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The most important source of inspiration for artificial gripping systems are natural gripping systems

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Abstract. The main role of a gripping biosystem is to grasp-grip a body-object, which can then be transferred from one place to another. Gripping biosystems can be very simple, like two areas of soft biological tissue that can grasp a body nearby, such as the extremities of the elephant's trunk, but also very complex as the human hand, considered the best gripping biosystem. Some gripping biosystems are adaptated to increase the safety of the grip such as the octopus arm which is provided with suction cups to compensate for the reduced friction in the aquatic environment. The paper first classifies biogrippers according to the grasp-grip method through which we distinguish gripping: by grasp, shellfish-like claws, beak, claws, jaws and fingers. Suggestive examples are given for each case, and in some cases even artificial variants that were more or less inspired by natural biogrippers considered as models. The few details of the mathematical modeling of the human hand grip can be extrapolated to all existing biogrippers that can be identified. The paper tries for the first time an exhaustive presentation of biogrippers in order to stimulate their in-depth study and to use as many of the natural gripping solutions and some of their features to optimize the artificial grippers used especially in robots.

Keywords: gripping biosystem, biogripper, gripper, mathematical modeling

1. Introduction

In nature there are a multitude of so-called gripping systems also called gripping biosystems. These gripping biosystems have as main function, even in some cases as single, or secondary function, respectively complementary, the gripping. The paper aims to present for the first time a brief but suggestive systematization of the main natural solutions of gripping systems found in various creatures that have been used as models, to a greater or lesser extent, for the realization of artificial

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grips used in robots. The topic of this paper was sequentially approached relatively long ago, if we refer to the works of G. Cuvier (1769-1832) and F. Reuleaux (1829-1905) [1]. This paper will present the gripping biosystems considered representative in an exhaustive attempt, which have inspired and can inspire the design of artificial gripping systems used mainly in robots.

2. Systematization of gripping biosystems

Following the study of the main categories of living things, it was established that the main classification criterion of the gripping biosystems is the way of actually realizing the grip – grasp of an object or grasping an object (body). According to this criterion, shown in Fig. 1, there are the following ways of grasping: grip by hugging, with jaws (pliers, beak), with fingers. In the case of gripping by hugging, the object is encompassed by the gripping elements, as we find in the octopus (the octopus arm), the elephant (the trunk), reptiles (the body itself) and primates (the arms).

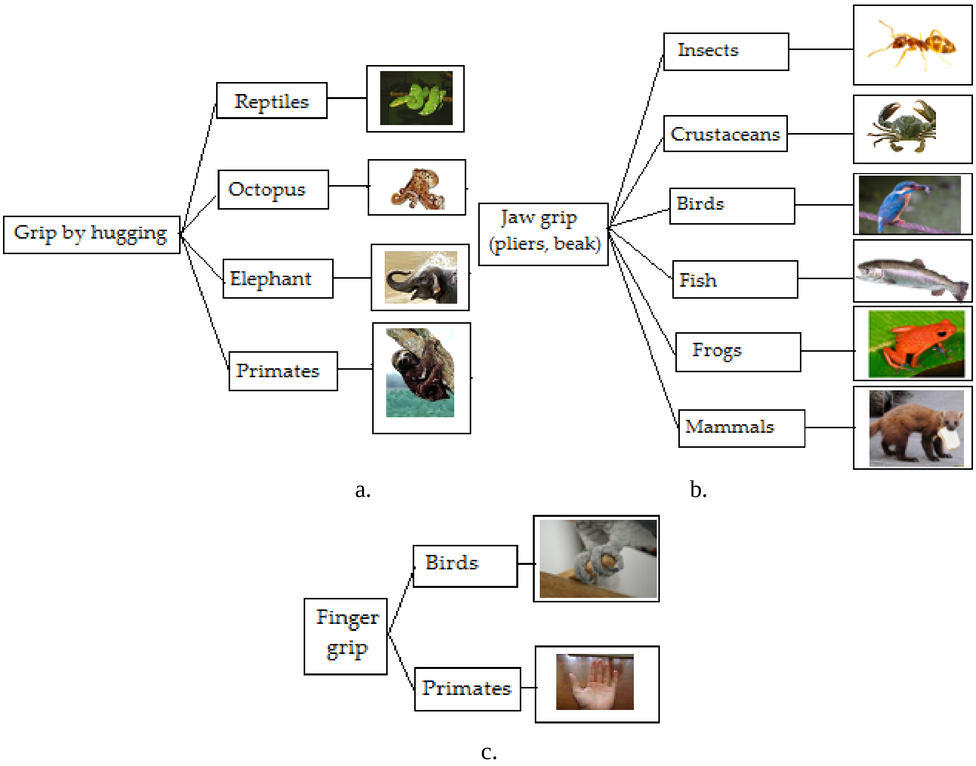


Fig. 1. Grip by hugging(a), grip with jaws (pliers, beak)(b) and grip with fingers(c).

