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

TESI MAGISTRALE IN MECHANICAL ENGINEERING

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Abstract: The methods of analysis of biologists profoundly differs from the ones of engineers, mainly because of their different interests and goals. The objective of this paper is to introduce a new approach for the study and comparison between biological species, giving a mechanical point of view to the analysis to make it suitable for engineers nowadays deeply interested in bio-inspired solutions in the robotic field. The approach follows the modelling of the jaws of seven species of fishes, profoundly different one from the other in shape, dimension and behaviors, as four-bar linkage mechanisms. The models are planar rather than spatial, where the fundamental muscles responsible for the opening and closing of the jaws are the inputs of the structures, while the jaws themselves which open and close are the outputs. The paper follows the modelling of all the species and the comparison on the basis of the mechanical features chosen during the analysis, fundamental for the implementation of a gripper. The one species with the overall most suited parameters is selected and the gripper is printed out once its bodies are modelled in 3D. Finally, grasping tests are successfully carried out with objects different in material, shape, dimension and stiffness, demonstrating the validity of the approach.

Key-words: bio-inspired, gripper, linkage mechanism, robotic, four-bar mechanisms

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] [2] [3], or inspired by the octopus arm [4] [5] [6]. As a fundamental step in the bioinspired approach, the analysis of the biological solutions results to be extremely important to develop innovative designs. It is a matter of fact that the analysis can be done with different tools, that mainly depend on the background of researchers and their goals. 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. [7].

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. Species too different one from the other, considering the anatomy and their functions, are in fact difficult to be compared.

Among all the possible species, fishes were chosen for the analysis, having interesting opening-closing jaw mechanisms, exploitable for example for the design of a manipulator, and having a large field of cases which differ profoundly one from the other.

The objective of this paper is in fact to propose an engineering approach to the study and comparison of marine species, taking into account some mechanical parameters of interest, such as the mouth's opening and closing speeds. 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 tools and methods typical of the engineering field. Some parameters of interest are presented and explained together with the most important features useful for the analysis.

The next step is to introduce 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. The structures are simplified from spatial to planar, but they are accurate [7], being able to well synthetize the motion of the jaws performed by each species. Furthermore, each link and constraint are highlighted to present the mechanisms as clearly as possible. From the analysis of these structures, which are more or less complex depending on the species, the mechanical quantities needed for the analysis are obtained. The muscles in charge for the opening and closing of the mouth are considered as the inputs of the structures, while the movement of the jaws are the outputs.

Then, 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. Additionally, a comparison between the measured velocities of each species taken by the literature is introduced, in order to present not only the effect of the structure itself, but also differences coming from the anatomy, mostly regarding the length of the muscles.

It will be exhibited how biological notions concerning the analyzed species can be confirmed by looking at the obtained results, demonstrating the validity of the proposed engineering approach.

Finally, 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

From a biomechanical point of view, living beings can be modeled as mechanical systems featured with rigid bodies connected through ideal joints, moved by external or internal forces generally exerted by muscles or due to the interaction with the external environment. This approach will be applied to the analysis of fishes' jaw, by adopting some tools that have been developed and applied in the field of applied mechanics. In this chapter these 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 [8]. 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 [7]. 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. This is quite advantageous because it simplifies the computation and the analyses.

Considering the mechanical analogy between the biological structure and the corresponding linkage structure, each mechanism has an input actuation that moves the first link (driver). In this particular case, the input is the contraction of the muscle. Motion is then transformed and transmitted to the final link (called follower) that generally corresponds to the jaw. 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.

Because several parameters will be related to the input actuation, particular attention should be paid to the possible definitions of muscle contraction. 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.

The first one, called "normalized contraction", considers the length shortening of the muscle normalized over the maximum length of the upper jaw of the relative species. The choice of the latter as the standardization unit derives from the necessity to compare different organisms that vary significantly in size. With this normalization it is possible to analyze how the gape angle changes as function of a length variation of the input muscle regardless of the dimension of the species. Therefore, the normalized contraction is computed as the difference between the length of the muscle at rest (l_0) and the length of the contracted muscle (l_1) over the length of the upper jaw (r). Figure 2.1 shows these characteristic lengths.

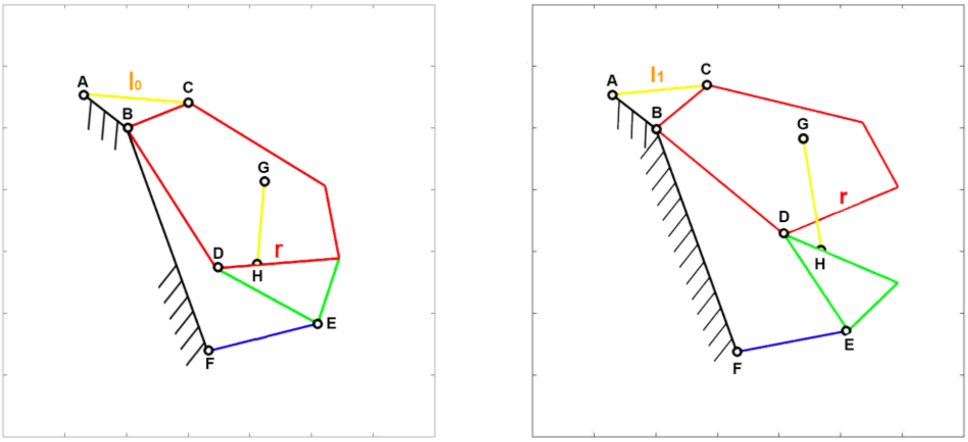


Figure 2.1 The upper jaw link is pointed out as r, the muscle length at rest is l_0 and the contracted one is l_1.

$$normalized\ contraction = \frac{l_0 - l_1}{r} \tag{1a}$$

Another useful normalization regards the length shortening of the muscle ($l_0 - l_1$) over its normal length at rest (l_0). It is practically a "percentage contraction" of the muscle.

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

Both of these contraction parameters will be used in the analyses, allowing to deduce different considerations.

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". As the name suggests, it describes the kinematic relationship between the output and input velocities. It is computed as the ratio between the differential of the jaw gape angle (φ) and the differential of the muscle length (l):

$$\varphi' = \frac{\frac{d\varphi}{dt}}{\frac{dl}{dt}} = \frac{d\varphi}{dl} \tag{1c}$$

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". With reference to Figure 2.2, S is the force the driver applies indirectly on the follower, while V is the velocity of the point of application. 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.

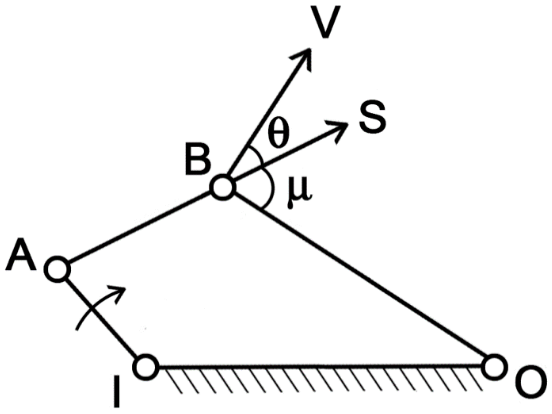


Figure 2.2 Pressure angle θ in a linkage mechanism. IA is the driver link, BO the follower link, AB is the coupler, V is the vector of velocity of point B, S the one of the force applied in point B.

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. This approach can compare more in depth how the skeletal mechanisms of these species function and so it allows to achieve interesting considerations from a mechanical point of view that can be used in the development of a bioinspired gripper.

In the next chapter, the jaw anatomy of some different species will be modelled and described through kinematic diagrams: a representation made up of segments and nodes that correspond respectively to links and hinges.

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* [9], *Micropterus salmoides* [10], *Eustomias obscurus* [11], the extinct *Dunkleosteus terrelli* [12], *Lepomis macrochirus* [13], *Chlorurus sordidus* [14], and the cartilage-fish *Chiloscyllium plagiosum* [15].

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 [16]. 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.

