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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

A mechanical approach for comparing marine species to develop bio-inspired grippers

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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1. Introduction

In the last years, more and more bio-inspired solutions have been adopted in the robotic field. In fact, new ideas are obtained by looking at animals' behaviors, capable of providing important mechanical advantages, such as manipulators derived from the tongue of chameleons [1], or inspired by the octopus arm [2]. While biologists usually prefer a qualitative approach more than a quantitative one, following anatomical analyses paired with geographical ones, engineers try to model living beings as mechanical systems, considering muscles as actuators, bones and articulations as linkage mechanism, etc. [3].
When considering big families of animals, it is not easy to perform a comparison that allows to individuate the best solution for a given problem by exploiting biological analyses.
The objective of this paper is to propose an engineering approach to the study and comparison of marine species. By exploiting these quantities, it can be noticed how the characteristics and behaviors of these species follow what comes from a pure biological analysis, allowing at the same time a valid comparison that otherwise, would not have been possible.
Seven species of fishes not belonging to the same families, showing many differences in their anatomy and behaviors, are considered to make the approach as generally valid as possible.
In Chapter 2, the mechanical approach to the analysis of fishes' mouths is described by using some parameters of interest which are explained together with the most important features useful for the analysis.
The third chapter regards the introduction of the different species taken into account, belonging to different families, which differs both in shape and in size, in feeding behavior, and particularly in the jaw anatomy. The jaws are presented in the form of linkage mechanism, in particular four-bar ones.
In the fourth chapter, the results from the kinetostatic analysis of the linkage mechanisms are extrapolated and graphs showing the comparisons between species for each mechanical parameter are derived.
In the last chapter, once selected the most suited species for its mechanical properties, a gripper is developed and printed, following the corresponding linkage mechanism. Some tests are

carried out to validate the effectiveness of its structure.

2. Mechanical Approach

In this chapter the mechanical parameters are introduced and explained, highlighting the advantages that can be obtained by applying this mechanical approach.
To simulate the biomechanics of the jaw of different species, their skeletal structures have been schematized as linkage mechanisms. The rigid parts in the jaw anatomy like bones are treated as rigid links that can move and rotate but cannot be deformed. It is important to clarify that bones shape is not interesting from a kinetostatic point of view. For this reason, bones with even complex shapes will be modeled through rigid straight beams. Similarly, the joints that connect the bones are approximated as hinges. Lastly, muscles are considered as actuators. When a muscle is activated, it reduces its length, thus moving the whole kinematic chain. This modelling approach is demonstrated to be able to represent quite precisely the biomechanics of skeletal structures [3].
In addition, all the jaw mechanisms of the fishes analyzed in this paper can be schematized as 2D structures, meaning that all the links can be considered to move on the same plane.
It is important to notice that each species uses different muscles for the opening and closing phase. With this in mind, the two phases have to be analyzed individually, as from a topological point of view the mechanism changes as the input force/displacement is applied on different links.
To better compare species that differ so much in shape and size, it is useful to normalize muscle contraction with respect to a specific length. Two normalizations of the muscle contraction are of particular interest.

$$normalized\ contraction = \frac{l_0 - l_1}{r} \quad (1a)$$

$$percentage\ contraction = \frac{l_0 - l_1}{l_o} \cdot 100 \quad (1b)$$

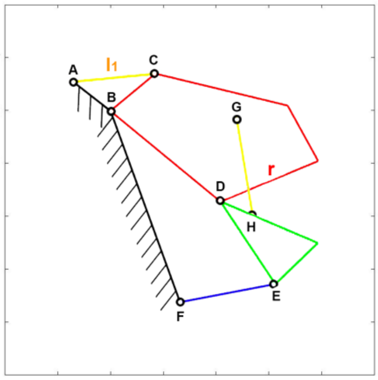


Figure 2.1: The upper jaw link is pointed out as r, the muscle length at rest is l_0 and the contracted one is l_1.

To describe how the mechanism is able to transmit motion from its input (muscle contraction) to its output (jaw motion), some kinematic parameters can be introduced. The first is the "geometric velocity" also called "instantaneous transmission ratio". It is computed as the ratio between the differential of the jaw gape angle (φ) and the differential of the muscle length (l):

$$\varphi' = \frac{\frac{d\varphi}{dt}}{\frac{dl}{dt}} = \frac{d\varphi}{dl} \quad (1c)$$

The higher its value the greater is the velocity amplification, meaning that the mechanism can transform a slow movement of the input into a fast output motion. However, a high value also means a decrease of the output torque. The geometric velocity is in fact inversely proportional to the force amplification.
Another parameter that is representative of the ability to transmit the motion is the "pressure angle". The pressure angle θ is defined as the smaller of the two angles generated by the directions of the force S and the velocity V.