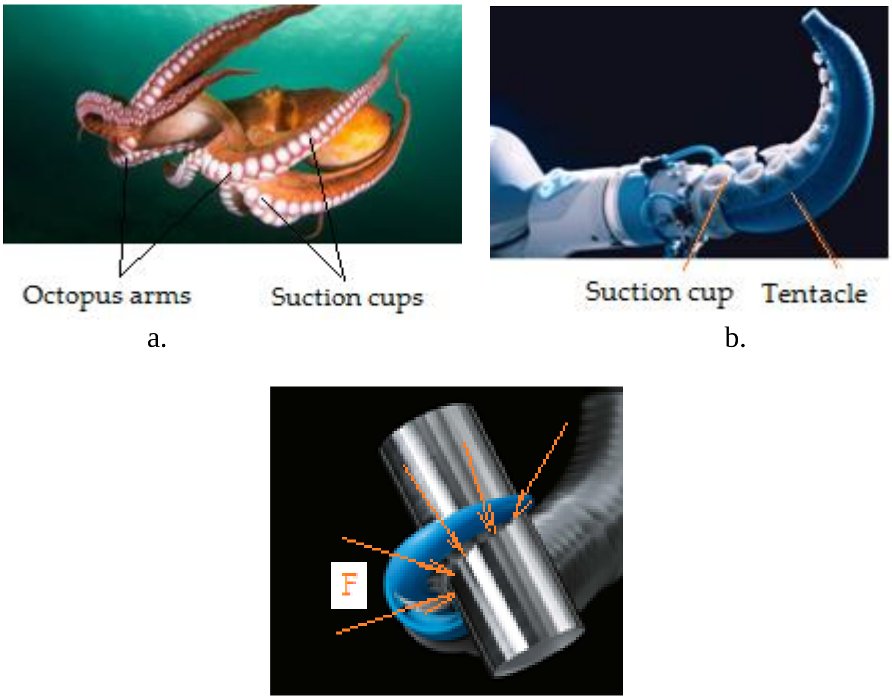
The gripping with jaws, pliers, or something similar, is found in crab and crayfish and other living things in this family and in some insects (ants, stag beetles, etc.).

Beak gripping is characteristic of birds. Also, the jaw gripping is a feature of all living things that have something like that, which is found in reptiles, but also in other living things such as fish, batrachians and mammals, like primates, which include humans. Finger grip is found in birds and primates (monkeys and humans). In birds, gripping is done with the help of claws, which usually have three or four fingers, and in primates with the help of the hand.

3. Gripping biosystems and examples of similar technical achievements

3.1. The octopus' tentacle

The octopus, as a marine creature, has eight tentacles with two rows of suction cups. Each tentacle can contain the object to be gripped, and the suction cups increase the safety of the grip in the water, where the friction is reduced.
Fig. 2a [2] shows an octopus with eight tentacles that can take on different configurations, including wrapping, and Fig. 2b [3] shows an artificial tentacle and an example of gripping an object with it in Fig. 2c [4] (F is the gripping force evenly distributed over the contact area between the tentacle and the gripped object).



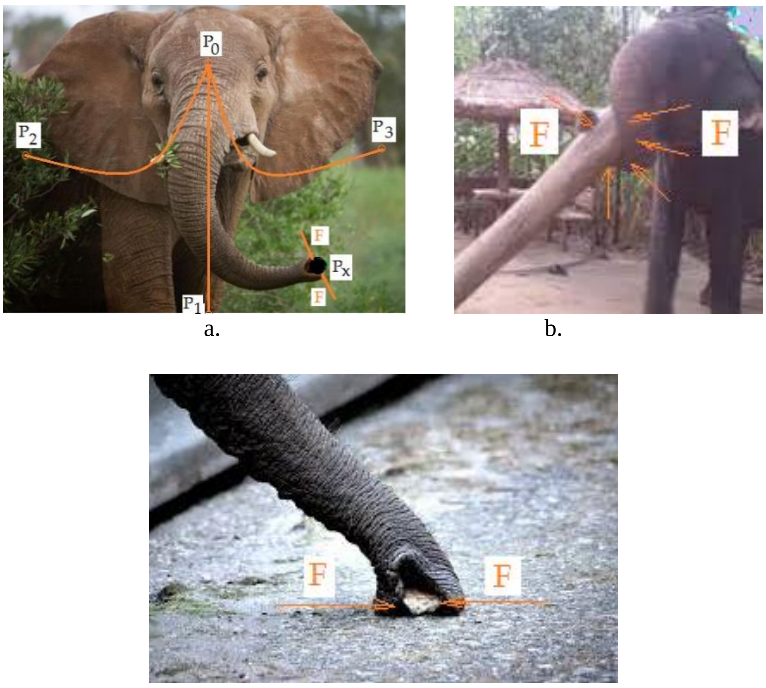
a. b.

c.

Fig. 2. Octopus tentacle: the natural shape in an octopus (a), the technical variant (b) and the example of gripping with an artificial tentacle (c).

3.2. The elephant's trunk

The elephant has a trunk[5] with which it can reach points in a relatively large space (Fig. 3a: P_0 being considered the point of origin, from which extreme points can be reached: P_1, down, P_2 on the left and P_3 on the right - in a vertical plane tangent to the elephant's face and similar in a plane perpendicular to the elephant's face: forward, downward and upward), with which it can grip by grasping various objects or by bilateral grasping with the extremities of the trunk. Due to the muscular structure, the trunk can develop high pressing forces on the gripped object which allows handling tree trunks (Fig. 3b, in which F is the gripping force evenly distributed on the contact area between the trunk and the gripped body). It should be noted that the trunk can grip small objects with the extremity similar to the grip with two elastic gripping areas (Fig. 3c), there are artificial grips of this type.

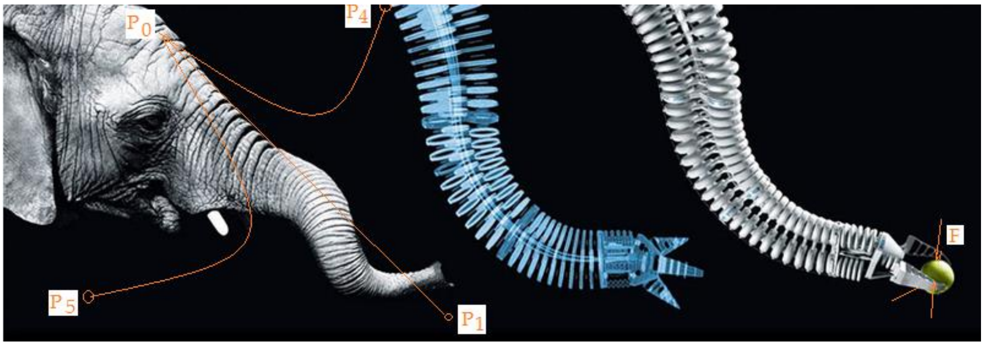


a. b.

c.