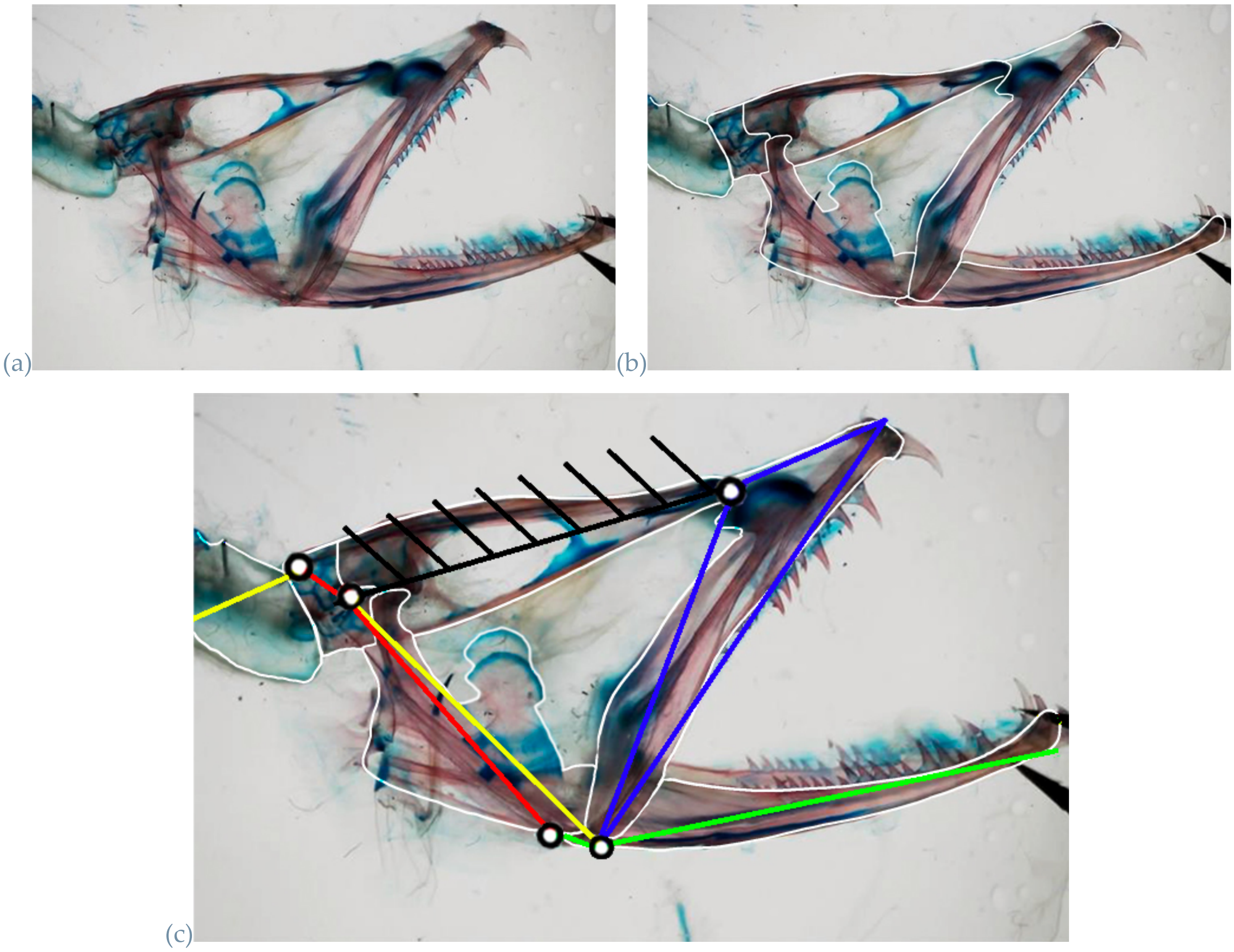


Figure 3.1 a) X-ray of *Eustomias obscurus*; b) X-ray of *Eustomias obscurus* with bodies highlighted; c) X-ray of *Eustomias obscurus* with bodies highlited and corresponding linkage mechanism. [17]

The structure is capable of moving its elements for simulating how the species open and close their mouths, as shown in Figure 3.2, where the closing mechanism of the *Cheilinus chlorourus* is shown. Each kinematic scheme and the resulting graphs are developed in Matlab.

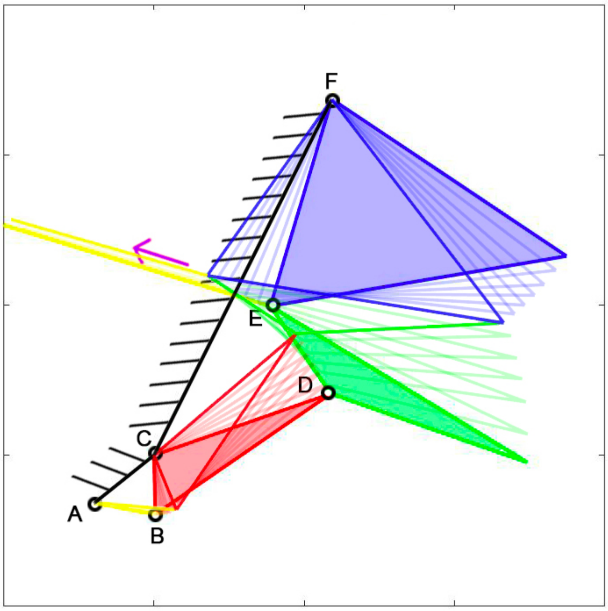


Figure 3.2 Kinematic scheme of *the Chlorurus sordidus* during mouth closing.

Cheilinus chlorourus belongs to the Labridae family, and it is native to the Indian Ocean and the western Pacific Ocean. This carnivorous fish can reach 45 cm in total length. Its feeding mechanism exploits the suction feeding, a technique through which it captures preys by generating a flow of water into a rapidly expanding mouth cavity [18]. It feeds mainly on benthic invertebrates such as mollusks and crustaceans.

The cranial osteology and muscles were observed by Westneat [19] in order to understand how the mechanism would work. The muscles responsible for opening and closing of the mouth are the levator operculi for the former, and the three adductor muscles for the latter [19]. The three adductor muscles are simplified in a single element.

Two mechanisms are derived, the anterior jaws linkage (FGHI) and the opercular linkage (CDEF) as shown in Figure 3.3. During opening of the mouth, the element corresponding to the levator operculi muscle contracts, resulting in a clockwise rotation of the red link below, which is the input of the opercular linkage. The opercular linkage is in fact the one on the bottom left, with the input, a fixed link above, the bottom one as the coupler and the right one as the output. The output of the opercular linkage is also the input for the anterior jaws one, which results in the mouth opening of the fish. For the closing phase, the input is directly attached to the jaws, corresponding to an overall adductor muscle. Its contraction in fact obligates the jaws to close.

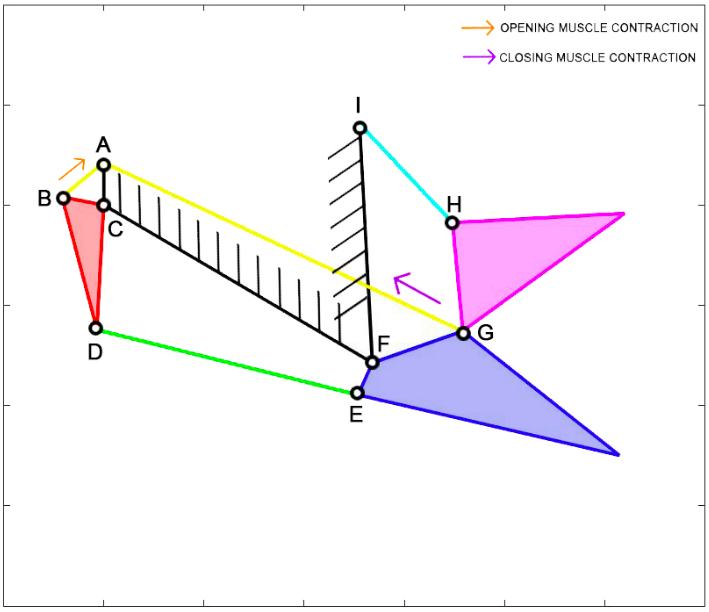


Figure 3.3 Kinematic scheme of the *Cheilinus chlorourus*.

Micropterus salmoides is a carnivorous freshwater fish belonging to the Centrarchidae family, native to the United States, Canada and Mexico. This species has been introduced widely as a game fish and is now cosmopolitan. Adults feed on fishes, crayfish and frogs; young feed on crustaceans, insects and small fishes. Sometimes cannibalistic. It is a large fish, reaching a maximum of 97 cm in length. The fundamental muscles during the opening and closing phases are the epaxial muscle, which is the one above starting from A, and the sternohyoid muscle, attached to the lower jaw (FG). The epaxial muscle is very long, covering the entire body of the fish [20]. The kinematic scheme is proposed by Olsen, Camp and Brainerd [21] as a four-bar linkage mechanism (Figure 3.4).

