Quantitative measurements of *Octopus vulgaris* arms for bioinspired soft robotics

Cecilia Laschi, Laura Margheri
*The BioRobotics Institute, Scuola Superiore Sant’Anna*

Barbara Mazzolai
*Center for Micro-BioRobotics@SSSA, Italian Institute of Technology (IIT)*
*Pontedera (Pisa), Italy*
Octopus vulgaris (phylum Mollusca, class Cephalopoda)

- No rigid structures:
  - virtually infinite number of DOF
  - all-direction bending
  - capability to squeeze into small apertures
    (same size of their brain capsule – Ex: 1-inch hole)
- Variable and controllable stiffness
- Manipulation and locomotion capabilities
- Distributed control (50x10^6 neurons in each arm, more than in the brain)

Objectives: studying the octopus and building a robotic octopus

Expected results:
- new science (new knowledge on the octopus biomechanics, motor control, sensory-motor behavior)
- New robotics technologies for sensing, actuation, and control
- an 8-arm octopus-like robot able to move in aquatic environments, elongate the arms, reach & grasp objects, squeeze
The octopus muscular hydrostat

Constant volume during contractions

- Longitudinal muscles
- Transverse muscles
- Oblique muscles

Questions from a robotics point of view:

- Where are insertions of longitudinal muscles?
- How is it possible for the nervous tissue to be stretched and reach elongations like the muscular or connective?
- How much force are the arms capable of exert?
- How much is the arm stiffness?

Muscular system as a modifiable skeleton
Need for quantitative data on the octopus anatomy and biomechanics, to set the specifications for the design of the octopus-like robot

Anatomy:
• Ultrasound imaging
• Histological analysis

Biomechanics:
• In vivo biomechanical measurements of arm capabilities

Characterization of the octopus arm for biomimetics
Characterization of the octopus arm for biomimetics

Need for quantitative data on the octopus anatomy and biomechanics, to set the specifications for the design of the octopus-like robot

Anatomy:
- Ultrasound imaging
- Histological analysis

Biomechanics:
- In vivo biomechanical measurements of arm capabilities

Mechatronic structure of artificial muscular hydrostat
Artificial muscular hydrostat performance
**Ecography**
- Non-invasive, destruction-free method
- Repeatable and rapid investigation
- *In vivo* examination of the arm internal structures on anesthetized animals
- 12 anesthetized *Octopus vulgaris* in a rectangular tank
- Esaote S.p.a. MyLab™Five VET
- Linear transducer LA435 (at 18 MHz)
  - Axial-lateral resolution: 0.085-0.104 mm

**Ecography on moving octopuses**

**Histology**
- To validate ultrasound imaging
- To study in detail muscle fibers insertions

Collaboration with Stazione Zoologica Anton Dohrn, Naples

Ultrasound imaging employed for the first time to explore *in vivo* the arms of *Octopus vulgaris*
In vivo measurements using ultrasound:

- Scanning of the Transverse, Sagittal and Horizontal planes
- Direct measurement of anatomical structures dimensions

Measures of the tissues density:

*Echo Intensity signal (EI)*
### Geometrical features (I)