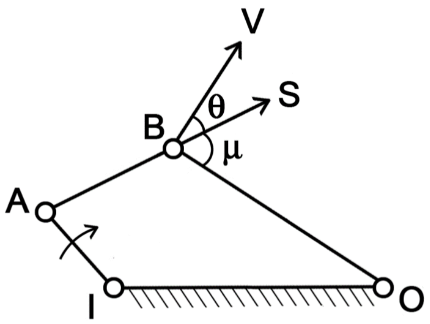


Figure 2.2 Pressure angle θ in a linkage mechanism.

It is clear that with an increase of θ the action of the force S on the follower becomes less effective. At the limit case of $\theta=\pi/2$ the force is completely unsuitable to transmit the motion. Therefore, the best condition is when $\theta=0$ in which the transmission is optimized.
Finally, as for many fishes the jaw motion corresponds to roto-translation, a new parameter called jaw protrusion is introduced to consider the linear displacement of the attachment point of the upper jaw with the lower one.
The mechanical model here introduced, together with main kinetostatic parameters defined, allows to simulate and analyze the jaw biomechanics of different species.

3. Kinematic schemes

To apply the methodology previously described, seven species of bony-fish and one species of cartilage-fish are considered, each one different from the others in size and shape. The species are *Cheilinus chlorourus* (Bloch, 1791), *Micropterus salmoides* (Lacepède, 1802), *Eustomias obscurus* (Vaillant, 1884), the extinct *Dunkleosteus terrelli* (Newberry, 1873), *Lepomis macrochirus* (Rafinesque, 1819), *Chlorurus sordidus* (Forsskål, 1775), and the cartilage-fish *Chiloscyllium plagiosum* (Anonymous [Bennett], 1830).
The seven species are chosen in order to analyze the behavior of seven different structures, varying both during the opening and closing phase one from the other, as it can be seen from the mechanisms shown in this chapter. This is important for proving how the proposed approach allows the comparison of species so different from each other.
The anatomy of the jaws is analyzed for each species, and the muscles responsible for the opening and closing movement of the mouth are identified, allowing to create the mechanical model of all the species considered, depicting them as one or more four-bar linkage mechanism. As an example, the Figure 3.1.a shows the head anatomy of *Eustomias obscurus*, highlighting its bones. From the observation of its cranium, it is possible to divide it in the key links and bodies, as in Figure 3.1.b. This step is of fundamental importance in order to understand how the structure works and to extract the linkage mechanism that is shown in Figure 3.1.c.

