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Influential feeding dynamics of sharks and mathematical formulas to estimate the power of biting by morphological data

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Mona Goharimanesh[1]*, Fereshteh Ghassemzadeh[2], Masoud Goharimanesh[3]

1. Biology Department, Ferdowsi University of Mashhad, Mashhad, Iran
2. Biology Department, Ferdowsi University of Mashhad, Mashhad, Iran
3. Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT

The mouths of some bony and cartilaginous fishes are located in the anterior part of their bodies, with a slight variation in sharks, which have theirs located in the abdominal part. This variation is evolutionary over time. The force exerted by the jaws of sharks in order to dismember their prey can be examined from two origins. The determined force exerted by teeth and muscles and the force as a result of torque arm through jaw distance. Although sharks apply less force compared to crocodile, their sharp teeth and mouth position provides much stronger effect. Moreover, several species are characterized with heavier upper jaw and this enhances the power. A mouth located in the anterior part of the body would have less force exerted. On the contrary, human jaw is shorter, which applies much more force. This paper relates the pre-branchial length and power with preying strength. According to this survey, a couple of predators were considered in terms of their mouth position, as well as different kind of feeding and ecological characteristics. Morphological data on several sharks were extracted and evaluated by MATLAB software to prove the following deductive hypothesis. The more the support distance (prebranchial length) to concentrated force was, the stronger the shark preyed on animals. The amount of torque had significant relationship with the lever distance and concentrated force. Besides, several formulas have been recommended to estimate the bite force and torque based on morphological characteristics.

Keywords: bite force, feeding dynamics, prebranchial length, torque, shark.

* **Corresponding author:** mona_goharimanesh@yahoo.com

Introduction

Sharks are precious aquatic animals. They are commonly termed fish; however, they are only distantly related to the classical (bony) fish [1]. Dosay-Akbulut (2006) reviewed a number of researches. Some shark-related objects, such as shark cartilage and its extracted materials, shark liver oil, shark's high level of urea can play significant role in the treatment of the cancer [2]. The trophic studies of *S. californica* were conducted in the Pacific Ocean via *in situ* study to observe the feeding performance and stomach content investigation. The use of stomach contents in sharks have been significant in identifying the role of sharks in relation to ecosystems; however, this method provides specific information on the latest feeding habits of sharks, while the stable isotope analysis gives more information about the assimilated food and their origin (benthic or pelagic, oceanic and coastal prey)[3].Feeding dynamics of Elasmobranches is a model to relate cranial morphology, bite force and feeding ecology in fishes [4]. In order to discover the organisms' ecology, the knowledge of functional morphological changes through the growth period is essential [5]. Functional morphology depends on changes in size, arrangement and materials of anatomical structures. In addition, Ecological function depends on the type of morphology through ontogeny [4].Although a strong correlation between jaw mechanics and prey selection has been demonstrated in bony fishes (Osteichthyes), yet the influence of jaw mechanics on feeding performance, in cartilaginous fishes (Chondrichthyes), remains unknown. For example, the great white (*Carcharodoncarcharias*) and the sand tiger (*Carchariastaurus*) possess characteristics such as tooth shapes which is believed to reflect dietary preference. The jaws of sand tiger and great white are adapted for rapid closure and generation of maximum bite force, respectively **[**6**]**. One simple fact remains that the feeding behavior and movement in sharks is rather complicated [7].Mechanical analysis on jaws of osteichthyes shows that food preference is related to jaws' mechanics and teeth structure [8]. But few studies have been conducted to find out such correlation in sharks [9]. Teeth sharpness has been regarded as a primary predictor of feeding behavior in sharks [10]. Other factors, such as gape angle, mass, mineralization of teeth and jaws, and finally prebranchial length and upper jaw are the main subject of this study.

Although, bite force is a factor for the beneficial function of shark's feeding, it is not the only effective factor on variation of diet in sharks [11]. It is predicted that species with sharper teeth has less bite force because sharp teeth facilitate preying. However, sharks with high bite force relatively have sharper interior teeth [12]. Research has shown that large species have hard preys, such as aquatic mammals, sea turtles and sea birds and some cartilaginous fishes. Therefore, they need to have great bite force [13].