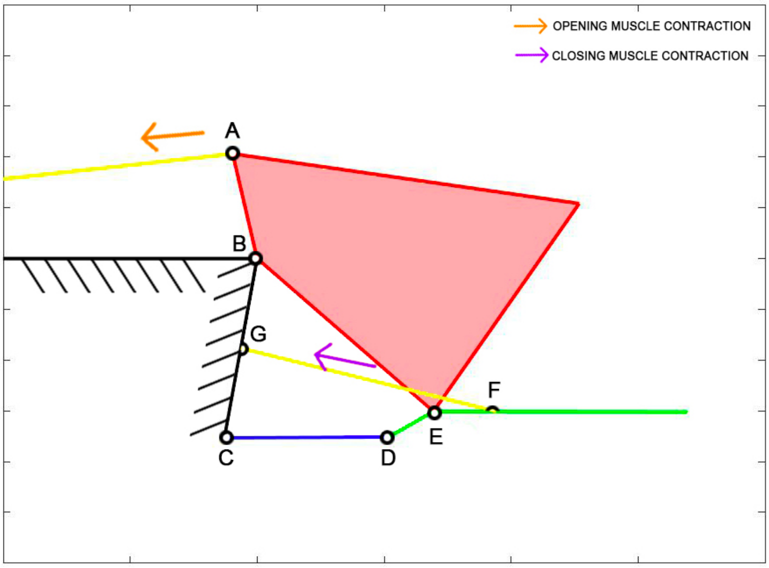


Figure 3.4 Kinematic scheme of *Micropterus salmoides*.

Eustomias obscurus is a deep-sea carnivorous fish belonging to the Stomiidae family, and it is native to the oceanic depths of the Atlantic Ocean. Its length is usually around 15 cm, and may grow up to 26 cm. They are apex predators and have enormous jaws filled with fang-like teeth. They are also able to hinge the neurocranium and upper-jaw system, which leads to the opening of the jaw to more than 100 degrees. This ability allows them to consume extremely large prey, often 50% greater than their standard length.

The epaxial muscle (from A, going towards the left), once again covering the entire body of the species, is responsible for mouth opening, where an additional head joint allows mouth opening to 120 degrees [22].

The kinematic scheme (Figure 3.5) is proposed by Burgess [7],where the contraction of the epaxial muscle allows the rotation of the input of the four-bar linkage mechanism, resulting in the rotation of the output link which produces mouth opening.

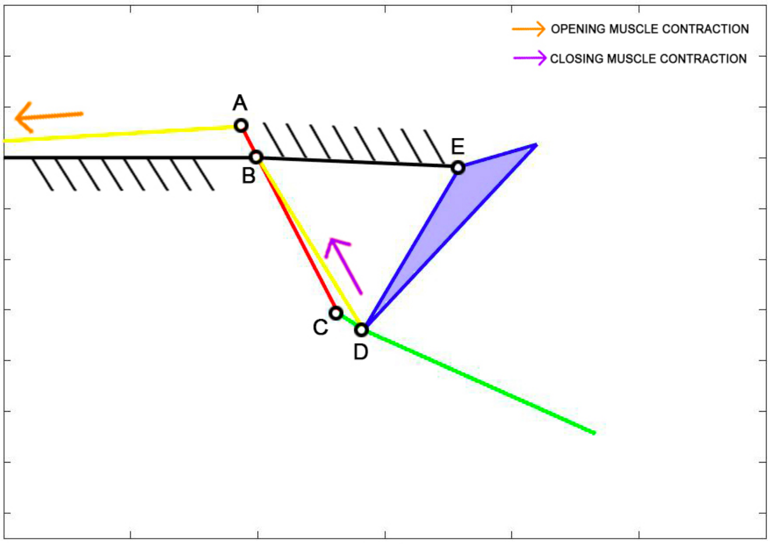


Figure 3.5 Kinematic scheme of *Eustomias obscurus.*

Dunkleosteus terrelli is an extinct placoderm fish, the largest armored jawed fish, which reached up to 8.79 m. It is known as a carnivorous fish, being able to both quickly open and close its jaw to perform suction feeding and have an extremely high biting force.

Anderson and Westneat [23] derived a kinematic model consisting in a single four-bar linkage mechanism, where the opening muscle is the epaxialis (AC), while the closing ones are the adductor mandibulae (GH) which are simplified as a single element in the scheme proposed in Figure 3.6.

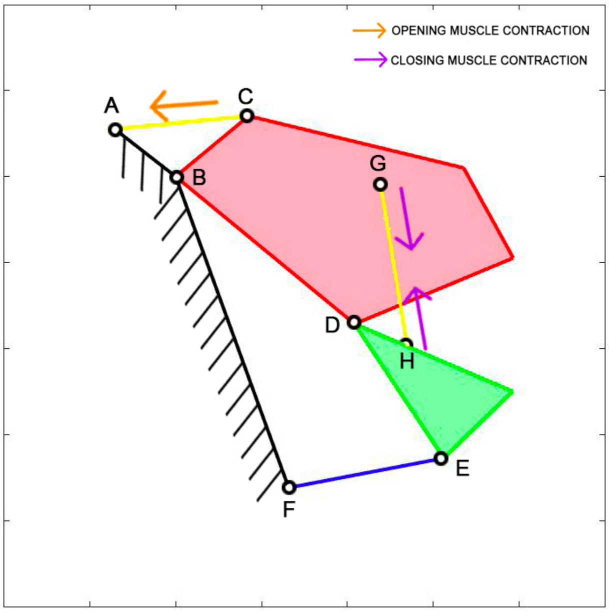


Figure 3.6 Kinematic scheme of *Dunkleosteus terrelli*.

Lepomis macrochirus is a carnivorous freshwater fish belonging to the family Centrarchidae, native to North America. Its length can reach 30 cm.

As for *Cheilinus chlorourus*, the levator opercula (CA) are responsible for mouth opening, while the two adductor muscles act during the closing phase [24].

The kinematic scheme [25] is shown in Figure 3.7, where once again the closing muscles are simplified in a single element (HG) and directly connected to the lower jaw. As opposed to the other species, Lepomis macrochirus has the upper jaw fixed.

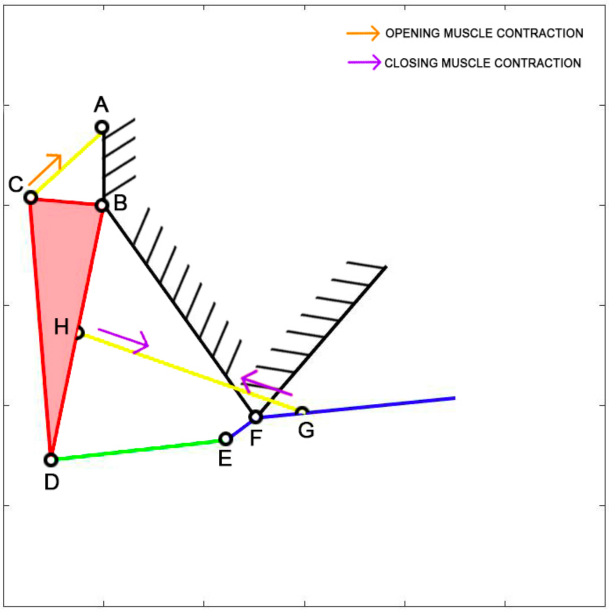


Figure 3.7 Kinematic scheme of *Lepomis macrochirus*.

Chlorurus sordidus belongs to the family Scaridae; it is the only herbivorous species considered in this study; it, usually bites off corals, and eats the symbiotic microalgae of the coral polyps. The species is widespread throughout the tropical waters of the Indo-Pacific region. It can reach a maximum length of 40 cm.

Belonging to the same order of *Cheilinus chlorourus*, the Labriformes, the levator posterior muscle and the adductor mandibulae are responsible for the opening and closing of the jaws, even though their size is quite different from the labrids [26]. While the contraction of the levator posterior (AB) acts as the input of the four-bar linkage mechanism in Figure 3.8 during the opening phase, the single overall adductor (from E) is connected to the jaws and its contraction results in the closing of the mouth.