Fig. 3. Elephant trunk as a gripping biosystem: the trunk of an elephant and its area of action (a), the gripping of a tree trunk (b) and the gripping with the ends of the trunk (c)

Inspired by the elephant's trunk, robotic arms like the one in Fig. 4[6] were made, which are also the origin of hyperredundant robots [7]. These robotic arms do not have the possibility of gripping through wrapping but they are endowed with simple grips with jaws or with mini-tentacle elements for gripping.



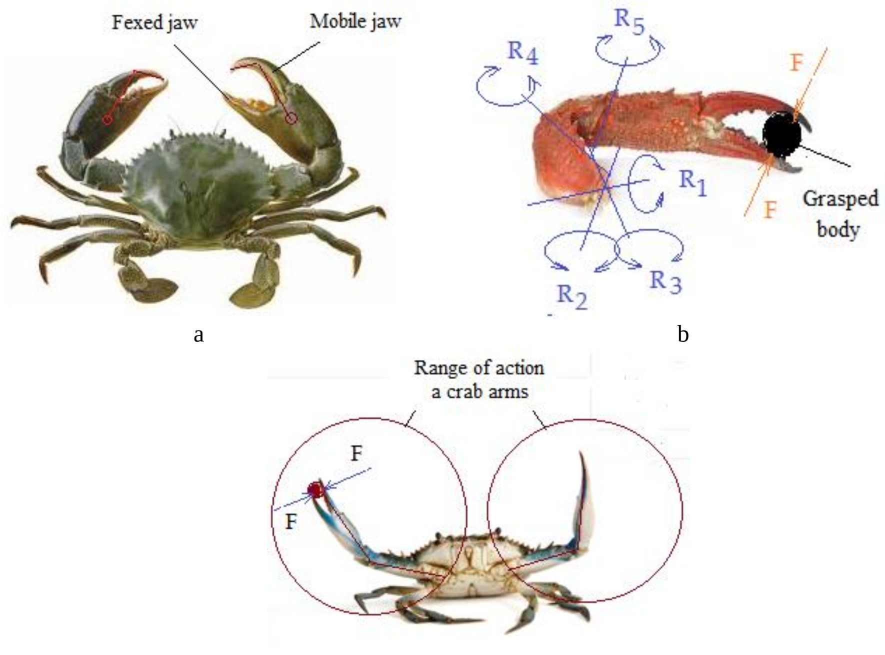
a b c

Fig. 4. Elephant trunk (a) as a model for trunk-like robotic arms (b) exemplifying grip with the gripper mounted at their extremity (c).

Through future developments a trunk-like element can be obtained to perform gripping through grasping (wrapping), similar to current ones, for relatively large objects, which can be equippped at the end with a shellfish-like claw gripper too for objects limited in size, small and medium-sized. We can take into consideration structures with two or three trunk-like items that act independently and grip at the same time or subsequently two, three or more objects, including through the gripping structure at the extremity of the trunk-like element.

3.3. Crab claws

The crab[8] or shellfish from this family have two arms endowed with claws, somehow oversized compared to the body itself, with which they can grasp as if we do with tongs objects of small and medium size, on which they can exercise relatively high forces. The claws of the two arms can be identical (Figure 5a) or different in size, case in which one is much larger than the other. The crab claws have only a mobile part that moves relative to a fixed part (Fig. 5a). A typical crab claw is shown in Fig. 5b. The claw is at the end of an arm, which has five degrees of mobility (R_1 ,…, R_5) which allows the claw to reach points in a relatively important space compared to the crab size (it depends on the crab species), see Fig. 5c[9].



a b

c

Fig. 5. Example of crab (a), crab arm (b) and range of action a crab arms (c)

Directly inspired by crab claws are some jaw gripping mechanisms (Fig. 6 - a two-armed crab-inspired robot equipped with two jaw grippers [10], which can be a model for robots used industrially or in services).

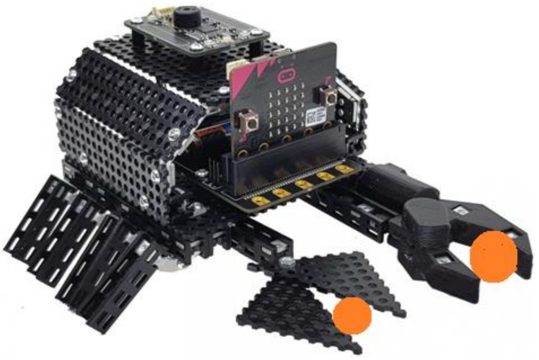


Fig. 6. Crab-inspired lego robot [10]

3.4. Bird's beak

The bird's beak is used to grip various objects-bodies needed to build nests or to feed the chicks. The beak performs the grip by bilaterally pressing on the gripped object (Fig. 7- in which F are the gripping forces).

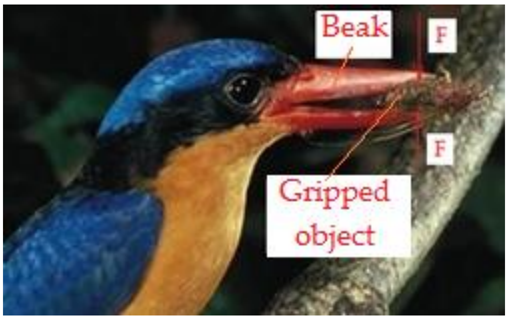


Fig. 7. Exemplification of a bird's beak grip

Depending on the shape of the beaks, which is very varied (Fig. 8), the application points of the gripping forces differ and the size of the gripped objects can be small (Fig. 9a), medium or even large (Fig. 9b), where F is the grip force. The shape of the birds' beaks can inspire different types of jaws for mechanical grips of this type.