Sharks have no high bite force because of their size; the great bite force is the result of being large-sized. In fact, large size can be one of the effective factors on bite force while head width is the best factor for predicting the bite force in sharks [12]. The longer and wider the head, for example, the more muscles involved and the harder the prey [13]. Relatively, 93% of bite force variety in anterior part of sharks is dependent of head width and prebranchial length [4]. Meanwhile, it should be considered that hardness of prey is related to the power of bite force and shape of teeth [12].Studies have shown that bite force in great white and sand tiger increased when the gap angle was increased [6]. In sand tiger, gape angle changes from 5 to 55 causes a change in bite force from 328 to 544 N (66% increase) and in white shark it ranges between 5 to 45 with corresponding bite force change of 1053 to 1329 N (26% increase). Besides, measures prepared by CT has shown that the mineralized cartilaginous layer in sand tiger is much thicker (3.5 mm) than great white (2.4 mm) [14]. In open gape angles, great white bites harder and in closer gape angles, sand tiger does harder but Constant Muscle Force (CMF) increased by developing the gape angles which is contrasting with mammals, with a decreasing bite bite force as the gape angle increases [14]. In sand tiger compared with great white, stress is 12% more, while bite force is 7% less. It is believed that jaws of great white are better structured for biting [6]. The bonnet head shark (*S. tibruro*) differs from other cartilaginous predators and bony fishes due to low bite force and lack of powerful jaws, feeding muscles and joined jaws. Although *S. tiburo* feeds on durophagous, it has the third least bite force among sharks. However, fast closure of mouth by adductor muscles can be an effective factor in feeding dynamics of sharks. In several cartilaginous sharks, acidic gastric enzymes are produced; probably, bonnet head has such enzymes which help during feeding. In fact, his might have physiological but not morphological changes [15]. Up to date, effects of factors such as teeth, gape angle, head mass and bite force have been considered. In this paper, firstly, effect of mass, height and width of head on bite force are studied. Besides, a new effective factor on feeding dynamics of sharks is recommended.

The remaining part of the paper is organized as follows. The next section surveys the material and methods. The most important geometric parts are considered in this section. In the third section, results are qualified where the curve fitting tools are employed to derive the best fitted formulas for the geometric parameters and in the fourth section, the paper is concluded.

Material and Methods

Since sharks are not easily captured, and due to problems in natural environment, their bite force is not readily measured[15],thus, all the data have been extracted from other papers and processed by MATLAB software (MATLAB and Statistics Toolbox Release 2012b, The Mathworks, Inc., Natick, Massachusetts, United States). Also, some graphs have been drawn to show the trends. Definitely, the requested energy, not bite force as for penetrating and biting the prey, determines how dangerous the shark is. Therefore, another factor as a material of energy is needed. Torque, also called moment or moment of force, is the tendency of a force to rotate an object about an axis. The magnitude of torque depends on three quantities: the force applied, the length of the lever arm connecting the axis to the point of force application, and the angle between the force vector and the lever arm [16]. In symbols:

$$\begin{aligned} \vec{\tau} &= \vec{r} \times \vec{F} \\ \tau &= r \times F \times \sin(\theta) \end{aligned} \tag{1}$$

where $\vec{\tau}$ is the vector of the torque, $\vec{r}$ is the displacement vector (a vector from the point from which torque is measured to the point where force is applied) and $\vec{F}$ is the force vector applying. Moreover, *r* is the length (or magnitude) of the lever arm vector, **F** is the magnitude of the force, and θ is the angle between the force vector and the lever arm vector [17]. The length of the lever arm is particularly important; choosing this length appropriately lies behind the operation of levers, pulleys, gears, and most other simple machines involving a mechanical advantage [16] (Fig. 1).

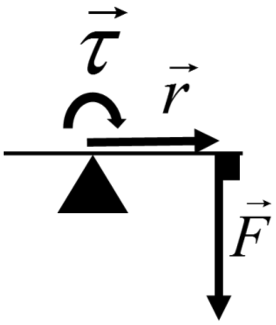

Figure 1. The Magnitude of torque depends on twovectors (r and f)

In the present study, R, θ and F represents the prebranchial length, gape angle and total bite force, respectively (Fig. 2).

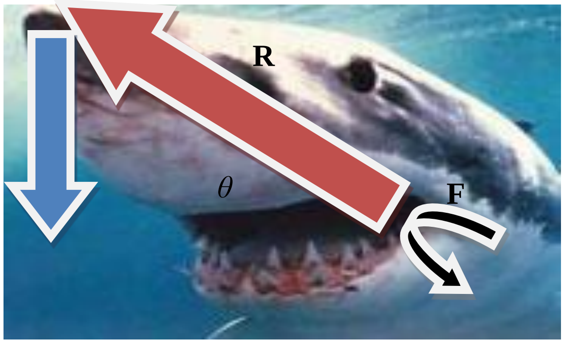

Figure 2. Demonstration of effective factors on moment in great white shark

In addition, several mathematical formulas have been derived by MATLAB that would be useful for estimating the bite force of different sharks. Table 1 represents a couple of morphological data of 10 species of sharks.

Table 2. Overview of the data [12, 13, 15]

species	Common name	Mass (gr)	Bite Force (N)	Standard Length (cm)	Prebranchial Length (cm)	Head width (cm)	Head height (cm)
Etmopterus lucifer	Balck belly lanternshark	54.83	3.58	15.5	3.25	2.1	1.45
Etmopterus spinax	Velvet belly lanternshark	377	1.36	32.53	6.98	4.35	3.93
Squalus acanthias	Spiny dogfish	1169	17.35	48.29	10.36	3.81	7.39
Chiloscyllium plagiosum	White-spotted bamboo shark	1487	78.11	55.29	9.93	7.2	5.4
Negaprion brevirostris	Lemon shark	1614	68.87	49.56	10.62	7.28	6.28
Heptrachias perlo	Sharpnose sevengills	1692	216.52	54.03	10.28	6.08	6.68
Heterodontus francisct	Horn shark	2199	192.54	55.5	11.55	9.45	8.42
Carcharhinus limbatus	Blacktip shark	9109	333.18	90.25	23.93	17.37	12.2
Carcharhinus leucas	Bull shark	159030	1101.49	170	37.35	32.35	31.7
Sphyrna mokarran	Great hammerhead	580598	3432	300	70	48	68.5

Moreover, someother formulas have been derivedfrom the provided data and MATLAB's curve- fitting analyzer which also made it possible to estimate the value of moment with regards to the different variables such as length, mass independent and head-width (Table 2).