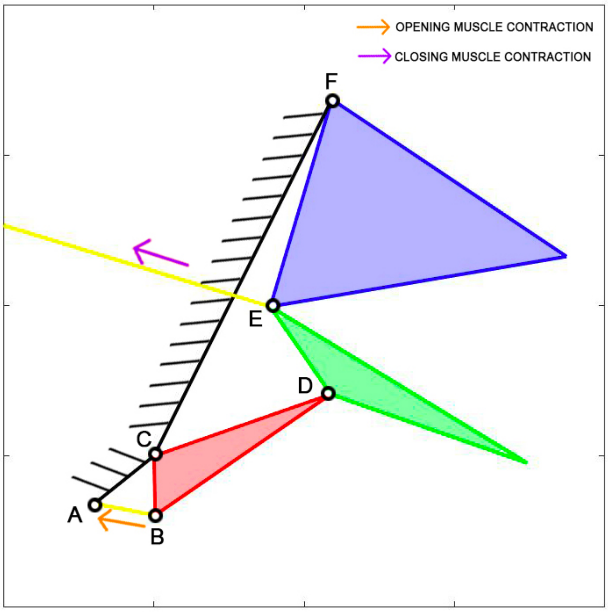


Figure 3.8 Kinematic scheme of *Chlorurus sordidus.*

Chiloscyllium plagiosum is a cartilage-fish belonging to the Hemiscylliidae family, which lives in the Pacific Ocean. This shark is carnivorous and feeds preferably at night, on small fish and invertebrates. It can grow up to 93 cm in length.

Ramsay and Wilga [27] proposed the kinematic scheme reported in Figure 3.9, where the mouth opening is due to the contraction of the coracohyoideus and the coracoarcualis muscles, depicted as a single element (AB). As for *Dunkleosteus terrelli*, the adductor muscles (HI) act during the closing phase.

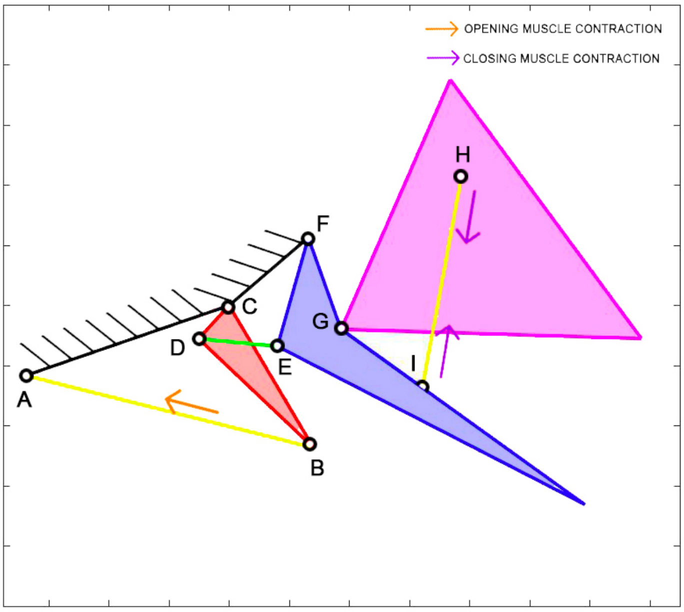


Figure 3.9 Kinematic scheme of *Chiloscyllium plagiosum.*

4. Results

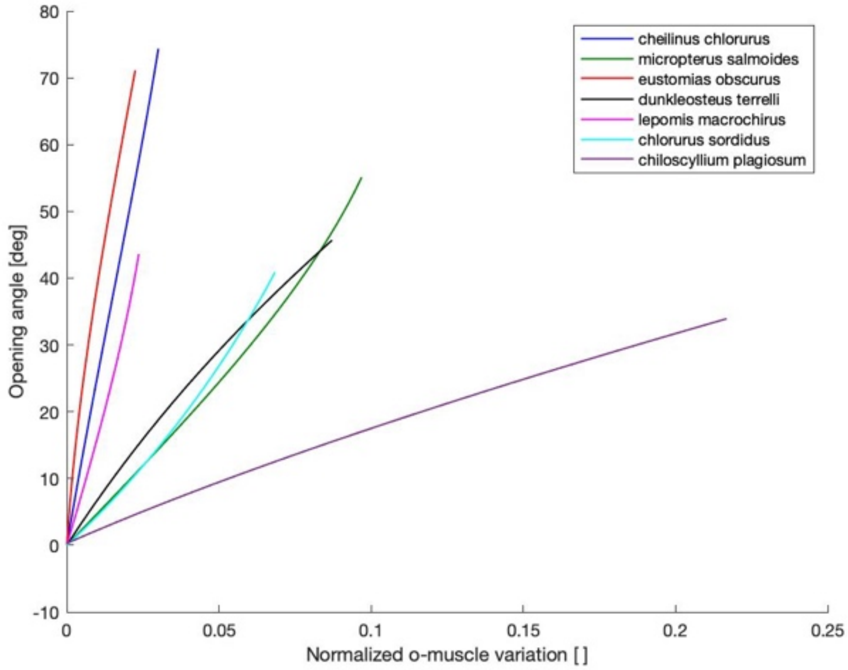
Having defined the species of fishes taken into consideration and the mechanical parameters that will be used, the kinematic diagrams introduced in chapter 3 are now analyzed under several aspects. First, the range of the gape angle of the jaw is compared. Then the velocity amplification of the different biological mechanisms is studied. After that, it is interesting to plot the jaw protrusion during the whole motion. Finally, the effectiveness of the linkage mechanism together with the muscle attachment is analyzed.

As explained, the first analysis performed is relative to the gape angle of the jaw. It is considered not only the maximum size of each species but also its behavior during the whole motion compared to the input. Two distinct analyses are carried out corresponding to the opening and closing phase of the jaw, as the input muscle changes

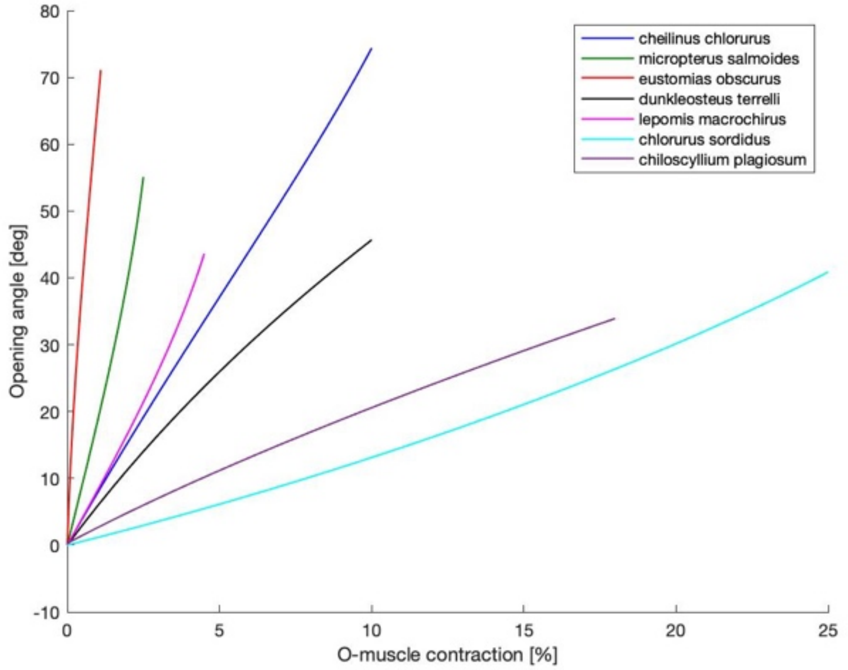
The gape angle of the jaw is studied related to the input muscle contraction. As already stated, two contraction parameters are used: the “normalized contraction” and the “percentage contraction”.

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.

Figure 4.1a shows the gape angle during the opening phase with respect to the normalized contraction of the opening muscle.



(a)

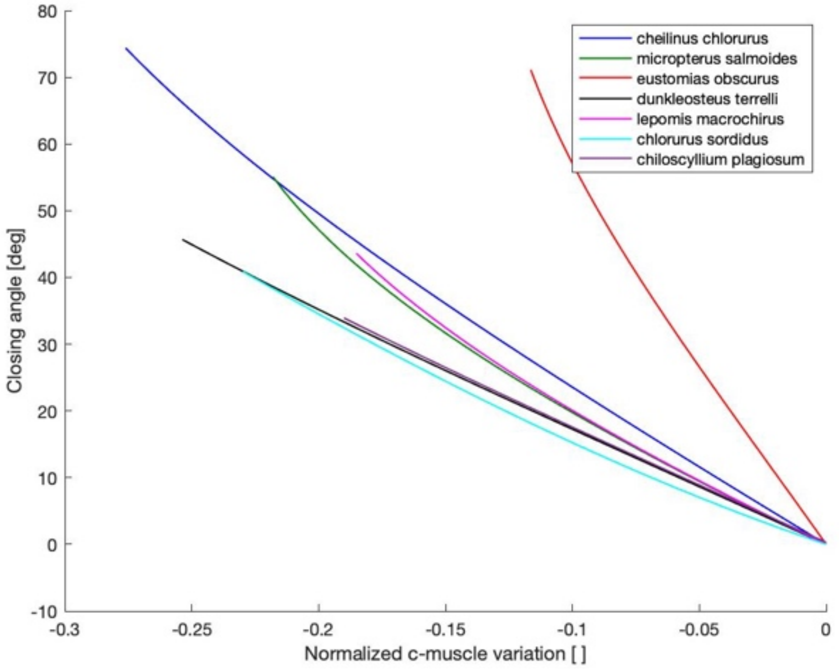


(b)

