The octopus arm muscles: bio inspiration for soft robotics

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The Octopus arm is a highly flexible limb composed of an incompressible tightly packed three-dimensional array of muscle and connective tissue fibers, which offer both a 'skeletal-like' support (by stiffening) and work as force actuators for movement generation. These are organized as a muscular hydrostat with constant volume that constrains the antagonistic action of muscles. The octopus organization in muscle and connective elements variously arranged might be the key for functional integration and the level of performance achieved in the real animal. In fact, the octopus morphology highlights the importance of the physical and dynamic properties of the material by which the embodiment interacts with the environment. A dramatic difference in the dimensions and arrangement of the myofilaments in the connective mesh is one of the key elements producing a difference in the limb performance.

Connective tissue in hydrostatic skeletons is essential for providing structural reinforcement and to control shape, transmit stress and store elastic energy. Two characteristics are fundamentally important: the mechanical properties of the connective tissue and its structural orientation. All this suggests importance for flexible musculature and for an arrangement of passive and active elements that embed part of the dynamic properties of the muscular element.

The octopus arm muscle has very unique electrophysiological properties, drastically different than that of vertebrates and arthropods neuromuscular systems. It has been shown that the cells of the various muscle types (such as transverse and longitudinal muscles) show no differences in membrane properties and mode of innervation. They are electrotonically very compact (localized synaptic inputs can control the membrane potential of the entire muscle cell) and lack of significant electrical coupling between muscle fibers. All this suggests that the neuromuscular system of the octopus arm has evolved to ensure an extremely precise localization of the arm function neural control.

Nonetheless, in the domain of cephalopod studies, there is also lack of sufficient knowledge about the control of cephalopods either single fiber or whole muscles and how changes in neuronal activity affect the muscle activation. How the octopus controls its muscle rest length and stiffness in single muscle fiber as well as a whole arm muscle is still an open question.

Dynamic investigations on octopus arm muscle fiber strip (muscle+ connective) started revealing the involvement of stiffening in movement generation and to elucidate the mechanisms through which this is achieved. In fact, during arm exercise it has been shown the existence of passive elastic forces modulated by the level of the arm activation and acting as storing energy compartments. This suggests the possible involvement of 'stored energy' and 'jamming force' factors that are special for muscular hydrostats because of the close interactions among muscle layers and connective tissue and of the octopus arm intrinsic organization in counteracting muscle layers.

Due to their interesting characteristics, soft-bodied animals became recently an important focus in robotics. In particular, the field of soft robotics currently draws significant research interest because of the potential of soft robots to better interact with real world environments. The octopus might therefore serve as guide to plan and construct soft miniaturized actuators and to develop new classes of smart flexible materials.