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Design concept and validation of a robotic arm inspired by the octopus

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ABSTRACT

The octopus is an invertebrate sea animal, considered as an interesting model of inspiration in robotics, due to its high dexterity, variable stiffness, and very complex behaviours, if compared with its position in the evolutionary scale. This paper reports the design of an artificial muscular hydrostat for developing an octopus-like robot. The experimental study consists of the fabrication of a set of mock-ups demonstrating some of the key features and patterns of movement of the octopus arm.

The experimental trials performed with the different mock-ups demonstrated the suitability of the silicone materials used and the patterns of actuators activation to replicate the typical octopus movements of elongation, shortening, bending, and reaching. They also confirm that control is simplified by the arrangement of muscles as well as by the mechanical properties of the muscular hydrostat.

1. Introduction

In robotics and AI (Artificial Intelligence), the principle of so-called “embodiment” is being widely applied to develop intelligent machines with effective behaviour in the real world. According to the principle of embodiment, developing intelligence requires a body and the capability of interacting with the environment [1]. This principle is further developing in “embodied intelligence”, which represents one of the current challenges of robotics research. According to the principle of embodied intelligence, adaptive behaviour is no more reduced to control and computation, but it emerges from the complex and dynamic interaction between the body morphology, sensory-motor control, and environment [2]. Part of the control is actually performed by the mechanical properties of the physical body. In simpler animals, it is more evident how adaptive behaviour is largely given by physical reactions of the body, as well as it is done for low-level sensory-motor reflexes in more complex animals [3]. This principle has been adopted in a wide range of current approaches to the development of intelligent artefacts [4].

The octopus, an invertebrate sea animal, can be considered as a paradigmatic example of bioinspired embodied intelligence, and specifically of how effective behaviour in the real world is tightly related to the morphology of the body. The octopus has dextrous capabilities and a rich behaviour, with respect to its position in the evolutionary scale ([5,6]). Most recognized theories explain that these enhanced behaviour and capabilities for interaction with the environment are due to the special morphology of the octopus body, and especially to the high dexterity attributed to the form and materials of the arms and their efficient neural control mechanisms.

The motor capabilities of its arms are far beyond any existing robot, for their dexterity and for the variability of their stiffness. The octopus arm has already been used as inspiration for robotic arms called “continuum robots” that have a continuous central structure and omnidirectional mobility. Continuum robots have a large number of redundant degrees of freedom, are typically flexible, and deformable (soft-bodied). A variety of actuators, joint designs, and mechanisms for continuum robots has been built. A recent and complete survey of such robots can be found in [7]. The common element that characterize quite all the existing robotic platforms inspired by the octopus arm (or similar structures) is the presence of rigid elements (back bones or endplates) providing a point to exert force and the use of mechanisms based on traditional robotics, versus the complete compliance and the stiffness controllability of the animal model.

One of the main features of the octopus is that its arms are composed almost entirely of tightly packed obliquely-striated muscle cells, which are organised into transverse, longitudinal, and obliquely orientated groups ([8,9]) as shown in Fig. 1. This special muscular organization forms structures called *muscular hydrostats* [10]. The main property of such structures is that their volume is constant during muscle contractions. The result is that if the diameter of a muscular hydrostat increases, its length decreases, and vice versa [10]. The transverse and longitudinal muscles can be considered to have a reciprocal antagonistic action, enabling the muscular system to serve as a modifiable skeleton, essential for the transformation of force into movement.

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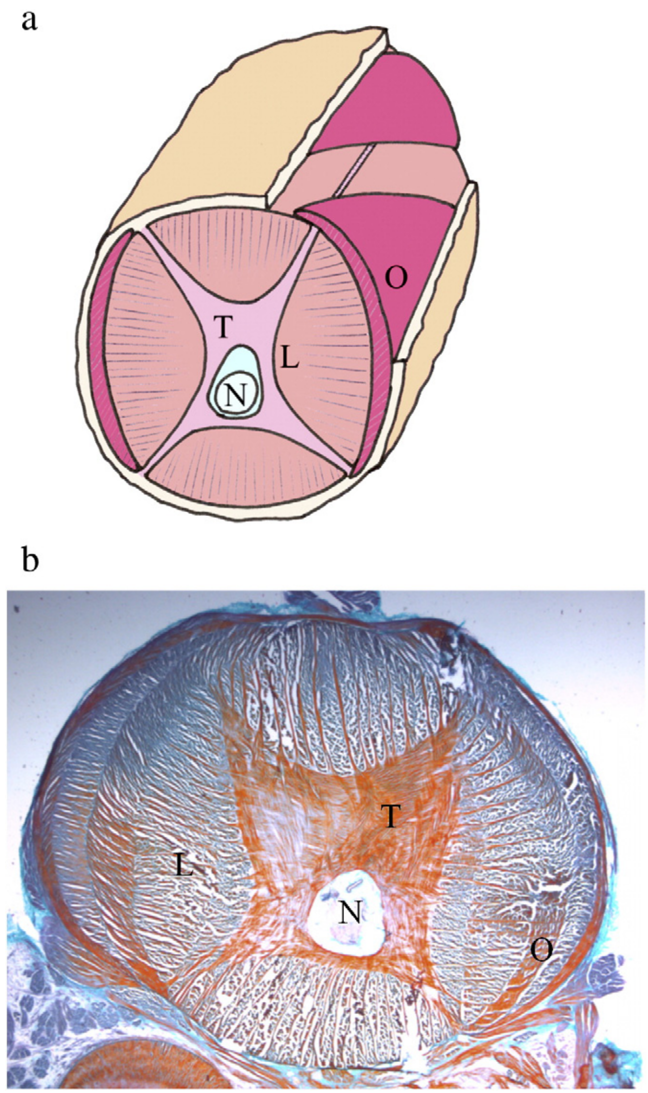