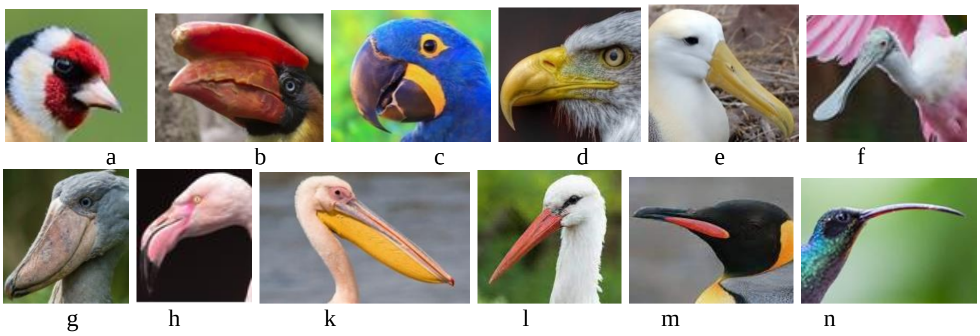
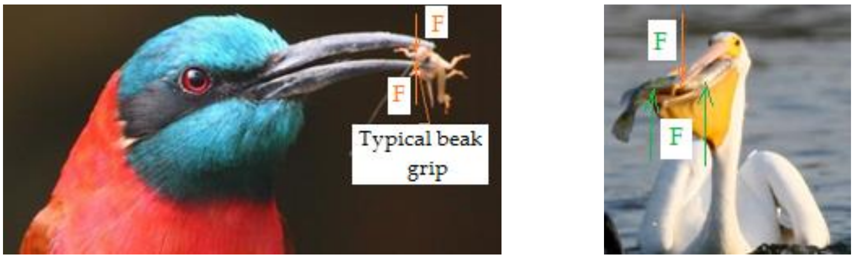


Fig. 8. Types of bird beaks as models for mechanical gripper jaws-selected by the author[11]



a b

Fig. 9. Exemplification of the beak grip of small bodies (a) and large bodies (b)

In the case of serrated beaks, they increase the friction and the safety of the object's grip, without considering the possibility of the jags (small teeth) penetrating the surface of the gripped object. Fig. 10a shows a grip control of a fish [12], and Fig. 10b shows the transfer of a fish from one bird to another [12], a delicate situation due to the risk of dropping the gripped body. This transfer operation is still difficult even between two advanced robots.

a. b.

Fig. 10. Beak gripping (a) and transfer of a body between the beaks of two birds (b).

3.5. The claws of birds

The claws of birds, which have a few toes, are very well adapted for gripping, especially since birds come in flight to gasp a bar (tree branch, electric wire, etc.). Figure 11 shows different types of claws, with four toes (the claws are arranged according to the relative arrangement of the toes: three plus one opposable and two by two opposable and depending on the relative size of the toes: toes significantly equal (Fig. 11 a and b), then the situations with the middle toe of the three slightly enlarged (Fig. 11c, d and e) or significantly enlarged (Fig. 11f), with four toes, two opposable (Fig. 11g) and three toes (two plus one opposable –Fig. 11h), and in Fig. 12 are represented situations of birds grasping various bar objects, associated with a grip (with F are noted the gripping forces exerted by the elements of the toes, a kind of phalanx, on the gripped body), excluded being the cases of the actual sitting of the birds on a surface.

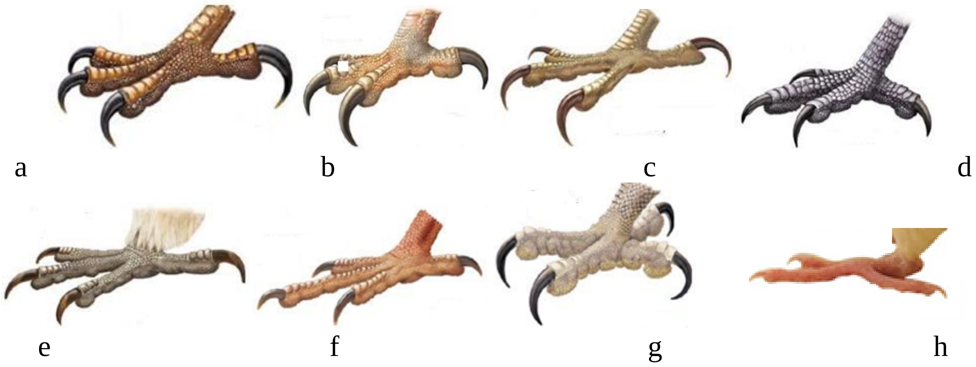
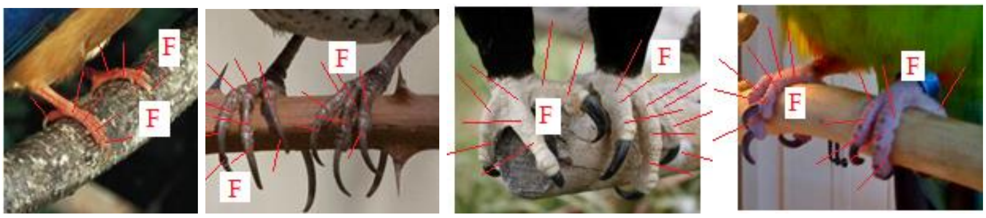


Fig.11. Types of claws from different species of birds [13-selected and completed by the author]



a. b. c. d.