<table>
<thead>
<tr>
<th>Structure</th>
<th>Ultrasound</th>
<th>Histology</th>
<th>$r$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transverse plane</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorsal longitudinal thickness</td>
<td>3.09±0.07 (2.8–3.4)</td>
<td>2.76±0.04 (2.6–3.0)</td>
<td>0.72</td>
<td>0.018</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>15.31±0.29 (13.4–16.2)</td>
<td>11.02±0.18 (10.2–11.9)</td>
<td>0.69</td>
<td>0.025</td>
</tr>
<tr>
<td>Lateral longitudinal thickness</td>
<td>2.19±0.04 (2.0–2.4)</td>
<td>1.64±0.03 (1.5–1.8)</td>
<td>0.81</td>
<td>0.005</td>
</tr>
<tr>
<td>Ventral longitudinal thickness</td>
<td>2.37±0.06 (2.1–2.7)</td>
<td>2.20±0.06 (2.0–2.5)</td>
<td>0.76</td>
<td>0.009</td>
</tr>
<tr>
<td>Transverse thickness</td>
<td>6.37±0.07 (6.0–6.7)</td>
<td>5.44±0.12 (5.0–6.1)</td>
<td>0.69</td>
<td>0.025</td>
</tr>
<tr>
<td><strong>Horizontal plane</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse thickness</td>
<td>4.73±0.08 (4.3–5.1)</td>
<td>3.97±0.08 (3.7–4.2)</td>
<td>0.79</td>
<td>0.006</td>
</tr>
<tr>
<td>Nerve cord ganglion extension</td>
<td>1.67±0.05 (1.4–1.9)</td>
<td>1.16±0.03 (1.0–1.3)</td>
<td>0.74</td>
<td>0.007</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>4.57±0.09 (4.3–5.0)</td>
<td>4.16±0.07 (3.9–4.7)</td>
<td>0.80</td>
<td>0.005</td>
</tr>
</tbody>
</table>

For muscle bundles: thickness and cross-sectional area; for a ganglion in the nerve cord: longitudinal extension and area. Measurements were taken at the same anatomical position and from the same arms of two animals (N=10). All extensions are given in mm, areas in mm$^2$. Results of Pearson’s correlations ($r$) between measurements taken during sonographic examination and comparable histological sections of arm taken post mortem are also given.
Geometrical features (II)

- Total area intrinsic musculature
- Dorsal versus ventral longitudinal bundles
- Transverse muscles area
- Length/Width Ratio = 26

Dorsal Longitudinal: 26% (total section)
Ventral Longitudinal: 19% (total section)
Measures of the tissues density

✓ **Echo Intensity signal (EI):**

Selection of the area of interest and grey-scale analysis, using standard histogram function

<table>
<thead>
<tr>
<th>Table 2. Mean and standard errors of echo intensity measurements of transverse and longitudinal fibers of <em>Octopus vulgaris</em> arm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Transverse plane</td>
</tr>
<tr>
<td>Sagittal plane</td>
</tr>
<tr>
<td>Horizontal plane</td>
</tr>
</tbody>
</table>

Echo intensity values (resolution, 8 bits; black, 0; white, 255) were determined by grey-scale analysis of the echo signals detected during sonographic examination. Results of Student’s t-test between transverse and longitudinal muscle echo intensity signals for each plane are also given. See Results for details.

Ultrasound investigation on moving animals

- Ultrasound techniques can be applied as non-invasive tool to investigate the arm structure and the behavior of the arm-nerve cord in vivo.

- A linear transducer (18 MHz) to examine the arm in freely moving octopuses during elongation/shortening, pulling and stiffening.

- Relationship between micro structure and whole arm movement.
The sinusoidal arrangement of the central nerve cord allows arms to achieve large elongation without mechanical constraints.
Ultrasound imaging and histology are applied to investigate arm morphology along the three planes, with the research of muscles insertions, the observation of the muscular and nervous tissues arrangement, to reconstruct a 3D map of the arm.

Muscles insertions observed on horizontal sections

Arm Horizontal section in sonographic images and corresponding histological sections

Muscles arrangement observed on transverse section
Results on octopus arm anatomy

Transverse Muscles:
small decrease in diameter allows large elongation (constant volume property)

Longitudinal Muscles:
insertion points along the arm allow local bending

Nerve cord:
sinusoidal arrangement allows arms large elongation without mechanical constraint


L. Margheri, C. Laschi, B. Mazzolai 2012 ‘Soft robotic arm inspired by the octopus. I. From biological functions to artificial requirements’. Bioinspiration & Biomimetics, In Press
Characterization of the octopus arm for biomimetics

Need for quantitative data on the octopus anatomy and biomechanics, to set the specifications for the design of the octopus-like robot

Anatomy:
- Ultrasound imaging
- Histological analysis

Biomechanics:
- In vivo biomechanical measurements of arm capabilities

Mechatronic structure of artificial muscular hydrostat
Artificial muscular hydrostat performance
Two-synchronized High-Speed cameras (DALSA Falcon1.4M100) with High-Resolution (1400Hx1024W @ 100 fps to 1400Hx200W @ 500 fps)

- Geometrical references on the external and internal walls of the tank
- Reconstruction of the scene
- Correction of optical reflection phenomena
- Movement analysis and measurement of the octopus using anatomical markers (eyes, arm tip)
Design of the Instrumental setup

- Design of dedicated devices based on a graduated tube in transparent Plexiglas and a supporting plate to measure one arm at a time, and useful to create a collaborative interaction with the animal for the acquisition of active measures.