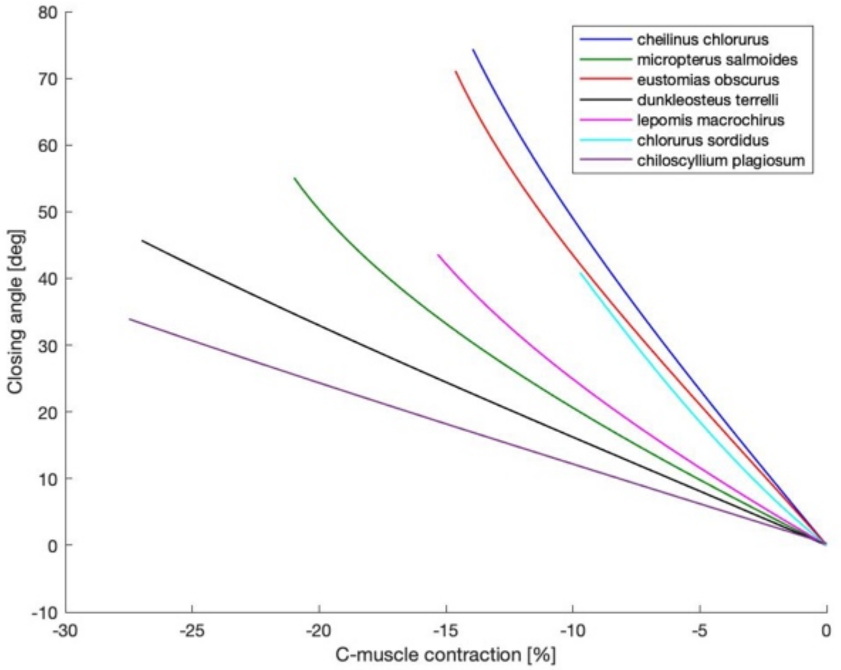
Figure 4.1 a) Opening angle with normalized muscle variation; b) Opening angle with percentual muscle contraction.

Reading the graphs from the left, all the species start with the jaw completely closed and open it through a contraction of the opening muscle. It can be seen that species like *Eustomias obscurus*, *Cheilinus chlorourus* and *Lepomis macrochirus* are characterized by a very sloped trend, their structure is in fact able to convert a small linear displacement into a large rotation through an amplification mechanism. Other species like *Micropterus salmoides*, *Dunkleosteus terrelli*, *Chlorurus sordidus* and *Chiloscyllium plagiosum* exhibit curves with a lower gradient. This can be addressed to the fact that they do not have a linkage mechanism that amplifies the motion significantly as the first species. However, it is interesting to see how the plots change in the Figure 4.1b, the gape angle with respect to the percentage contraction of the opening muscle. The first thing to notice is that some species have changed position: *Micropterus salmoides* has become more sloped while *Cheilinus chlorourus* and *Lepomis macrochirus* are slightly more horizontal, and, finally, *Chlorurus sordidus* is much more horizontal. This is due to the size of their muscles, while *Micropterus salmoides* has a very long opening muscle, the others have it smaller. With the same linear contraction, the bigger is the muscle, the smaller is the percentage contraction. From these two graphs it can be deduced that while some species achieve an amplification in motion through a linkage mechanism, other achieve it thanks to a longer muscle. Finally, it can be seen that the shark *Chiloscyllium plagiosum* exhibits a horizontal line in both graphs, it means that it misses both a structure of bones that amplifies the motion and a long opening muscle.

Figures 4.2a and 4.2b show the gape angle variation during the closing phase and so it is plotted with respect to the closing muscle contraction. Changing the input, the mechanism is completely different from the opening one. In these graphs, the models start with the jaw opened (left part of the graphs) and they close it bringing the gape angle to zero (right part of the graphs).



(a)



(b)

Figure 4.2 a) Closing angle with normalized muscle variation; b) Closing angle with percentual muscle contraction.

An interesting fact observed in both the opening and the closing graphs is that the gape angle has quite a linear behavior in all the species considered. This is interesting because considering how complex all the linkage mechanisms are, having a linear relationship between input and output is not trivial.

The considerations achieved so far can be better observed through the analysis of the geometric velocity of the linkage mechanism. As already explained, it is a mechanical parameter used to estimate how a linkage mechanism converts the input velocity in output velocity.

Figure 4.3 shows the "geometric velocities" during the opening phase of the jaw. It can be seen that every species considered exhibits a horizontal pattern, proving again the linear relationship between input and output.

The only exception is *Eustomias obscurus*, that has a peak at the beginning of the motion, where the upper and the lower jaw are completely closed. A so high value is due to the alignment of two links in the mechanism that generates a significant amplification of the velocity from input to output. However, it also means that a very high force is needed to open the jaw in that range, making the initial degrees of the opening phase quite difficult. The possible explanation to this particular configuration is that in reality *Eustomias obscurus* has its jaw always partially open so it never starts the opening of the jaw from 0°. It has in fact very long and sharp teeth that allow it to capture the pray without closing completely the jaw.

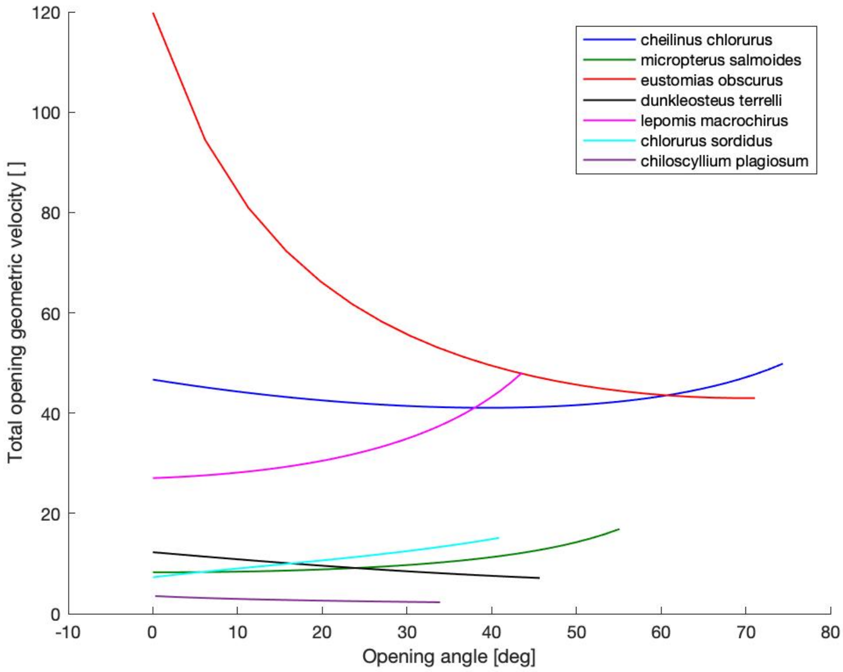


Figure 4.3 “Geometric velocities” during opening.

Before focusing on the values of the different geometric velocities of the seven species it is necessary to remember that all of them apart from *Chlorurus sordidus* use the suction feeding and so they need to achieve a very fast opening of the jaw. It is possible to observe again that some species amplify the opening velocity thanks to their linkage mechanisms: *Eustomias obscurus*, *Cheilinus chlorourus* and *Lepomis macrochirus* are in fact on top. As already explained *Micropterus salmoides* does not amplify the opening velocity through the linkage mechanism, in fact its geometric velocity is limited, much lower than the first species. However, it is capable of using the suction feeding mechanism thanks to a long muscle that can achieve high speed contraction leading to high opening velocity. Even *Chiloscyllium plagiosum* has an interesting behavior, it has again a very low geometric velocity but unlike *Micropterus salmoides* it does not have a long opening muscle. So, it does not achieve high velocity nor through amplification neither through a faster input. It uses a mechanism that consists in the locking of the jaw through a particular alignment of the links and muscle, in this way the muscle can contract without the motion of the jaw and only when it is completely loaded the jaw is unlocked releasing the stored energy achieving very high speeds. Finally, as expected also *Chlorurus sordidus* has a very low geometric velocity, it is in fact a vegetarian fish that does not need the suction feeding.

Even though a comparison of only seven species is limited, it already showed three completely different solutions to achieve fast opening of the jaw. 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*.