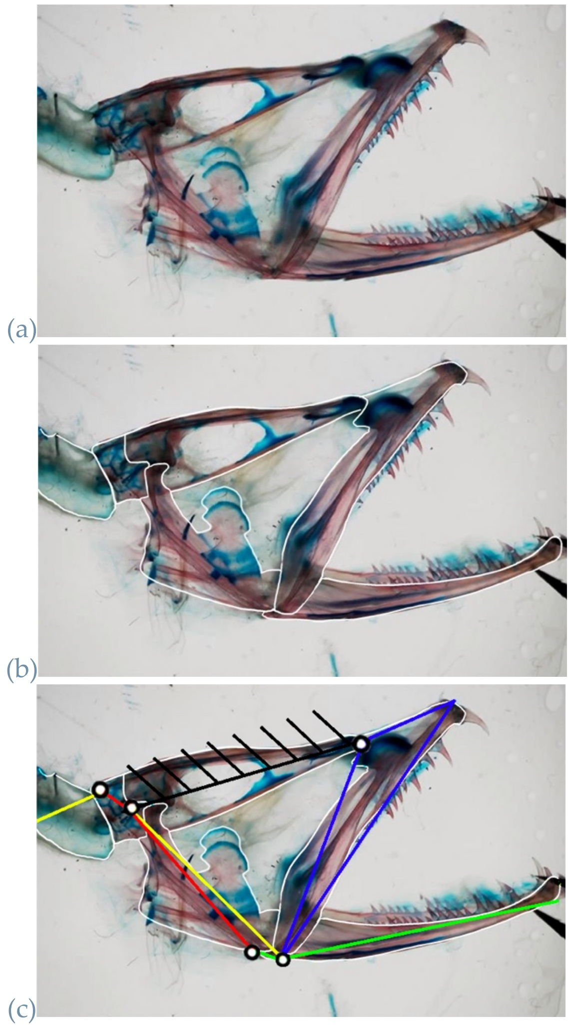


Figure 3.1 a) X-ray of *Eustomias obscurus*; b) X-ray of *Eustomias obscurus* with bodies highlighted; c) X-ray of *Eustomias obscurus* with bodies highlited and corresponding linkage mechanism.
(Schnell, Muséum national d'Histoire naturelle)

The structure is capable of moving its elements for simulating how the species open and close their mouths. In Figure 3.2, as an example, the linkage mechanism of the *Chlorurus sordidus* is shown [4].

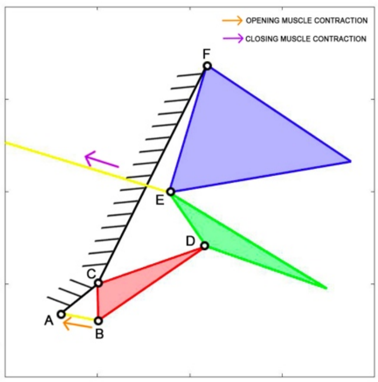
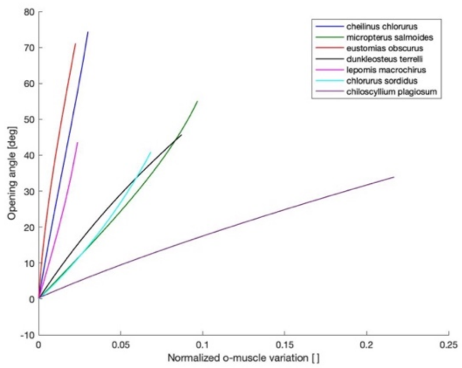


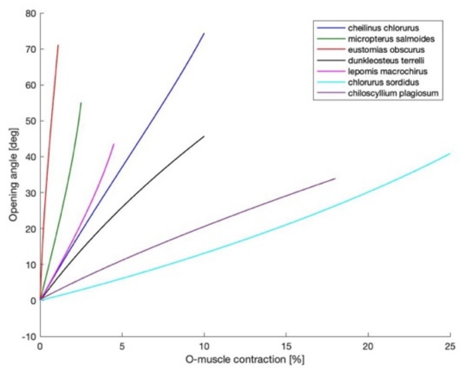
Figure 3.2 Kinematic scheme of the *Chlorurus sordidus*.

4. Results

Having defined the species of fishes taken into consideration and the mechanical parameters that will be used, the kinematic diagrams introduced in chapter 3 are analyzed under several aspects, with the most interesting ones here reported. First, the range of the gape angle of the jaw is compared. The gape angle of the jaw is studied related to the input muscle contraction. As already stated, two contraction parameters are used: the "normalized contraction" and the "percentage contraction". They are both useful because the considerations that can be deduced from them are different. The first one aims at comparing how the biological structure converts a linear motion of the muscle into the jaw rotation, without considering the length of the muscle. Therefore, it is focused primarily on the linkage mechanism. The second one instead takes into account the size of the muscle and so focuses on the input actuation.
Figures 4.1 a) and b) show the gape angle during the opening phase.



(a)



(b)

Figure 4.1 a) Opening angle with normalized muscle variation; b) Opening angle with percentual muscle contraction.

Then the velocity amplification of the different biological mechanisms is studied, as seen in Figure 4.2 where the "geometric velocity" during opening phase is shown. It is necessary to remember that all of them apart from *Chlorurus sordidus* use the suction feeding, a technique through which it captures preys by generating a flow of water into a rapidly expanding mouth cavity, and so they need to achieve a very fast opening of the jaw.
Three completely different solutions to achieve fast opening of the jaw are observed. The first one is related to the structure, on which species such as *Cheilinus chlorourus* and *Lepomis macrochirus* rely on. The second one is due to having a big muscle such as the one of *Micropterus salmoides*. The last one is the snapping behavior used by *Chiloscyllium plagiosum*.