✓ The plate is used to:
  - Support the octopus positioning and perform the task.
  - Enable the octopus to use external handhold.
  - Assure that the measured values are referred only to the arm inside the tube.
  - Easily determine which arm is inside the tube and is used for the task.

- The tip of the tube can be sensorized (i.e. load cell) with a purpose-made packaging anchored to the opening of the tube.

  - 10mm d for a 200g octopus
  - 60mm d for a 1600g octopus
In Vivo Measurement of the Octopus Arm

Biomechanical Measurements

- Elongation Strain (active, static: max/reference length)
- Shortening Strain (active, dynamic: time function)
- Force: isometric (dynamic, contr./relax phases)
- Force: with variable elastic loads (dynamic, contr./relax phases)
- Stiffness (dynamic, contr./relax)

Direct measurement of the arms active mechanical properties in moving octopuses

- L. Margheri, C. Laschi, B. Mazzolai
  ‘Soft robotic arm inspired by the octopus. I. From biological functions to artificial requirements’.
- B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi
  ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’.

Bioinspiration & Biomimetics. In Press
Measure of the Arms Reference Length

- **Record** the octopus with the two stereo cameras during the jet propulsion movements
  - Speed record 100 fps

- **Kinematics movement analysis** to define the central part of the stereotyped trajectory (max acceleration)
  - Eye’s coordinates @ 10 frames

- **Reference length** reconstructed considering the distance between the eye and the arm tip, using the external and internal references

- **Reconstruction** of the measure with geometric pinhole camera model, considering the position of the plane of motion
Elongation Strain Measurement

Method

- 24 octopus \((O. vulgaris)\)
  - 24 animals from Naples
  - Different sex (8 Female, 16 Male)
  - Different Weight (140 ÷ 560g)
- Training Phase
  - 2÷5 sessions
  - 15 elongation tasks each
  - Bait position from proximal to distal
- In vivo Measurement
  - Elongation
  - Arm reference length
- Measurement in anesthesia
  - Mantle, Arms, Total Length

Collaboration with Stazione Zoologica Anton Dohrn, Naples
Elongation Strain Results

- Setup validation and methods applicability on a large number of animals
- Measures on arms used by each animal in performing the task
- 237 elongation movements
- Strain (Elongation Ratio): difference between the max length ($L$) during elongation and the reference length ($\ell_0$) during propulsion, normalized in respect to the reference length ($\ell_0$)

- 70 % of length variation (mean strain) corresponding to a 23% of diameter reduction in a cone with constant volume

\[
\frac{\Delta L}{L_0} = \frac{1}{\left(\frac{\Delta R}{R_0} + 1\right)^2} - 1
\]
Shortening

Method
- Additional elastic element
- Recording during arm pulling
- 559 measures

Results
- Mean shortening 20%
- Max shortening 50%
- Velocity 17 mm/s (mean)
Isometric Force Measurement

Method

- Integrated force sensor
- 2 octopuses (*O. vulgaris*, different sex and weight)
- 494 + 434 measurements/subject
- Different bait positions during different tasks to measure the Isometric pulling force capability in different points along the arm

- Isometric Pulling Force:
  - vs. Target distance
  - vs. Arm Length

- Grasp-point to base distances: 150, 200, 250, 300, 350 mm
- $F(t)$ – contr/relax
- $F(\text{max})$ isometric – arm length
- Grasp point position
Isometric Force Results (I)

Grasp-point = Target distance = 0.75 arm length

- The distal quarter of the arm can be used as end effector, while the proximal part is used to exert forces.