Fig. 12. Exemplification of claw grasping in various bird species

The claws as a gripping means have been carefully studied [14,15] and all the necessary structural, kinematic and dynamic details have been presented in principle, which obviously can continue in certain directions. It is worth noting that the claws have soft tissue areas on the side of the body on which they sit, which absorbs the shock when gripping and increases the contact area to increase the safety of the grip (it is recommended to deepen this aspect for the larger use of such solutions for mechanical gripper jaws of this type). It is noteworthy that relatively recently some drones have been equipped with 2 clawed legs, like birds, so that they can be fixed on tree branches or similar objects (Fig. 13 [16]).

a. b.

Fig. 13. Drone with claw feet (a) and this drone attachment to a tree branch (b).

It is also noted that the claw can be used for a proper grip, similar to a hand, as shown in Fig. 14, in which the grip forces are denoted by F.

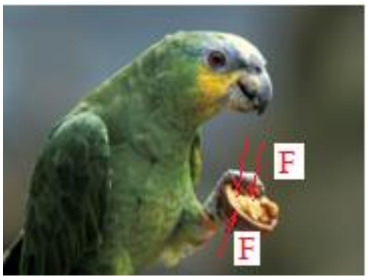


Fig. 14. The grip of a body by the claw of a parrot similar to the hand grip.

Claw-like technical solutions may endow some mobile robots with the specification that these solutions can provide grip for attachment to some objects but also, in some cases, grip for handling objects. Mechanical claws can also have two fingers, three or four fingers, one phalanx, two phalanges or three phalanges. They can be designed modularly and of various types of dimensions: small, medium, large or even very large, for example for a range of bird-type robots of various sizes.

3.6. Jaw grip

The jaws can be used to grasp objects by several categories of living things, especially reptiles, fish, batrachians and mammals, for which details will be given below.

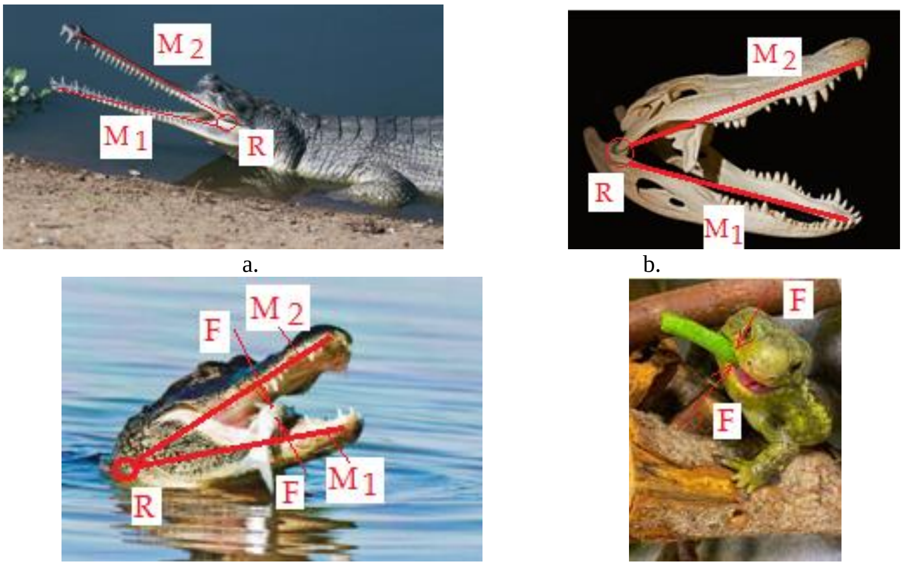
3.6.1. Jaw grip in the case of reptiles

Reptiles have two jaws with which they can grasp a body, without taking into account the penetration of their fangs into its surface. The jaws can be opened depending on the species of reptiles and their size, with the specification that especially in snakes due to the structure of the jaw joints they can be opened additionally. An example of a reptile is shown in Fig. 15a, in this case a crocodile with open jaws (the two jaws M_1 and M_2 are connected by a coupling similar to a rotating coupling R, which can also be seen in Fig. 15b, in which there are the same notations on a crocodile skull, where the rotation-type joint between the jaws is much better observed), and in Fig. 15c [17] an example is given of a body being caught by a crocodile and in Fig. 15d [18], an object gripped by a lizard (figures in which the gripping forces were noted with F).

The additional opening capacity of the jaws found in some reptiles can be used as a source of inspiration for jaw grippers, which open in two steps, in the first step for small and medium-sized bodies, and in the second step for large bodies.

3.6.2. Jaw grip in fish

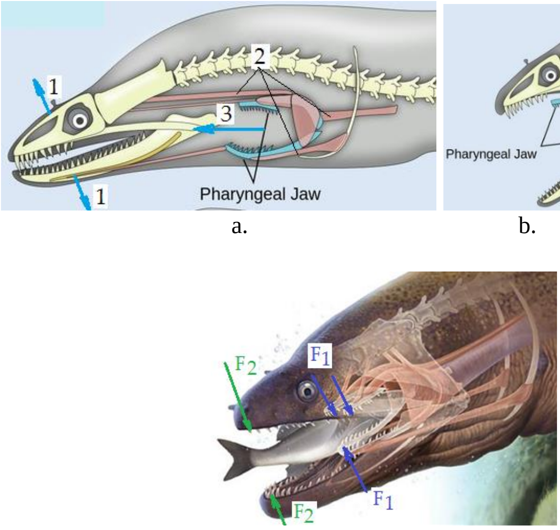
Fish can generally grasp other fish with their jaws. The jaws open, grasp the prey and by closing it is initially fixed between the jaws. In order to be able to grasp, the jaws have the ability to open and close due to the proper bone and muscle structure [19]. A special case is the fish species that has a secondary jaw in the pharynx (Fig. 16a and b [20]). In this case, when the main jaw is opened in the direction of the arrows 1, due to the set of tendons 2, the pharyngeal jaw advances after the arrow 3, according to Fig. 16a, and reaches the position in Fig. 16b, in the phase where it can grip an object (another fish). It should be noted that the upper pharyngeal jaw has two identical parts (see Fig. 16c).



a. b.

c. d.