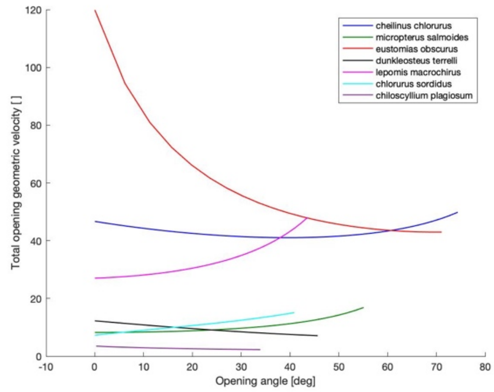


Figure 4.2 "Geometric velocities" during opening.

After that, it is interesting to plot the jaw protrusion during the whole motion, shown in Figure 4.3. Almost all the species are characterized by a translation along the x-axis meaning that they stretch out their mouth forward during feeding. This is a feature that is very helpful during the capture of the prey, because the jaw is extended towards it increasing the effectiveness of the suction feeding.

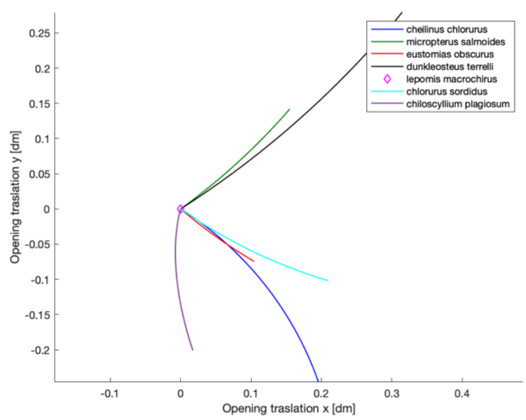


Figure 4.3 Shift during opening.

Finally, the effectiveness of the linkage mechanism together with the muscle attachment is analyzed through the pressure angle.
In Figure 4.4 the pressure angles of some species are represented. While the best transmission of motion happens when the pressure angle is close to 0°, a value higher than 45°÷50° usually means the mechanism requires a very high force to complete the motion.

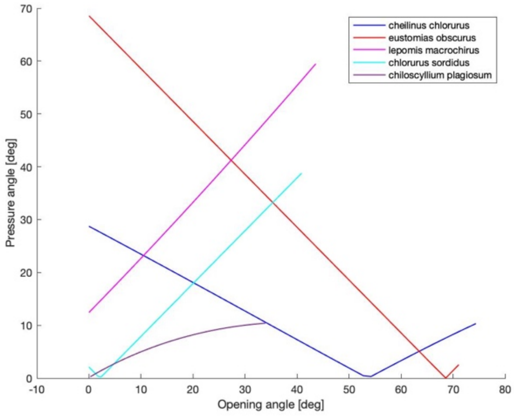


Figure 4.4 Pressure angle for the linkage mechanism.

5. 3D Printing and testing

The last step of the analysis is the implementation of a gripper, based on the kinematic schemes seen in the third chapter. Among all the species analyzed, the *Chlorurus sordidus* paired good values for the pressure angles (always below 40°), with low values of the geometric velocities during both opening and closing of its jaws. For these reasons it appears to be a valid choice, so it is selected as the candidate for the realization of the gripper.
Firstly, each link of the four-bar linkage mechanism of the kinematic scheme of the species is modelled as a 3D body with the software SolidWorks, as seen in the Figure 5.1. The maximum value of the angle of mouth opening follows the behavior of the species analysed in chapter 4, so it is limited to 40°.

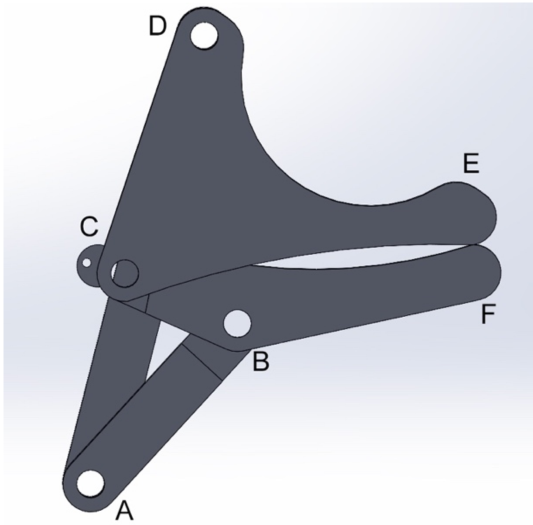


Figure 5.1 3D bodies on SolidWorks of the linkage mechanism of the *Chlorurus sordidus.*