Time for task: 20-50 sec
Contraction time: 1-2 sec

\[ F_{iso(max)}: 49.8 \text{ N (L2)} \]
\[ l: 400 \text{ mm} \]
(Animal mass = 1600g, 494 measures)

\[ F_{iso(max)}: 26.8 \text{ N (R3)} \]
\[ l: 200 \text{ mm} \]
(Animal mass = 476g, 434 measures)

\[ F_{iso(average,arm)}: 40 \text{ N (male)} \]

Similar pattern as muscle fiber
Isometric Force Results (II)

Measurement of the arm rest length and total stiffness

- \(\ell_0\) = length at which maximum active contractile force is developed
- Rest length (length at which force is zero): \(\ell_{\text{rest}} = 0.34 \ell_0\)

- \(F_{\text{max}}/\text{Area} = 7.9 \times 10^4 \text{ N/m}^2\)
- Arm Stiffness during isometric contractions: \(K_{\text{tot}}\) (slope) = \(1.87 \times 10^2 \text{ N/m}\)
Stiffness - Force with variable elastic loads

Study of the effects of different elastic loads on the contractions of octopus arm and measurement of stiffness in dynamic conditions

Method

✓ Integrated force sensor
✓ Integrated springs with known stiffness
✓ Different bait positions during different tasks to measure the force capability in different points along the arm

• $F(t)$
• Force – arm length
• Force – velocity (contraction/relaxation velocities)
• Stiffness (stress-strain)
Effects of different external elastic loads

**Force - displacement**

![Graph of force vs. displacement for different elastic loads](image)

<table>
<thead>
<tr>
<th>Mean apparent stiffness modulus</th>
<th>Max apparent stiffness modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.59 N/mm</td>
<td>3.6 N/mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean stiffness rate</th>
<th>Max stiffness rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.099 N/mm·s</td>
<td>2 N/mm·s</td>
</tr>
</tbody>
</table>

Similar pattern as muscle fiber

\[ K_{(arm)} = 9.5 \times 10^5 \text{ N/m}^2 \]

(Elephant trunk = 10⁶ N/m², Wilson et al 1991)
### Results on octopus biomechanics

**Elongation:**
70% of arms mean elongation corresponding to 23% of diameter reduction

**Shortening**
- Mean shortening 20%
- Max shortening 50%
- Velocity 17 mm/s

### Force:

<table>
<thead>
<tr>
<th></th>
<th>Max Pulling Force</th>
<th>Mean Pulling Force</th>
<th>Grasp Point Position</th>
<th>Contraction Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>49.8 N @ 400 mm (m=1600g)</td>
<td>40N with arm length 400 mm</td>
<td>0.75 of total arm length</td>
<td>1-2 sec</td>
</tr>
<tr>
<td></td>
<td>28.6 N @ 200 mm (m=476g)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Stiffness**
- $9.5 \times 10^5$ N/m²
- Max velocity 2 N/mm*s
The mechanical measurements of the octopus arm capabilities have been used in the model to obtain information about the arm visco-elastic properties and muscle activation function.

From characterization to modelling and simulation

Visco-elastic model for octopus arm
Active component:
- Elastic element of stiffness \( k_p \)
- Viscous element \( B \)
- Active state element (contraction of muscle for each received stimulus) contractile force \( C \) and rate constant \( \beta \) of exponential decay: *activation function*

Passive component:
- Elastic element of stiffness \( k_i \)

External load:
- Elastic forces element of stiffness \( k_e \)
- Gravitational mass \( M \) and viscosity \( D \)

Equations of motion:
\[
\begin{align*}
k_p x_1 + B \dot{x}_1 + C e^{-\beta t} &= k_i x_2 \\
k_i x_2 + k_e x + D \dot{x} + M \ddot{x} &= 0
\end{align*}
\]

Force generated by arm (input in the model):
\[
F_e(s) = \frac{k_e k_i C}{(s + \beta) \{ B(k_i + k_e)s + k_i k_p + k_i k_e + k_e k_p \}}
\]
Isometric contractions

Force measurement in isometric condition

Input: Isometric force $F(t)$ (contr/relax) for different lengths

Imposed arm stiffness:

$K_{tot} = 1.87 \times 10^2$ N/m

Iteration tests in the model

- $K_p = 3.357 \times 10^5$ N/m
- $K_i = 3.355 \times 10^5$ N/m
- $B = 100$ N/sec/m
- $C = 10$ N
- $\beta = 2$
Contraction against different elastic loads

Initial visco-elastic parameters
- $K_p = 3.357 \times 10^5$
- $K_i = 3.355 \times 10^5$
- $B = 100$
- $C = 10$
- $\beta = 2$

- Input: measures of force (t)
- Output: measures of displacement (t)

The simulations with the model are in good agreement with the experimental measurements.
When interpreted in a behavioral context, the elongation efficiency reveals the potential for biomechanical influences on predation, exploring, or animal-animal interaction (mating).

The size or the sex of the animal may have an impact on the mechanical efficiency, or different arms may show different performance.

The instrumental setup used to measure the mechanical capability of the arms to elongate and reach a food target has been used on 19 animals different for sex and size (12 males and 7 females, Dorsal Mantle Length range 72.5-122.4mm, longest arm lengths range 320-565mm) to investigate possible differences among the 8 arms or different animals.
Females achieved higher elongation percentages (75%, SD 26%) than males of a same size (61%, SD 33%, t-test, p<0.05).

Difference is higher when comparing the arm R3 (hectocotylus in males), with 87% (SD 38%) for the females versus 54% (SD16) for the males.

Smaller size octopuses achieved higher average elongation percentages (72%, SD 28%) than larger octopuses (63%, SD 32 %)

Favorite arm use: octopuses preferentially use L3 arm (longest arm)

First assessment of biomechanical quantification as a potential method for the study of octopus behavior and differences among individuals.

OBJECTIVE
Extracting bio-inspired criteria to develop innovative attachment/detachment mechanisms.

SUCKER INVESTIGATION

<table>
<thead>
<tr>
<th>Method</th>
<th>10^{-3}</th>
<th>10^{-4}</th>
<th>10^{-5}</th>
<th>10^{-6}</th>
<th>[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Resonance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal section of arm and sucker</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultrasound</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecography</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal section of sucker</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Histology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal section of arm and sucker</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CryoSEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal section of sucker</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MRI, Ultrasound, Histology, and CryoSEM images are shown.

MRI: Magnetic Resonance Transversal section of arm and sucker.
Ultrasound: Ecography Transversal section of sucker.
Histology: Transversal section of arm and sucker.
CryoSEM: Transversal section of sucker.

Longitudinal section of arm and sucker and Transversal section of arm and sucker images are also shown.

Denticles and nervous structures and Internal structure of the denticles images are shown.

CENTER FOR MICRO-BIOROBOTICS IIT@SSSA
**Why 3D Reconstruction?**

Sucker 3D reconstruction is most important in order to obtain the all spatial information necessary to address new biological knowledge and investigation, as for example: physical dimensions, morphological information, spatial arrangement of different tissues, etc. Moreover, 3D reconstruction is required to generate a surface mesh for later numerical processing.

**Images and Videos**

[Images of 3D reconstructions from MRI and Histology]
# Measurements of the Active Strain of the Octopus Arm vs Artificial Arm

<table>
<thead>
<tr>
<th>Biological Results (Octopus vulgaris)</th>
<th>Robotic Solution and Performance</th>
<th>Measure method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Muscles</td>
<td>Design Arrangement</td>
<td>70% of arm elongation corresponding to 23% of diameter reduction</td>
</tr>
<tr>
<td>Longitudinal Muscles</td>
<td>Design Arrangement</td>
<td>Max Pulling Force 49.8N@400mm (m=1600g) 26.8N@200mm (M=467g) Mean Pulling Force 40N with arm length 400mm (100g) Time to contract 1-2s</td>
</tr>
<tr>
<td>Nerve Cord Arrangement</td>
<td>Sinusoidal arrangement at the arm rest length while has a distension during the elongation</td>
<td>Large elongations can be achieved using a sinusoidal arrangement for cables</td>
</tr>
</tbody>
</table>