Fig. 15. The jaws of a crocodile (a), a crocodile skull (b), the grip of a crocodile (c) and a lizard (d)-completed by the author



a. b.

c.

Fig. 16. Fish with double jaw: general structure (a), pharyngeal jaw in the advanced position (b) and gripping a fish with the two jaws (c-completed by the author).

The pharyngeal jaw thus reaches the area where it can first grasp the gripped body for temporary fixation, pressing with the forces F $1_{,}$ then the main jaw ensures full safety of the grip, with the forces F_2 (Fig. 16c [21]). This solution can be considered for some technical variants of special jaw grippers.

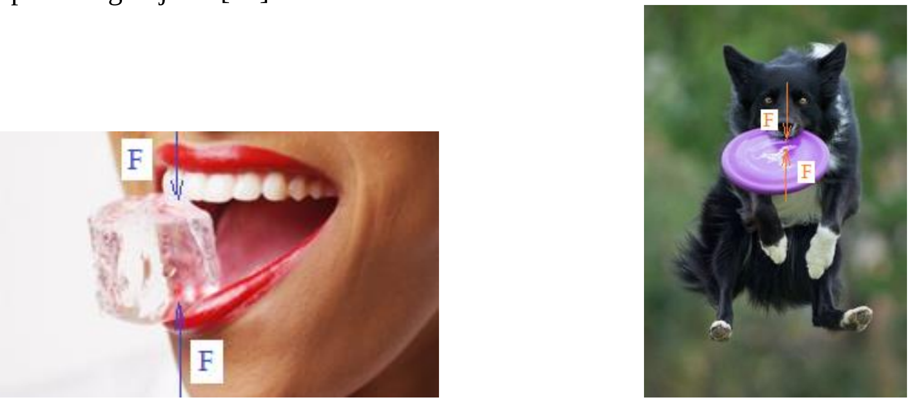
3.6.3. Jaw grip in the case of batrachians

The batrachian family includes a multitude of frog species. All frogs have a mouth that they can open and close to grasp small and medium-sized bodies(Fig. 17). Similar to this mouth, resembling one generated by the jaws, there are several types of grippers with jaws in which, compared to the natural shapes, the jaws themselves can be optimized.

Fig. 17. A frog grasping an egg with force F jaws (image modified by the author).

3.6.4. Jaw grip in mammals

All mammals can grasp an object with their jaws. The jaws are considered in the first phase to perform the grip without affecting the surface of the gripped body, only fixing the gripped body to the gripper - the assembly of the two jaws. Fig. 18a gives an example of a human jaw grip, but all mammals with similar or slightly different jaws can do this, as do dogs, for example (Fig. 18b), which can even grasp moving objects [22].



a b

Fig. 18. Human jaw grip (a) and a dog grasping a moving disc (b)-completed by the author.

The jaws have been and continue to be a source of inspiration for mechanical grippers, well known and widely used in robotics [19, 23].

3.7. Gripping in the case of insects

Insects are of virtually infinite variety. Many of them have specialized components or can be used to grasp other bodies. There are only two cases here, namely ants and stag beetles. Ants, which can grasp and move objects much larger than themselves, have many actions in which they grasp different bodies. Fig.19a gives an example of an ant gripping a cocoon — an egg from which another ant will come out [24]. The stag beetle is a medium-sized insect that has two movable antlers with which it can grasp other bodies as if using tongs, as seen in Fig. 19b, in which a stag beetle grasps another one with its antlers, acting with gripping forces F [25]. It is noteworthy that in this action, the first stag beetle is anchored to the bark of the tree, through the ends of four limbs and does not lose its grip on it, which is another case of gripping. Fig. 19c gives an example of a mechanical jaw gripper similar to stag beetle antlers [26].

a b c

Fig. 19. Example of grip in the case of an ant (a), a stag beetle (b)-completed by the author and an example of a mechanical jaw gripper like stag beetle antlers (c)

3.8. Hand grip in primates

Hand grip is characteristic of primates, i.e., monkeys and humans. Monkeys grasp with their hands almost similar to humans (Fig. 20a, which shows the grip of a body with the hand on the upper limb, but also the grip of a branch of the tree with the hand on the lower limb), also use the hand to hang of the branches of the trees (Fig. 20b), which is gripping, similar to that of birds clinging to the branches of trees or other similar objects. It is noteworthy that some monkeys, such as orangutans, have hand-shaped endings at the extremities of all four limbs, which is also an adaptation to tree life, in which the grip is secure when done with all four hands (see Fig. 20c where a grip with the four hands is exemplified — in Fig. 20 with F the gripping forces were noted).

a b c

Fig. 20. Hand gripping of a body by an orangutan (a), an orangutan grasping the branches with hands (b) and grasping a tree trunk with all four hands (c)-completed by the author

Human hand grasping has been and will continue to be the subject of many studies [23,27,28]. The human hand is considered the most powerful grip system, the result of a very long period of evolution. It is estimated that the human hand can have around 7 billion [19] configurations, most of which correspond to configurations for gripping bodies of different sizes and shapes. This paper only mentions the case of human hand grip and its special potential as a model for very similar artificial grips, as in the case of hand prostheses, or artificial finger grips for robots that can have two, three, four, five or even six fingers.

In order to highlight the grasping and minimanipulation performance of the human hand, a multitude of studies have been done [28,29,30,31], but with emphasis on grasping and less on minimanipulation. They focused first on highlighting the structural features of the human hand by identifying the type of components, the types of joints between them and determining the degree of mobility, and then on highlighting the functionality of the human hand to estimate its grasping capabilities. From the first perspective, the structural one, the human hand is composed of three types of elements (bones), namely: 8 carpal bones, 5 metacarpal bones and 14 phalanges (Fig. 21) [29].

