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Tools and Methods for Experimental In-vivo Measurement and Biomechanical Characterization of an *Octopus vulgaris* Arm

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Abstract—**This work illustrates new tools and methods for an *in vivo* and direct, but non-invasive, measurement of an octopus arm mechanical properties. The active elongation (longitudinal stretch) and the pulling force capability are measured on a specimen of *Octopus vulgaris* in order to quantitatively characterize the parameters describing the arm mechanics, for biomimetic design purposes. The novel approach consists of observing and measuring a living octopus with minimally invasive methods, which allow the animal to move with its complete ability. All tools are conceived in order to create a collaborative interaction with the animal for the acquisition of active measures. The data analysis is executed taking into account the presence of an intrinsic error due to the mobility of the subject and the aquatic environment. Using a system of two synchronized high-speed high-resolution cameras and purpose-made instruments, the maximum elongation of an arm and its rest length (when all muscles fibres are relaxed during propulsion movement) are measured and compared to define the longitudinal stretch, with the impressive average result of 194%. With a similar setup integrated with a force sensor, the pulling force capability is measured as a function of grasp point position along the arm. The measured parameters are used as real specifications for the design of an octopus-like arm with a biomimetic approach.**

I. INTRODUCTION

Biologically-inspired approaches have been traditionally widely adopted in robotics [1]-[2]. Bioinspiration can help develop biomimetic robots that are more suitable for unstructured environments and that show better performance in terms of reactivity, adaptability, robustness, more compliant and stable mechanisms [3]-[8].

The octopus is a paradigmatic example for bioinspired robotics. The octopus arm shows peculiar features, such as the ability to bend in all directions, to produce fast elongations, and to vary its stiffness. The octopus achieves these unique motor skills thanks to its peculiar muscular structure. In fact, octopus arms belong to what are called *muscular hydrostat* structures, which are composed almost entirely of muscles and lack totally of skeletal systems [9]. Different muscles arranged on orthogonal planes generate an antagonistic action on each other in the muscular hydrostat. This structure does not change its volume during muscle contractions, and it allows bending, elongating, and varying the stiffness of the arm, as well as performing a rich variety of complex, high dexterous and finely controlled movements, that are source of inspiration for the researchers in the field of robotics. Most of the studies on these structures focus on the biomechanical aspects, describing how their morphology and property permit the variety of movements in a qualitative way, or they have the goal to elucidate the interplay between their biomechanics and their control system [10]-[11]. Other works describe the motor activity and nervous system with an *ex vivo* investigation or passive approach based on external stimuli applied on single muscle fibres [12]. These works do not totally describe how the whole physical structure acts in its natural environment and they lack of a mechanical characterization of the active behaviour of the tissues at all from a macroscopic viewpoint. A study of the percent expansion within the tongue during protrusion was conducted in animals as lizards, armadillo and opossum using artificial markers and cinematographic film with a resulting range from 70% to 106% [13]. Whereas in literature there are no similar works describing the active properties of an octopus arm from a mechanical viewpoint.

The goal of this work is to improve knowledge on the octopus arm biomechanical properties obtaining a first quantitative *in vivo* mechanical characterization. New data are extracted by measuring the elongation capability and pulling force of an octopus arm, in order to acquire quantitative data of the mechanical behaviour of the structure useful as biomimetic specifications.

II. MATERIALS AND METHODS

Observation and non-invasive measurements have been carried out on a specimen of *Octopus vulgaris* in a 120x210x80 cm tank, with salted water and rocks. The size of the tank allows the octopus to move and to easily access to the measuring devices. The *Octopus vulgaris* specimen (mass 1600g) was caught in the Mediterranean shore.

A. Setup video and camera calibration system

With the purpose to obtain objective parameters with an accurate but non-invasive method, a system composed of two-synchronized high-speed cameras (DALSA *Falcon1.4M100*) with high resolution (from 1400Hx1024W at 100 *fps* to 1400Hx200W at 500 *fps*) was positioned in stereo configuration, with their viewing angles normal to the tank facets (one in respect to the frontal side and one to the lateral side), during all the experiments. Two grids (0.02 m

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spacing) were placed and fixed on the two internal walls of the tank, on the opposite side with respect to cameras; in addition, 2 measuring rods were fixed on the external side of the facets in front of each camera. These geometric references were used for the reconstruction of the scene, the correction of optical refraction phenomena and the measurement of the octopus anatomical parts. The choice of using fixed grids with known position as references permits to provide more mobility to the cameras if needed and even more flexibility for the tracking of octopus unpredictable dynamic.