In Figure 4.4 the “geometric velocities” during the closing phase of the jaw are illustrated. Generally, all the species studied have a geometric velocity that slightly decreases toward 0°. This means that the amplification of the speed is at its minimum when the jaw is closed. A possible explanation is that high velocity amplification is useful when the jaw is completely open allowing to be fast in the first instants of capturing the prey. Another reason could be that, due to kinetostatic duality, lower geometric velocity means higher transmitted force, so it is possible that it is more efficient to achieve the highest force when the jaw is closed. By looking at the values, the three species that have the lowest geometric velocities are *Dunkleosteus terrelli*, *Chiloscyllium plagiosum* and *Chlorurus sordidus*. All of them in fact are species that do not close the jaw only to avoid the leak of the food, but also bite to cut it and crash it: the first two species bite their prey while the last one is vegetarian but need a strong bite to crumble the coral. Therefore, for these three species having a low geometric velocity during the closing phase means a higher transmitted force to the jaw and so it helps them to achieve high biting forces.

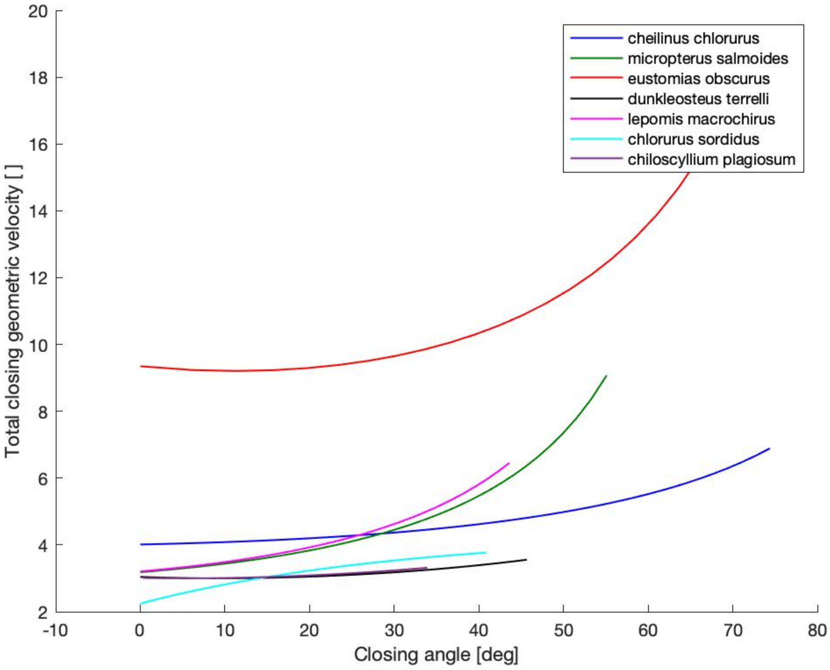


Figure 4.4 “Geometric velocities” during closing.

Figure 4.5 shows how the “geometric velocities” at 0° change from the opening phase to the closing phase. In all the seven species the closing geometric velocity is lower than the opening one. It is explained by the necessity of achieving higher speeds during the opening phase to achieve the suction feeding, meaning that for these species it is more important to be fast in opening than in closing the jaw. The species that do not see a large difference from opening to closing are the ones that either achieve high velocities with other ways or *Chlorurus sordidus* that does not exploit the suction feeding.

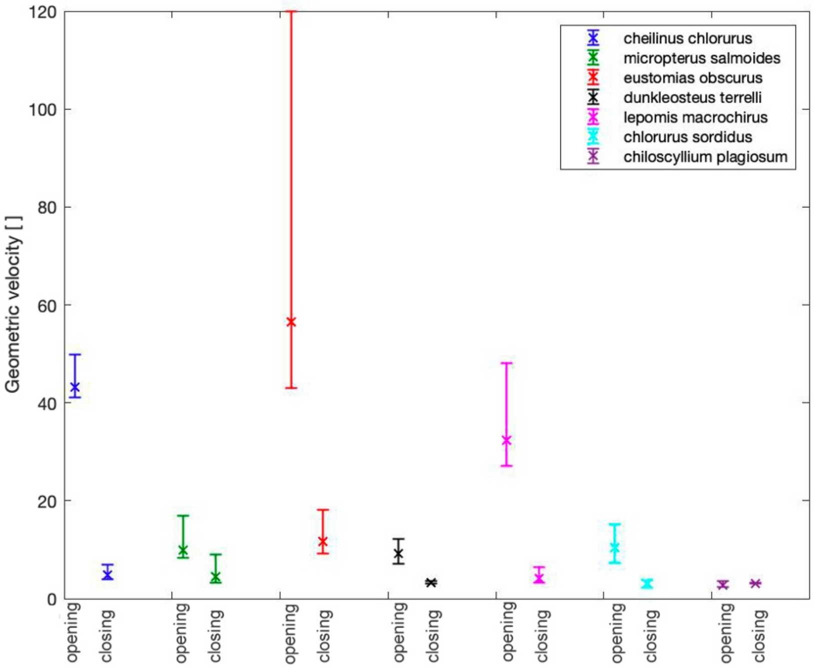


Figure 4.5 Variation of the "Geometric velocities". Opening on the left, closing on the right.

In Figure 4.6 the measured mean velocities from paper obtained from literature are illustrated. Even though they achieve these velocities through different solution, all the species that use the suction feeding mechanism have faster motions compared to *Chlorurus sordidus* that is also the only one with a slower opening speed. An important consideration that can be done is that normally in biology papers the mean velocities are measured and discussed, however with a mechanical approach, the study of the linkage mechanism can deliver more information, allowing to study the forces and speeds during the whole motion.

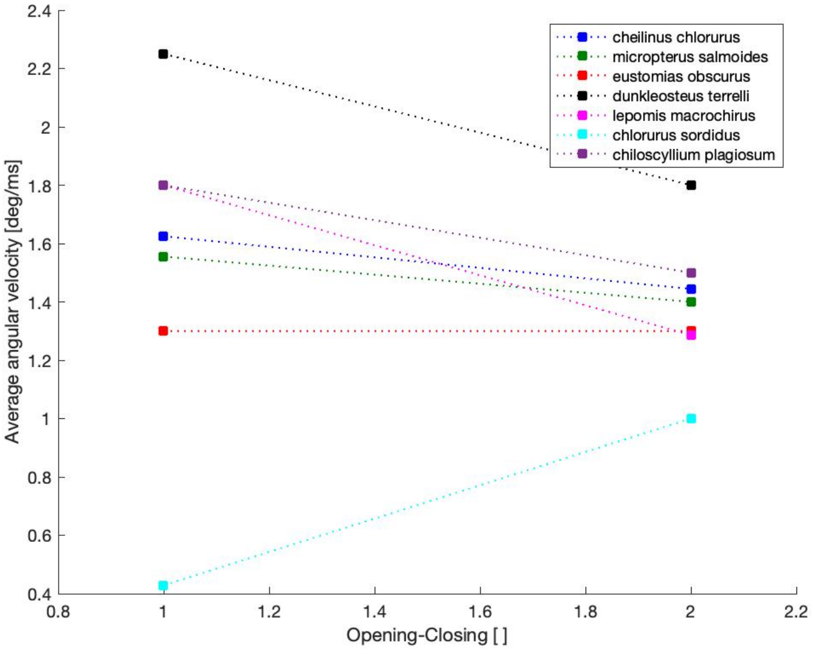


Figure 4.6 Average angular velocities from literature. Opening on the left, closing on the right.

Another interesting analysis can be done by observing how the jaw moves in the plane while it opens. Figure 4.7 shows the jaw protrusion during the whole motion. 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 [28].

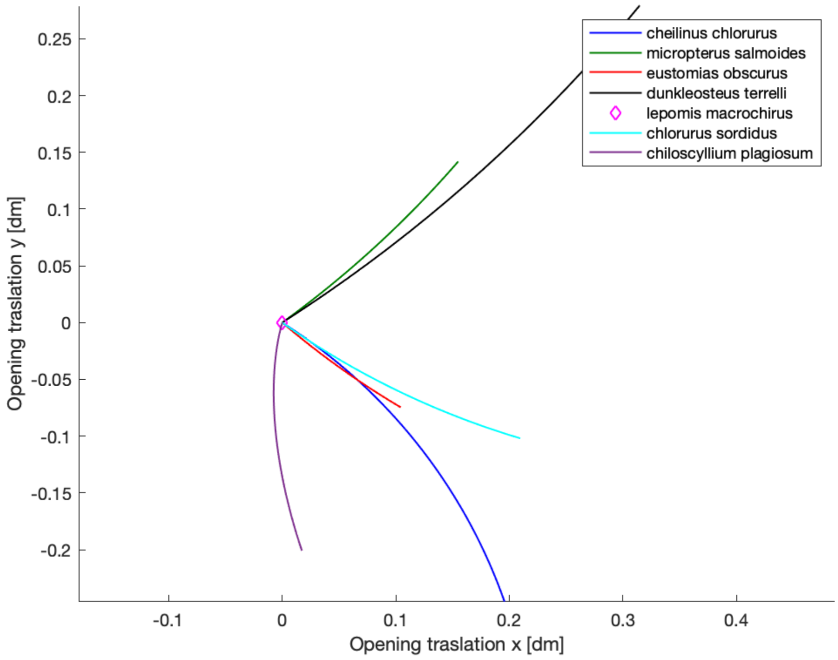


Figure 4.7 Shift during opening.