**Mechanical performance**

<table>
<thead>
<tr>
<th><strong>Transverse Muscles</strong></th>
<th><strong>Design Arrangement</strong></th>
<th><strong>Mechanical performance</strong></th>
<th><strong>Nerve Cord Arrangement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>70% of arm elongation corresponding to 23% of diameter reduction</td>
<td>Sinusoidal arrangement at the arm rest length while has a distension during the elongation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Input to model for the design of SMA helical and define</td>
<td>Large elongations can be achieved using a sinusoidal arrangement for cables</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultrasound (MyLabFiveVET@18MHz)</td>
<td>Ultrasound (MyLabFiveVET@18MHz)</td>
</tr>
</tbody>
</table>

**Histology** (Milligan-Trichrome staining)

**In vivo biomechanical measurement**

(2 octopuses, 928 max of pulling force)

**Grasp Point Position**

0.75 of total arm length

End effector position and active arm length

---

**Measurement Table**

<table>
<thead>
<tr>
<th>Biological Results (Octopus vulgaris)</th>
<th>Robotic Solution and Performance</th>
<th>Measure method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Muscles</td>
<td>Design Arrangement</td>
<td>70% of arm elongation corresponding to 23% of diameter reduction</td>
</tr>
<tr>
<td>Longitudinal Muscles</td>
<td>Design Arrangement</td>
<td>Max Pulling Force 49.8N@400mm (m=1600g) 26.8N@200mm (M=467g) Mean Pulling Force 40N with arm length 400mm (100g) Time to contract 1-2s</td>
</tr>
<tr>
<td>Nerve Cord Arrangement</td>
<td>Sinusoidal arrangement at the arm rest length while has a distension during the elongation</td>
<td>Large elongations can be achieved using a sinusoidal arrangement for cables</td>
</tr>
</tbody>
</table>

**Mechanical performance**

<table>
<thead>
<tr>
<th><strong>Transverse Muscles</strong></th>
<th><strong>Design Arrangement</strong></th>
<th><strong>Mechanical performance</strong></th>
<th><strong>Nerve Cord Arrangement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>70% of arm elongation corresponding to 23% of diameter reduction</td>
<td>Sinusoidal arrangement at the arm rest length while has a distension during the elongation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Input to model for the design of SMA helical and define</td>
<td>Large elongations can be achieved using a sinusoidal arrangement for cables</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultrasound (MyLabFiveVET@18MHz)</td>
<td>Ultrasound (MyLabFiveVET@18MHz)</td>
</tr>
</tbody>
</table>
Design of transverse actuators inspired by the octopus muscles arrangement

- Radial net configuration with straight interweaving of transverse muscle fibers
- Key-role of the trabeculae in maintaining circular the transverse section during contraction

Transverse Muscles: SMA springs

4 arcs configuration:
- too simplistic
- not shape preserving
- not bioinspired
- lower efficiency

More efficiency in the reduction of the diameter

B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’. *Bioinspiration & Biomimetics*. In Press

Measurements of the Active Strain of the Octopus Arm vs Artificial Arm

- Measured 70% of arm strain during elongation obtained with 23% diameter reduction

Transverse Muscles: SMA springs

- 23% of diameter reduction has been used as specification input in the model for the design of the SMA helical to define:
  - NiTi Alloy mechanical properties
  - Wire diameter
  - Average spring diameter
  - Number of coils
  - Heat treatments

B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’. Bioinspiration & Biomimetics. In Press
Measurements of the pulling force applied by the octopus arm vs artificial arm performance

- Results of the force measurements (40 N mean, 1-2 sec contraction time) are used as specification in setting the longitudinal actuators of the robotic arm prototypes.
- Cables have been covered with sheaths to reduce friction and avoid silicone damages.
- The grasp point position at a 0.75 of total length has been used to allow grasping during the arm prototype pulling tests.

**Longitudinal Muscles:** longitudinal cables + sheaths

---

B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’. *Bioinspiration & Biomimetics*. In Press

Nervous tissue of the arm nerve cord has a sinusoidal arrangement at the arm rest length while is extended during elongation.