B. In vivo measurement of the arm rest length

Because of the ability of the animal to remove all kinds of artificial components [14] and the capability to quickly change the colour or even the texture of the skin, the measurement of the arm rest length requires the use of anatomical markers (like eye and arm tip). Considering the extreme dexterity of the animal and the continuous movements of the arms in an aquatic environment, we have measured the octopus during the propulsion movement. This movement is characterized by a parabolic trajectory covered through a jet of water from the funnel. In the central phase of the trajectory the animal swims headfirst with arms trailing behind line-up. The hypothesis is that during this middle part the arms muscles are all relaxed, see Fig.1a. The octopus was recorded with the two cameras during the jet propulsion movements, performed with a parabolic trajectory completely in a virtual plane perpendicular to the frontal camera optical axis. The kinematics analysis of the movements (trajectory, tangential velocity and acceleration features) has been reconstructed in order to have a numerical reference to define the middle part of each trajectory, where the arm measures have been extracted. The maximum acceleration value has been used to identify the central part of the trajectory, where the arms are horizontal and we measured the length. The images from the frontal camera were analyzed to reconstruct the kinematics stereotyped patterns and to measure the length of the arm, whereas the images from the side camera were used to verify that the movement trajectory was in a virtual plane parallel to the frontal camera plane and to extract depth information of the plane itself. For each frame describing the central phase, the rest length of the L2 arm, (see Fig.1b), corresponding to the one used to obtain the maximum elongation (see Results) was calculated with geometric pinhole camera model and considering the position of the plane of motion. The rest length was reconstructed considering the distance of the projections of the eye and the arm tip points on the grid of the internal side of the tank and the rod on the external side. The apparent difference between these two measures caused by the refraction phenomena in water and to the different scene depth was calculated and used as proportionality factor to calculate the real length of the arm at the depth corresponding to the plane of motion.

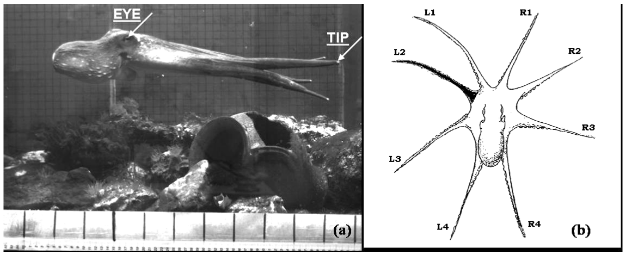

Fig. 1 (a) Frame of the central part of a characteristic parabolic trajectory of the jet propulsion movement; (b) map of the octopus arm [15], with L2 colored for identification.

The arm measures result affected by an intrinsic error due to the movement of the subject and the flexibility of the arm in the aquatic environment. In order to minimize the errors, the length of the arm was calculated several times for different frames with different depths of the plane of motion, but under the same external condition relative to the stereo camera system position and light. The measures dataset was analysed with a statistical approach using the fundamental concepts of the errors theory to finally define the most probable measure of the length of the arm considered and a range of measures around the average value that includes the uncertain factor for the measure itself.

C. In vivo measurement of arm active maximum elongation

To evaluate the arm maximum elongation, a dedicated instrumental set-up was developed to directly interact with the octopus, driving the arm's protrusion. The method is to lead the octopus to elongate one arm in back straight manner as much as possible using the contraction of all its transverse muscle fibres. The setup used for this aim is essentially composed by a solid graduated tube in transparent Plexiglas (1m length, diameters: internal 60mm, external 62mm, see Fig.2).

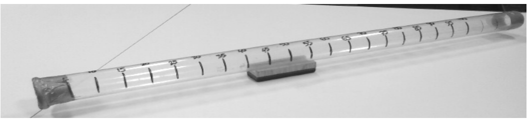

Fig. 2 Dedicated tool to drive the protrusion of one octopus arm and to measure its length.

The tube can be placed inside the tank and a bait, fasten with a thread, can be inserted inside the tube and pushed down the tube itself.