Fig. 1. Octopus arm sections. Schematic drawing (a) and histological picture (b): (O) oblique, (T) transverse and (L) longitudinal muscles; (N) nerve cord.

Applying the basic principles of this smart muscles arrangement to build an artificial muscular hydrostat is one of the key aspects of the design of the octopus-like arm in the research carried out by the authors [11]. The main advantage is that the complexity of developing mechanisms and actuators for achieving the same dexterity of the octopus arm is simplified by this smart muscular structure, as some of the muscle deformations are in fact passive. On the other hand, materials have a functional role in the design of the octopus body, as they must show the active and passive mechanical properties of the octopus arm tissue.

2. Design and modelling of an artificial muscular hydrostat

The work presented here has the purpose to design a robotic arm with some of the octopus arm features, such as the ability to elongate, to bend in all directions, to control its own stiffness. More specifically, we present the design of an artificial muscular hydrostat, where the longitudinal muscles and the transverse muscles have been taken into consideration, as well as their reciprocal actions. The longitudinal artificial muscles run along the arm length and the transverse muscles are represented by radial actuators lying on a plane perpendicular to the longitudinal muscles replicating the arrangement of the real octopus (Fig. 1). The robotic arm consists of four longitudinal muscles and a number of transverse muscles in parallel, whose number depends upon the total arm length (Fig. 2). Like the biological arm, the central part does not contain muscles (in the octopus, it contains ganglia and nervous fibres).

2.1. Elongation and shortening

The arrangement proposed for the artificial muscular hydrostat provides a significant advantage in the elongation mechanism, like in the animal model. When the longitudinal muscles contract and the transverse muscles are relaxed, the arm shortens. In contrast, when the transverse muscles contract and the longitudinal muscles are relaxed, they are 'squeezed', and the arm greatly elongates. Likewise the animal model, this derives from the fact that the structure does not change its volume during the contraction. For this reason, there is a known relation between its diameter and its length, considering the structure as a cylinder, that is:

$$L = \frac{V_0}{\pi(0.5D)^2} \tag{1}$$

where D is the diameter, L is the length and V_0 is the constant volume of the cylinder.

The relative variation of D and L, expressed in percentage, is independent from the numerical values of the geometry of the arm and it is given by the following relation:

$$\frac{\Delta l}{L_0} = \left(\frac{\Delta D}{D_0} + 1\right)^{-2} - 1 \tag{2}$$

where L_0 and D_0 are the initial length and diameter, respectively. When L_0 is greater than D_0, then small reductions of the diameter correspond to large increases of the length. In the geometry of the octopus arm, we always have $L_0/D_0 > 1$ and typically $L_0/D_0 > 10$. This is a very important property for the robotic arm, because with small contractions of the transverse muscles one can passively achieve great elongations and the elongation speed is also higher than the speed of contraction of transverse muscles. This feature affects the requirements for the artificial muscles, which need to be compliant enough to allow passive elongation, and do not need to perform large contractions.

2.2. Bending

Thanks to the hydrostatic structure, the octopus is also able to bend its arms by using just the longitudinal muscular elements. More in detail, this movement is produced by the contraction of one of the four longitudinal muscular bundles and by a light contraction of transverse muscles. These latter muscles have only the role to ensure that the diameter remains constant during longitudinal contraction, in

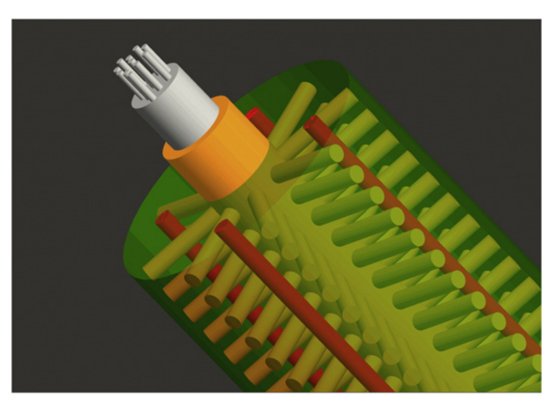

Fig. 2. CAD design of the overall structure of the robotic arm artefact.