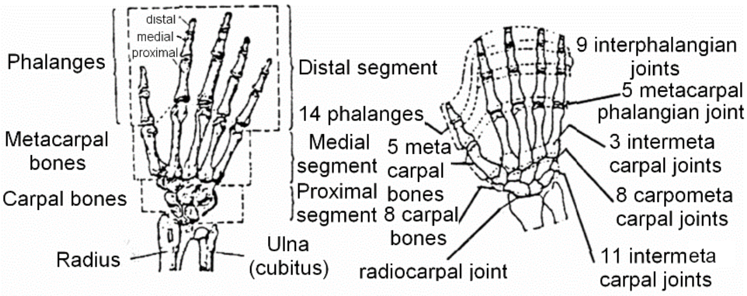


Fig. 21. Bone structure of the human hand [29].

These include single or bimobile joints (kinematic couplings) as follows: 11 intercarpal joints, 3 metacarpal joints and 9 interphalangeal joints. In addition, there are 8 carpal-metacarpal joints and 5 metacarpal-phalangeal joints. The result is a total of 27 elements (bones) and 36 joints. As a result, the degree of mobility of the human hand results in M = 35, only at the level of the phalanges there is a degree of mobility of $M_f = 19$ [32]. It is significant that the special possibilities of having different configurations and of grasping a wide variety of objects, of proportional dimensions to those of the hand, is also the approximate observance of the gold section, the ratio of 1,618 (Fig. 22), between the dimensions of metacarpal bones and the first phalanx (13/8 = 1.625), between the dimensions of the first phalanx and the second phalanx (8/5 = 1.6) and between the dimensions of the last two phalanges (5/3 = 1.66).

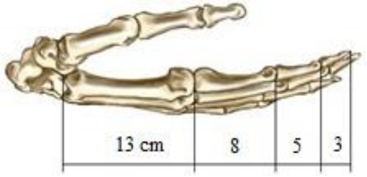
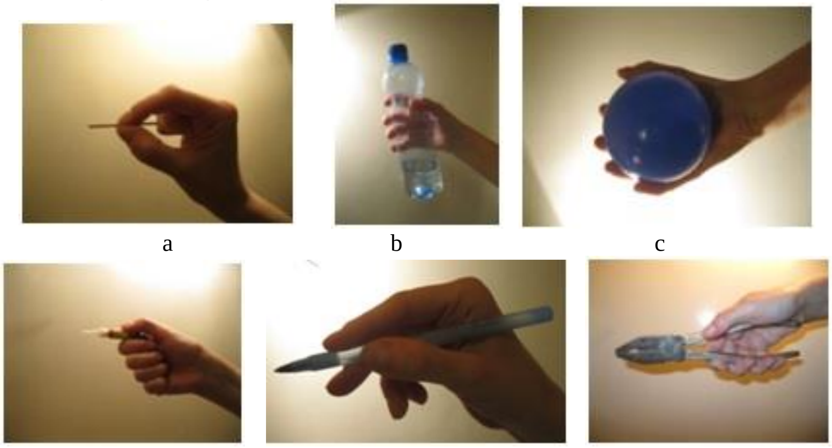


Fig. 22. Highlighting the "golden section" on the human hand.

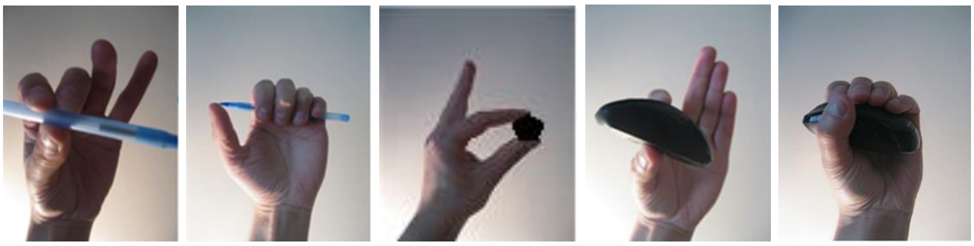
To illustrate the main types of grip that can be performed by the human hand, the examples in Fig. 23 are given [28].


a b c

d e f

Fig. 23. Main types of human hand grip.

The other important action that can be taken is to minihandle the gripped object, ie to change its position without changing the fingers used for gripping or transferring the object from one finger grip to another finger grip by changing the contacts between the fingers and the gripped object. Fig. 24 shows some examples of human hand grasping, and Fig. 25 shows three examples of minihandling of a pencil-type object, experiments performed by the author [33].



a b c d e

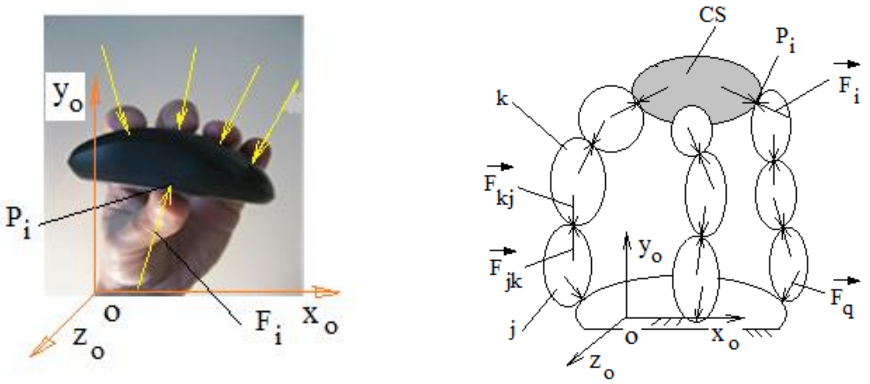
Fig. 24. Examples of human hand grip for objects of various sizes

a b c

Fig. 25. Examples of minihandling of an object between the fingers of the human hand.