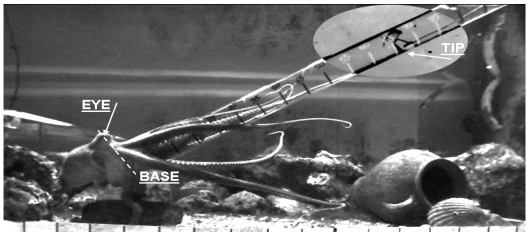

Fig. 3 Frame captured during the measurement of the maximum elongation with L2 arm.

The idea is to attract with the bait the octopus to insert one or two of its arms for measuring into the tube, maintaining the remaining arms and the body outside. As the octopus inserts one arm inside the tube the prey is pulled up to induce the animal to elongate the arm and to reach the maximum length trying to catch the prey (see Fig.3). In this way the tube has both the role of physical guide and direct measuring instrument.

D. In vivo measurement of the arm pulling force

The arm pulling force, due to the coordinated action of the four bundles of longitudinal muscles, was measured by using an instrumental setup developed by the Authors, constituted of a graduated tube, integrated with a force sensor (PCE-FM1000) and a support plate. The solid graduated tube was jointed in the centre of the support plate (see Fig.4a), which is the base and support of the entire instrumental setup. This structure enables the octopus to use external handhold, assuring that the measured force values are attributable only to the arm inside the tube.

The monoaxial load cell was enclosed in a purpose-made packaging that can be anchored to the opening of the tube, in the opposite side respect to the plate (Fig.4b, 4c). A ring screwed along the sensitive axis of the load cell was used to connect an high resistance thread, where a bait can be hanged. With this setup the octopus locates on the plate, inserts an arm inside the tube, grasps the bait and then pull to catch the food (Fig.5).

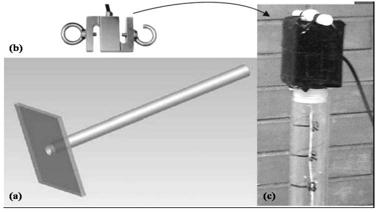

Fig. 4. (a) CAD design of the measuring instrument; (b) load cell; (c) package with the load cell anchored into the opening of the tube.

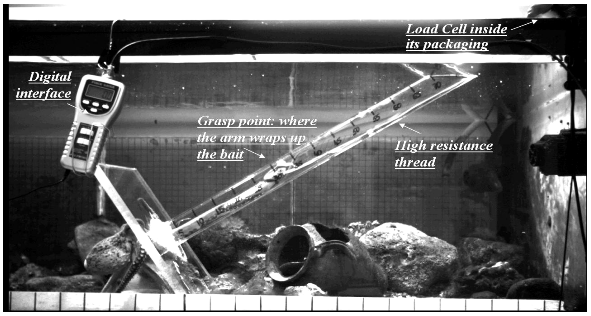

Fig. 5 Frame captured during a measuring force experiment. The bait, inside the tube of the measuring instrument, is hanged through the high resistance thread to the load cell. The load cell inside its packaging is anchored to the opening of the tube and maintained out of the tank's water. The digital interface of the load cell is connected to the pc station and synchronized with the cameras.

The force sensor acquisition data system was synchronized with the stereo camera system in order to identify which arm was used during the task and to correlate the position or the movement of the arm with the measured force. The position of the bait, corresponding to the grasp point along the arm, has been changed in different experiments in respect to the open side of the tube. The bait, fasten to the thread connected to the load cell, was placed at a distance corresponding to 150, 200, 250, 300 and 350 mm from the plate, and for each "grasp-point distance" the tensile force was recorded during the trials time. Therefore, it was possible to characterize the isometric pulling force applied with one arm with respect to the distance of a target from the body of the octopus and in function of time.

III. RESULTS

A. Reconstruction of the arm rest length

A dataset of 30 trajectories in jet propulsion was collected and analyzed to define the range for the rest length of the measured arm (L2). The dataset of measures was analyzed with MATLAB (MATLAB 7.0, The MathWorks Inc., Natick, MA), obtaining a Gaussian probability distribution. The precision percentage of the measure process, calculated as the difference between each measure and the average value weighted on the average value itself, results of 97%.

$$P_e = 1 - \sum_{k=1}^{n=30} \left(\frac{\ell_k - \bar{\ell}_0}{\bar{\ell}_0} \right) = 97\%$$