The bodies are 3D-printed in ABS (Acrylonitrile Butadiene Styrene), with an infill percentage of 20%, and the dimensions maintain the same ratios of the kinematic scheme.
Regarding the functioning of the gripper, a tension spring is place between the upper and lower jaw in order to keep the jaws closed, simulating the behavior of the closing muscle of the species. The motor acts on the link A (AB) transmitting the rotation, following the behavior of the opening muscle.
Once printed, the pieces are assembled with the servomotor and the spring, adequately sized, and mounted on a sheet of plexiglas to replace the AD piece as frame, to be ready to conduct the gripping tests.
Objects with different shape, dimension, material and stiffness are selected, and some trials are carried out to verify the correct functioning of the gripper. In Figure 5.2 there is the example of a pencil sharpener, with a smooth surface. The tests are conducted by controlling the servomotor with the Arduino One board, with the addition of an amplifier.

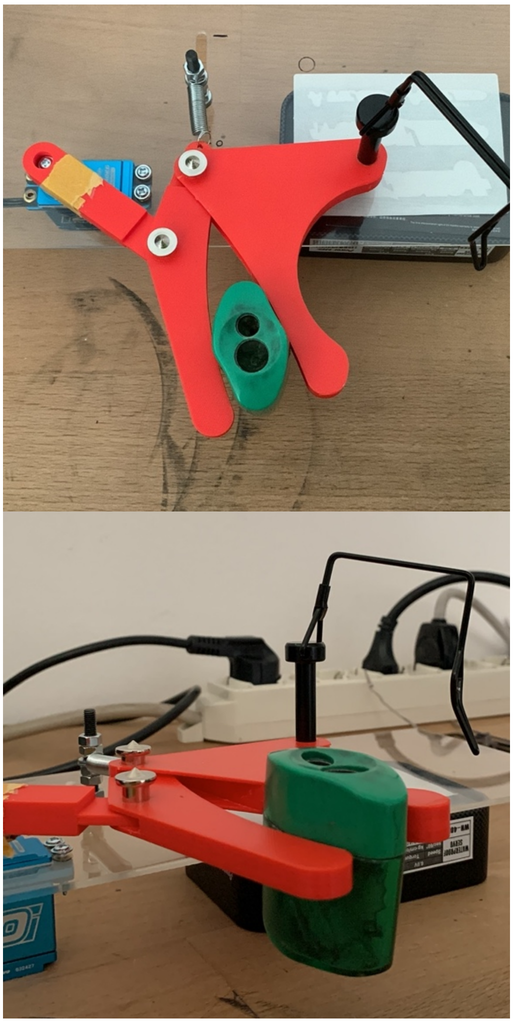


Figure 5.2 Grip test of a pencil sharpener with two views.

On the basis of the carried-out tests, the gripper inspired by the jaws of the *Chlorurus sordidus* results to be adequate for the grasping of objects with either rough or smooth surface, different shape and dimension, according to the maximum opening of 40 degrees.

6. Conclusions

The quantitative approach proposed is based on mechanical parameters to compare species different one from each other, in order to give to engineers a method capable of selecting and analyzing the most suited choice in developing bio-inspired solutions. Seven species of fishes are modelled as four-bar mechanism and compared with each other in mechanical terms such as geometric velocities, pressure angles and more. The comparison not only confirms some pure biological characteristics, such as feeding methods or different diets, but it is a reference to choose the best option among all the species, depending on the requirements to meet. In this case, the idea is to create a small gripper, so by looking at the comparison graphs, the *Chlorurus sordidus* appears to be the best choice. Following the realized kinematic scheme, the links are modelled as 3D bodies and printed in ABS. Different tests consisting in lifting objects with variable shapes, dimension, material and stiffness are carried out to verify the correct functioning of the gripper, demonstrating the validity of the approach.

As future developments, the approach can be applied on different species, and can be used to realize other grippers or bio-inspired solutions. An implementation may be the step from the purely planar analysis made in this paper, to the spatial one, to realize new manipulators capable of grasping and lifting objects and moving them in space. More complex designs can be implemented, with an increasing number of DoF that requires more elaborate control strategies.

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