Based on the experiments performed, a mathematical modeling of the grip can be outlined. It is considered the case of the grip of a solid object of any shape for which (according to Fig. 26a) were represented contact forces F_i applied by the fingers in the contact points P_i ($i = 1, ..., n$), on the grasped object, and starting from this situation we moved to the general case of grasping a solid body (CS), as part of a solid body system, according to Fig. 26b. The following is a brief description of the mathematical modeling of the grip.

If a non-deformable (rigid) solid body system is considered, Fig. 26b and Fig. 27, on which *external forces act* $\vec{F}_q$ (driving and gravitational forces) with the moments generated by them $\vec{M}_q$ ($q = 1, 2, ..., n$), and inside (at the couplings between the bodies) *the internal connecting forces* $\vec{F}_{kj}$ with the moments generated by them $\vec{M}_{kj}$ ($k = 1, 2, ..., n$; $j = 1, 2, ..., n$; $k \neq j$), the conditions of static equilibrium of the system of solid bodies under the action *of external forces* and *forces of internal connections* are expressed (considering the corresponding moments) by the equations (solidification theorem [34]):



a. b.

Fig. 26. Outline of contact forces in the case of gripping an object of any shape: gripping a real object (a); outlining the grip of an object as part of a solid body system (b).

$$\begin{cases} \sum_{q=1}^{n} \vec{F}_q + \sum_{k=1}^{n} \sum_{\substack{j=1 \\ j \neq k}}^{n} \vec{F}_{kj} = 0 \\ \sum_{q=1}^{n} r_q \times \vec{F}_q + \sum_{q=1}^{n} \overrightarrow{M}_O(\vec{F}_q) + \sum_{k=1}^{n} \sum_{\substack{j=1 \\ j \neq k}}^{n} \vec{r}_j \times \vec{F}_{kj} + \sum_{k=1}^{n} \sum_{\substack{j=1 \\ j \neq k}}^{n} \overrightarrow{M}_O(\vec{F}_{kj}) = 0 \end{cases} \tag{1}$$

where $\vec{r}_q$ and $\vec{r}_j$ are the position vectors of the points of application of the forces $\vec{F}_q$, respectively $\vec{F}_{kj}$ [34].

We first consider the simplified case of the grip of a solid body (CS), elastically deformable, on which only the contact forces act $\vec{F}_i$ (Fig. 27), perpendicular (normal) on a tangent plane (Π $_i$) to the surface of the body at points P_i (i = 1, ..., n), generated by the contact elements of the gripper, considered non-deformable solids S $_i$ (fingers), which contact the body at points P_i.

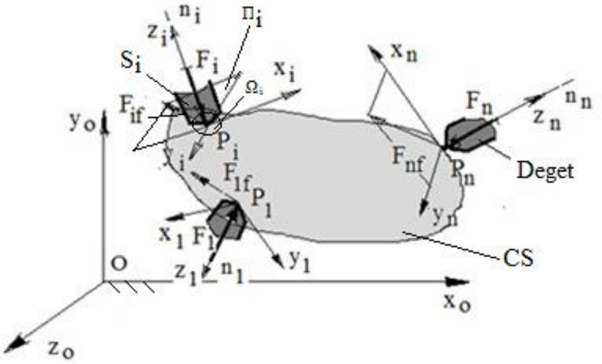
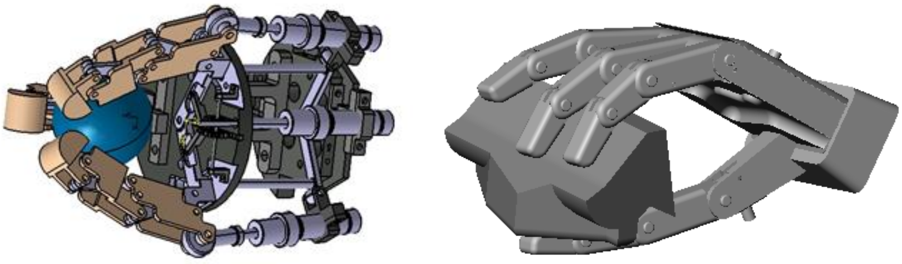


Fig. 27. The general case of contact forces in the grip of a deformable solid body.

By projecting equilibrium conditions on the axes of an Oxyz triorthogonal reference, a number of linear scalar equilibrium equations can be obtained that are used to determine the internal reaction forces and the external dependent forces of the system. The mechanical gripping system, respectively the gripping mechanism, is assimilated, in a first stage, with a system of rigid bodies out of which one is the gripped body. Based on this simplified case, the situation of considering the deformability of the contact elements (fingertips) in the area of contact with the gripped object or the deformability of the gripped body (object) can be treated.

This approach to the static balance of the gripped body can be considered in all cases of gripping with various biogrippers, such as those already presented. Obviously, the mathematical modeling of the grip can be deepened but this is not the object of this paper.

The following are two examples of anthropomorphic finger grips made under the coordination of the author (Fig. 28).



a b

Fig. 28. Three-finger (a) and four-finger (b) anthropomorphic grips

4. Conclusions

Based on what is presented in this paper, the following conclusions can be drawn:

- gripping biosystems are often the result of millions of years of evolution and have very interesting gripping characteristics;
- the main criterion for classifying biogrippers is how to perform the grip, according to which we distinguish the following cases of grip: by grasp, shellfish claw-like, beak, claws, jaws and fingers.
- all living things, from insects to mammals and primates, respectively, perform in a simpler or more complex form the operations of grasping certain bodies, objects, of various shapes and sizes for the actual gripping but also for the manipulation of those bodies;
- gripping biosystems were and still can be models for obtaining artificial grips used especially for robots, which are becoming more and more efficient.

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