- Large elongations can be achieved using a sinusoidal arrangement for cables.

B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’. Bioinspiration & Biomimetics. In Press

Muscles insertions along the arm allow multiple point bending

Longitudinal Muscles: longitudinal cables with insertion points along the arm allow multiple point bending

The arm prototype rely on additional cables from the base of the arm and fitted to several points along the arm length, thus improving bending capability

B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi ‘Soft robotic arm inspired by the octopus. II. From artificial requirements to innovative technological solutions’. Bioinspiration & Biomimetics. In Press
Octopus-like arm mock-up

Simplified version of the longitudinal and transverse actuation system

Design of an artificial muscular hydrostat

- Longitudinal muscles
- Transverse muscles
- External connective tissue
- Central nerve cord channel

- Longitudinal cables
- Transverse SMA springs
- External braid
- Central electric wires
- Sensorized skin with suckers


PATENT PENDING
Soft actuators for the artificial muscular hydrostat

*SMA (Shape Memory Alloy)*

Pros:
- lightweight
- flexible
- high work density
- simple electronic drivers
- high possibility of miniaturization

Cons:
- low strain (5-8%)
- low efficiency
- relatively high current
- low bandwidths
- non-linear behaviour
- wide hysteresis

Spring shape (more than 300%)

Water environment which facilitates cooling

All – nothing activation and antagonistic arrangement
SMA (Shape Memory Alloy) spring

SMA spring with a PTFE sheath in distilled water coupled with silicone parallelepiped 25x10x5 mm that provides a restoring force

- 12 coils
- inner diameter: of 1 mm
- wire diameter of 0.2 mm
- thermally insulated with a shrinkable PTFE sheath
- 1.2 A of activation current
Development of the mechanical interface between the soft actuator and the muscular unit

First transverse section mock-up

1 second of 600 mA direct current and then 50% duty cycle pulse current

6 SMA springs:
- 0.2 mm Flexinol® wire diameter
- $<D>/d = 6$ (cycle life parameter)
- Spring internal diameter = 1 mm

Silicone / braided sleeve:
- External diameter = 28mm
- Internal diameter = 20mm
Octopus-like robot arm

4 longitudinal cables, from base to tip
12 transverse actuators, 8 SMA springs each, uniformly distributed along the arm

Photo by Massimo Brega, The Lighthouse
Octopus-like robot arm

The last 13 cm are passive, with no actuation.

4 longitudinal cables, from base to tip
12 transverse actuators, 8 SMA springs each, uniformly distributed along the arm.

Sensorized skin
(University of Reading)
Octopus-like robot arm

Bending

Elongation
Octopus-like robot arm

Design and development of a soft robotic octopus arm exploiting embodied intelligence

M. Cianchetti, M. Follador, B. Mazzolai, P. Dario, C. Laschi
Robotic OCTOPUS

Mather J A, 1998

Though the octopus arms are not specialized and they all can perform the same functions, they are used more often for:
- pair 1: reaching, fetching, grasping, sensing;
- pair 2: crawling, elongation, shortening;
- pairs 3 and 4: crawling and standing

The sensorized skin covers the arms

The robotic octopus works in water and its buoyancy is close to neutral.
Conclusions

- In biomimetics / bioinspired robotics, biology gives specifications for the design work
- Descriptions and models available in biology literature may be insufficient for this role
- Additional quantitative data may be needed, measured with the robotics perspective and objectives
- Example of translation of biological measures into robotics specifications
- The first prototypes represent a good translation of biology into robotics
Thanks

SSSA OCTOPUS Team:
• Paolo Dario
• Barbara Mazzolai
• Matteo Cianchetti
• Laura Margheri
• Andrea Arienti
• Maurizio Follador
• Marcello Calisti
• Michele Giorelli
• Federico Renda
• Francesco Giorgio Serchi
• Alessia Licofonte
• Ilaria Baldoli
• …our octopuses

Acknowledgments to:
European Commission in the ICT-FET
OCTOPUS Integrating Project, #231608

www.octopus-project.eu