There are basically two groups based on the translation along the y-axis. The first one includes *Dunkleosteus terrelli*, and *Micropterus salmoides* that see an upward elevation of the jaw. The second one instead, consisting of *Cheilinus chlorourus*, *Eustomias obscurus*, *Chlorurus sordidus* and *Chiloscyllium plagiosum*, has a downward motion of the jaw. It is quite interesting that the species belonging to the first group have the opening muscle directly connected to the upper jaw, the lower jaw is moved only as a consequence of the rotation of the upper one. In the second group instead, the opening muscle is connected through a kinematic chain to the lower jaw first. Therefore, the upward or downward translation of the jaw is determined by which part is directly rotated and which one is instead consequently moved.

As already explained the pressure angle is an indicator of the effectiveness of the linkage mechanism in transmitting the input force into the output motion. In Figure 4.8 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.

It can be seen that all of these species have values below this threshold. The only exceptions are *Eustomias obscurus* in the first 20° of jaw opening and *Lepomis macrochirus* when its jaw is completely open. In both cases the pressure angle is high because there is an alignment of the links that generates an inefficient transmission of the force. However, as anticipated above, *Eustomias obscurus* does not close its mouth completely, never reaching this bad condition. For *Lepomis macrochirus,* instead, it is possible that normally it does not open the jaw that much.

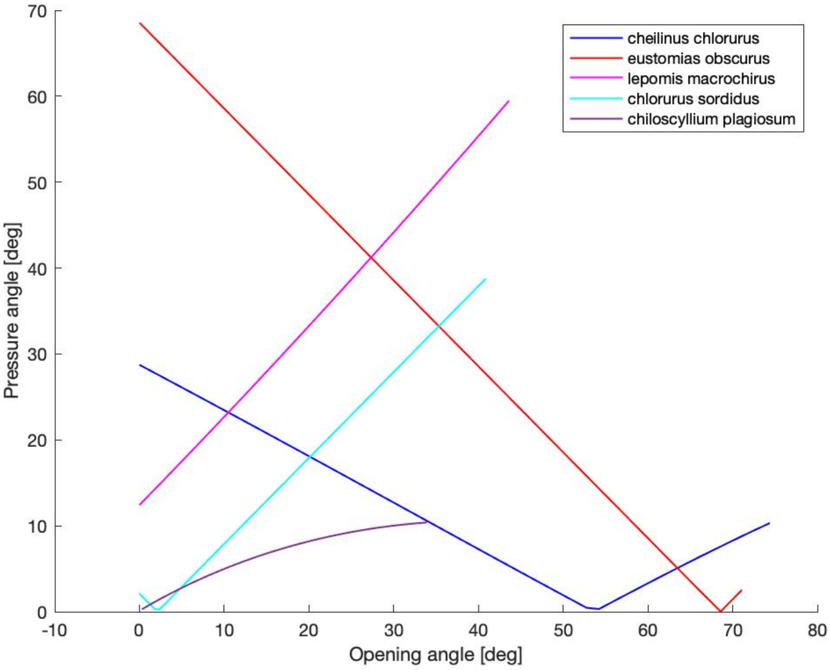
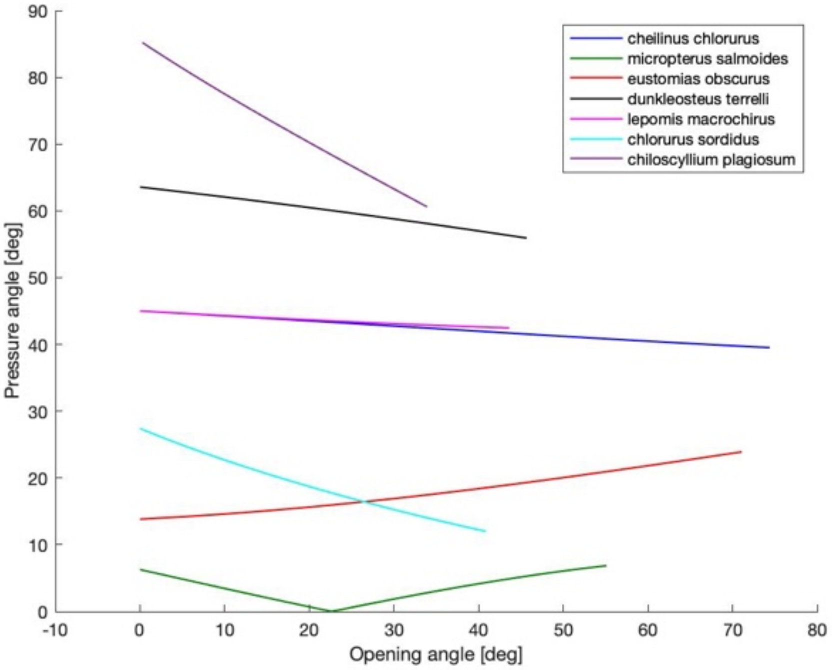
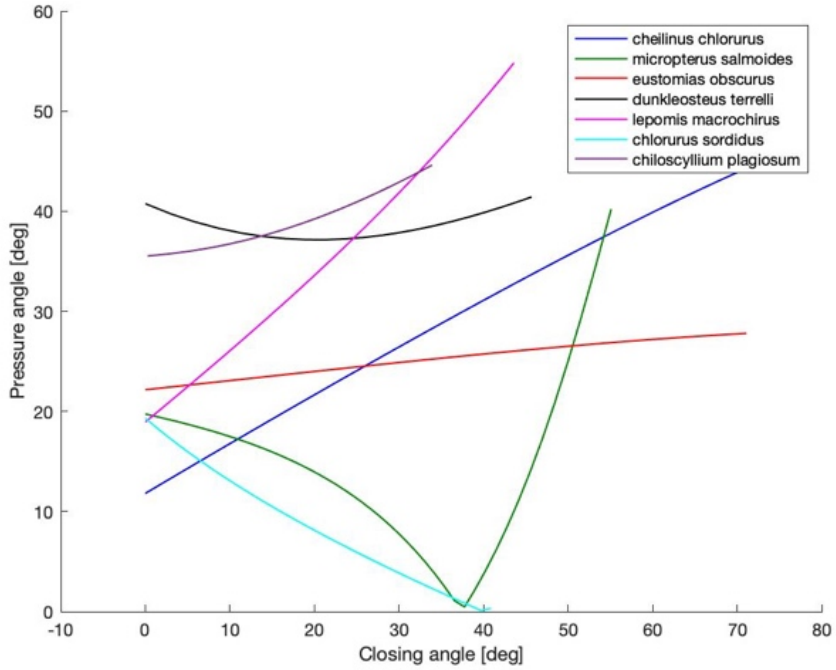


Figure 4.8 Pressure angle for the linkage mechanism.

Figures 4.9a and 4.9b show the pressure angles in muscle's attachment area during respectively opening and closing. The smaller the angle, the better the alignment of the muscle with the link motion and so the better the transmission.



(a)



(b)

Figure 4.9 Pressure angle in muscle's attachment area. a) During opening; b) during closing

During the opening 5 species keep the pressure angle below 50° obtaining a quite adequate transmission. The two species that do not follow this behavior are *Dunkleosteus terrelli* and *Chiloscyllium plagiosum* that shows pretty high values. The pressure angle of the latter in particular starts close to 85° which means that when the jaw is completely closed the action force of the opening muscle is perpendicular to the direction of motion of the first link. This normally would be considered a bad condition for the transmission; however, it is the demonstration that *Chiloscyllium plagiosum* uses a snapping mechanism to achieve high opening velocity. Thanks to a pressure angle close to 90° it can contract the muscle and store energy while the jaw is not moving and release it in an instant.

During the closing phase, all the species analyzed are characterized by pressure angles below 50° allowing a decent transmission of the muscle force to the closing mechanism. Again, the values of *Lepomis macrochirus* in the last range of motion can be explained by considering a smaller opening range.