The average value for the n = 30 analyzed frames:

$$X_m = \frac{1}{n} \sum_{k=1}^{n} x_k = 334.8mm$$

was estimated as the most probable value attributable to the rest length of the arm. The variance:

$$\sigma^2 = \sum_{i=1}^{N} \frac{(x_i - \mu)^2}{N} = 18mm$$

combined with the average value were used to define the density function of probability distribution for the measure of the rest length. The variance (σ^2) represents also the uncertain value due to the casual intrinsic error that affects each data. Consequently we have defined three "*ranges*" for the rest length of the measured arm in which is possible, with different probability, to consider the transverse muscle mass in a relaxed condition, and therefore can be used as reference range for the evaluation of the longitudinal arm active stretch, see Table. I.

Table. I Range of arm rest length measures.

	min [mm]	**max [mm]**	**%**
$x_m \pm \sigma^2$	321.4	348.2	68.3
$x_m \pm 2\sigma^2$	308.0	361.7	95.7
$x_m \pm 3\sigma^2$	294.5	375.1	99.7

B. Octopus arm maximum elongation and active stretch

In 55% experiments with the tube, the octopus used the L2 arm to complete the task, with a maximum measured length corresponding to 650 mm. This value can be compared to the range of rest length in order to define the active longitudinal stretch range. With reference to the smaller range for the rest length (334.8 ± 18 mm) of L2 arm and comparing the minimum and the maximum values of the range with the maximum length in elongation, the result is an active stretch range of 186-203%. Further, comparing the average value of the same range with the maximum elongation, results an average active stretch of 194%.

$$\lambda_{active} = \left(\ell_{\max}/\ell_{0,\min}\right) \div \left(\ell_{\max}/\ell_{0,\max}\right) = 186\% \div 203\%$$

C. Octopus arm isometric pulling force

The isometric pulling force was measured in respect to different distances of the target from the base of the arm (L2). The octopus grasps the bait in a point along the arm corresponding to ¾ from the base in respect to the total arm length, whereas with the distal quarter wraps around the bait. Thus, it was also possible to characterize the variation of the pulling force capability along the arm in respect to the actual length of the arm (Table. II). The time of the observed stereotyped movement to apply the maximum force was around 20 to 50 seconds, mostly used to wrap around the bait, while 1-2 seconds was the time necessary to execute the real contraction. Positioning the bait at a distance of 150, 200 and 250 mm from the plate the maximum pulling force capability increases slowly, whereas shows a pick force at 300 mm from the base, corresponding to an actual length of 400 mm, and then rapidly decreases moving the bait away towards 350 mm distance (Fig. 6).

Table. II Relationship between maximum measured isometric pulling force, target distance and actual arm length.

Grasp-point, ℓ_g **[mm]**	***Actual Arm Length L_a*** **[mm]**	***F iso max*** **[N]**
150	200	33.2
200	267	35.8
250	333	37.2
300	400	49.8
350	467	13.8

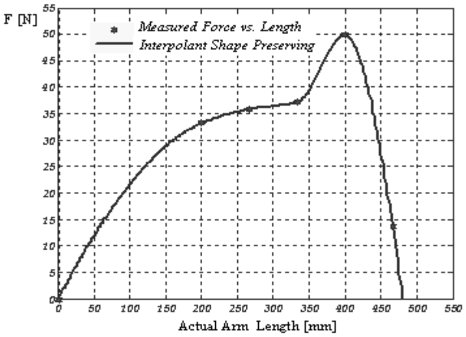

Fig. 6 Maximum measured isometric pulling force in respect to the length of the arm.

The actual length with which the maximum pulling force is applied corresponds to a measure included in the range of the arm's rest length, when all fibres are relaxed. This datum has been related with a biomechanical characteristic of the skeletal muscle fibres that asserts that the optimal length of a fibre to apply the maximum isometric force is 1-1.2 times its rest length [16].

IV. DISCUSSION

Biomechanics general principles and purpose-made instruments are applied on a specimen of *Octopus vulgaris* in order to quantitatively define arm mechanical active properties, such as stretch ability and pulling force capability. The new instrumental setup and method are able to characterize *in vivo* the octopus arm, through a direct but minimally invasive approach that leaves the animal free to act with its complete ability. The measured parameters are relevant as background values, and in particular as real specifications for the choice of the most suitable materials and actuation system, for the next design of a biomimetic octopus-like arm.

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