It has the focus in the Natural Orifice Transluminal Endoscopic Surgery, NOTES, where the abdominal cavity is reached exploiting the natural cavities. It was established to adopt a pair of SPAs for closing the clamp and a single SPA for opening. The prototype grasper, with the SPAs prototyped in house, was submitted to a campaign of laboratory validation tests that gave positive results. In Fig. 3 the principle of operation and an image of the grasper prototype are shown.

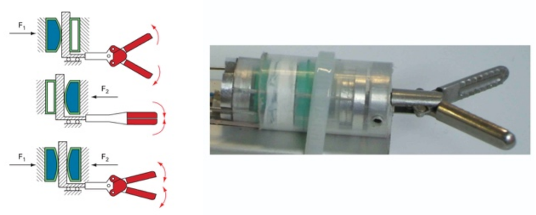

Fig. 3: Principle of operation of the actuation module of the surgical grasper, to the left, and the prototype manufactured, to the right.

Collaborative robotics

A finger of a grasping end-effector of a collaborative robot has been developed. It is a silicone rubber actuator made of tube wrapped in a polyamide inextensible square-meshed gauze. The gauze contains the radial and axial expansions of the tube and guides the bending movement of it through appropriate circumferential cuts that realize the joints of the actuator, similar to those of the human finger. A predictive formula was achieved to design the actuator in order to kinematically mirror the object to be grasped (a video has been included as supplementary material of the extended abstract).

IV. Conclusions

The paper shows the main results of the research activities carried out by the authors in the field of Pneumatic Muscles and Soft Pneumatic Actuators for use in active orthoses, medical devices and robotics. In this field a wide use was made of computer aided design tools and of the finite element method for designing and sizing of the actuators and devices in which they have been applied. The actuators presented are pneumatic muscles and square-sized and circular-sized SPAs. The former were applied to a scoliosis brace, to a massage device and to a spinal unloading brace; the latter, to a surgical grasper, the main results of which have been described in the paper. Finally, a novel bending actuator was applied in the field of the collaborative robotics.

The research presented here has aimed not only at developing innovative solutions but also at measuring itself with process design and prototype construction. The limit that the authors have encountered is due both to the limited availability of funding and to the difficulty of finding companies interested in investing in systems with a strong technological content. The availability of financing aimed at developing innovative solutions for the market, but with a high percentage of failure risk, would be desirable.

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[1] M. G. Antonelli, P. Beomonte Zobel, F. Durante, T. Raparelli, “Additive manufacturing applications on flexible actuators for active orthoses and medical devices”, Journal of Healthcare Engineering, Volume 2019, Article ID 5659801, 2019.