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 (Figure 3.8). 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.

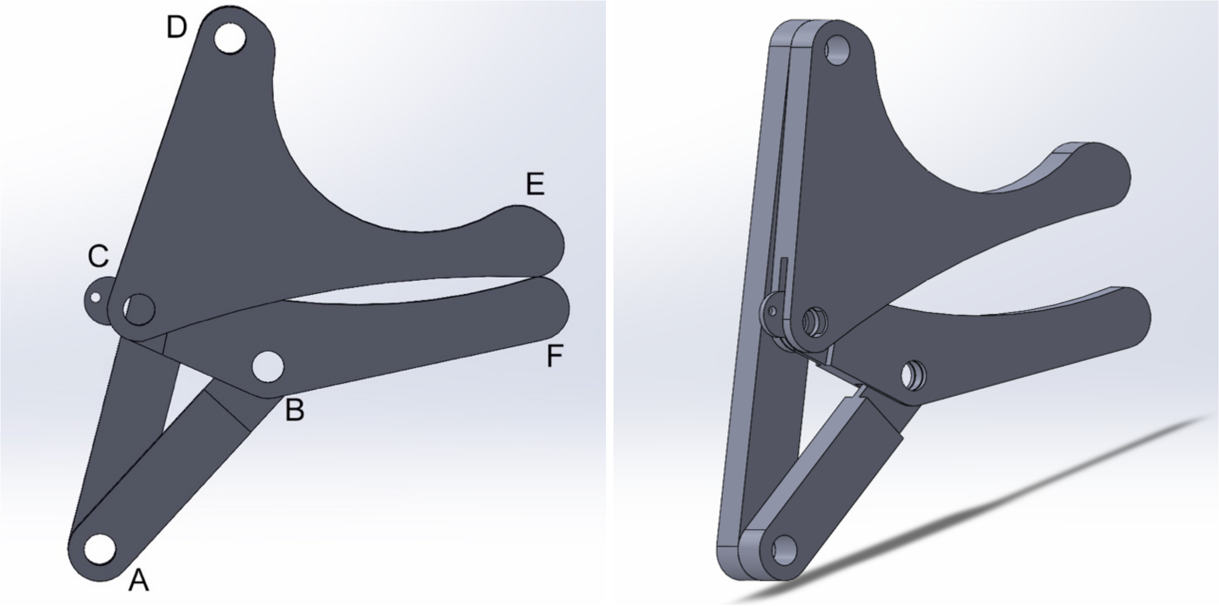


Figure 5.1 3D bodies on SolidWorks of the linkage mechanism of the *Chlorurus sordidus.*

The maximum value of the angle of mouth opening follows the behavior of the species analyzed in chapter 4, so it is limited to 40°. The upper body CDE represents the upper jaw, with a slot on C for the connection with the lower jaw. The lower jaw BCF has on C a small hole for the insertion of the tensional spring that operates to keep the jaws closed. On the bottom it is connected to the link A (AB), which is the input link of the four-bar linkage mechanism. The servomotor operates on the link A which transfers the rotation to the jaws, overcoming the stiffness of the spring in order to achieve the opening of the mouth. Finally, the semi-vertical piece AD is the frame. Both the bottom line of the upper jaw and the upper line of the bottom jaw are not straight, to guarantee a better grip.

The bodies are 3D-printed in ABS (Acrylonitrile Butadiene Styrene), with an infill percentage of 20%, with the results shown in Figure 5.2. The dimensions maintain the same ratios of the kinematic scheme, in particular link A (AB) is 7 cm, the frame (AD) is 14 cm. For the bottom jaw the upper part (CF) is about 10 cm, the bottom one (BF) is 7 cm and the left one (CB) is about 3.5 cm. For the upper jaw, the bottom part (CE) is 10 cm, the left one (CD) is 7 cm, the bottom one (DE), without considering the extrusion, is about 9 cm.

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 transmitting the rotation, following the behavior of the opening muscle.

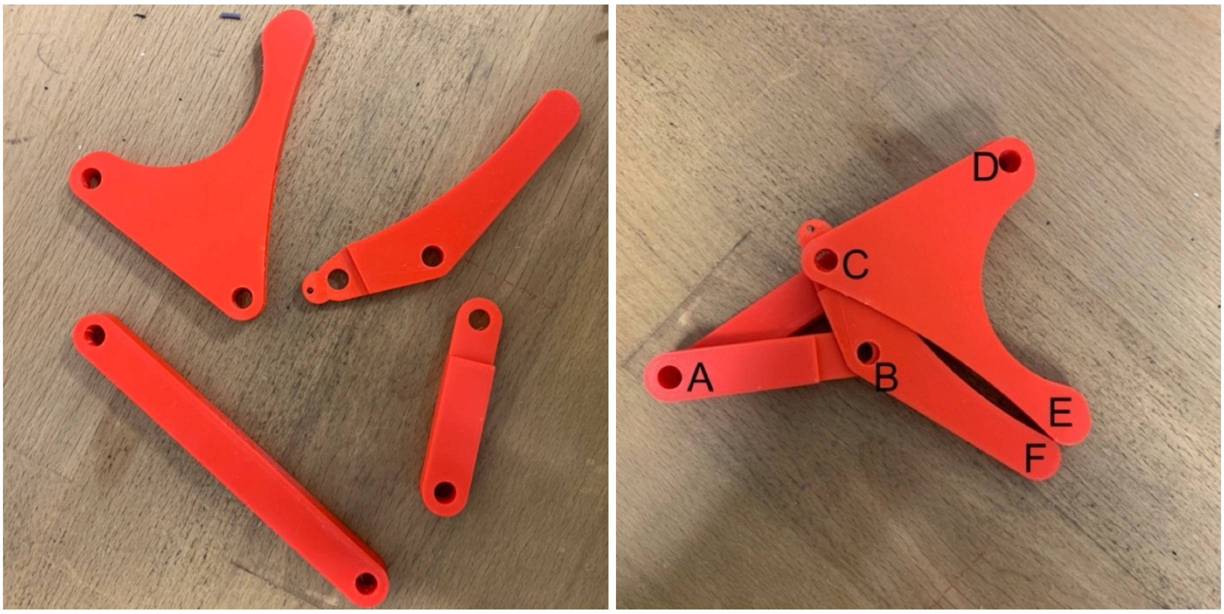


Figure 5.2 Printed pieces following the linkage mechanism of the *Chlorurus sordidus*.

The motor torque and the stiffness of the spring are calculated on the basis of the four-bar mechanism, as seen in Figure 5.3, where M is the torque of the motor and F_{el} the force of the spring. The calculations are carried out considering lifting a sphere of 0.5 kg, with a friction coefficient of 0.5 (polystyrene on polystyrene), and a maximum displacement of the spring of 23 mm, based on the maximum contraction of the muscle of the *Chlorurus sordidus*. As a result, the values, that has to be intended as maximum, are 1.2 N/mm for the stiffness, and approximately 2.2 Nm for the motor torque.

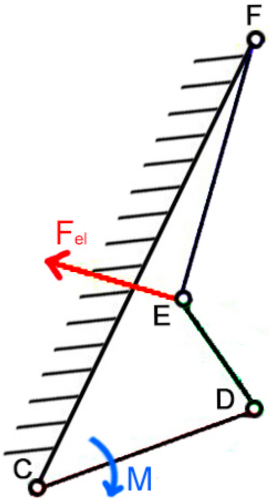


Figure 5.3 Four bar-linkage mechanism highlighting motor torque and spring force.

Once printed, the pieces are assembled together with the servomotor and the spring 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 5.4 two views of the grasping of an eraser are shown, while in Figure 5.4 there is a pencil sharpener, with a smoother surface than the previous object. The tests are conducted by controlling the servomotor with the Arduino One board, with the addition of a power supply. Specifically, the three cables of the servomotor are connected one to a ground pin of the Arduino board, one to the digital pin, in particular a PWM (pulse width modulation), and the last one to the power supply, which is in turn connected to a ground pin of the Arduino. The motor is a servo WH-40kg and the voltage imposed by the power supply during the tests is set to 5÷6 Volts.

Figure 5.4 a) Grip test of an eraser with two views. b) Grip test of a pencil sharpener with two views.

Based on 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 biological world has plenty of behaviors and mechanisms interesting from the engineering point of view to implement innovative solutions in the robotic field. In the last years an increasing focus on bio-inspired designs can be observed, despite the gap in knowledge between biologist and engineers, used to profoundly different approaches when it comes to analyzing species.

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. After sizing both the spring and the servomotor required for the case, 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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