Results and Discussion

The graphs and formulas were derived from the curve fitting toolbox in MATLAB software using data of Table 1**.** As demonstrated, a relationship existed between force and parameters such as mass, length, head height, head width and prebranchial length, respectively. Overall, the quantity of bite force gradually increased. The data showed that all the parameters caused an increase in bite force (Figs. 3, 4, 5, 6 and 7). As shown by the slope of Figure 3, in low weight sharks (below 100 kg) the growth of bite force and mass was more. There existed an upward trend for mass and bite force (Fig. 3).

The mathematical formulas below provide the magnitude of bite force in different species of sharks. It illustrated the scaling of bite force relative to mass (no.1 of Table2).

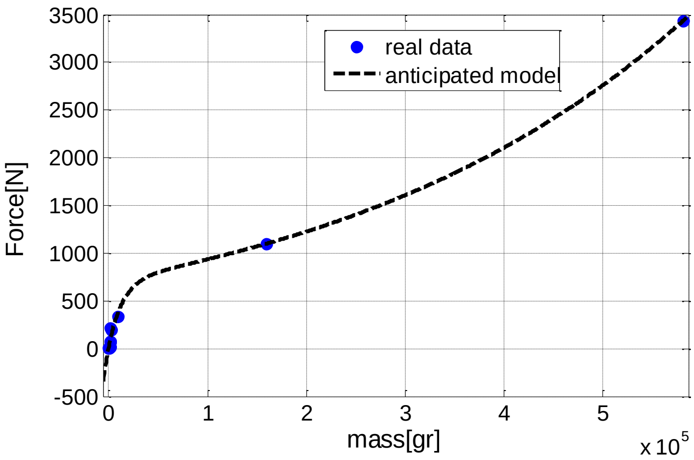

Figure 3. Graph illustrating the scaling of bite force relative to mass

Table 2. Formulas generated using curve fitting toolbox

No.	Dependent Parameter	Independent Parameter	Formula	*a*	*c*	*c*	*d*	R-Square
1	Force	mass	$F = a \times \exp(b \times m) + c \times \exp(d \times m)$	714	2.7×10^{-6}	-696.1	-7.127×10^{-5}	0.9975
2	Force	length	$F = a \times l^{b} + c$	0.074	1.961	-6.374		0.9975
3	Force	Head height	$F = a \times h^{b} + c$	8	1.4	-13.35		0.9952
4	Force	Head width	$F = a \times \exp(b \times w) + c \times \exp(d \times w)$	102.9	0.073	-182.7	-0.159	0.9977
5	Force	prebranchial length	$F = a \times p^{b} + c$	1.085	1.897	1.897		0.9977
6	Torque	length	$\tau = a \times l^{b}$	0.005694	3.078			0.9999
7	Torque	mass	$\tau = a \times m^{b}$	0.003847	1.352			0.9988
8	Torque	Head weight	$\tau = a \times w^{b}$	0.009084	4.415			0.9992

By preparing the data of length in various sharks' species as well as the formula below, illustrating the scaling of bite force and length, it would be possible to estimate the applied bite force (no.2 of Table 2). Figure 4 also shows a moderate rise in the value of bite force. It illustrates that there exist a high correlation between bite fore and length in different shark's species.

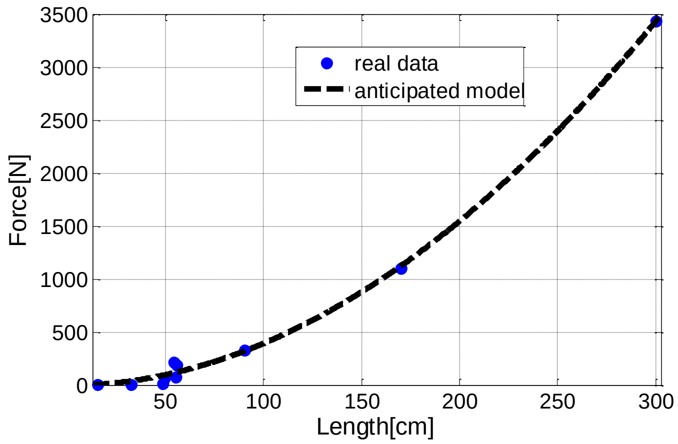

Figure 4. Graph illustrating the scaling of bite force relative to length

From Figure 5, a considerable upward trend exist between the value of bite force and head height, however, it experienced a steady rise in the case of head-width (Fig. 6).

Head height and width are other morphological factors useful in the estimation of bite force (no.3 & 4 of Table 2).

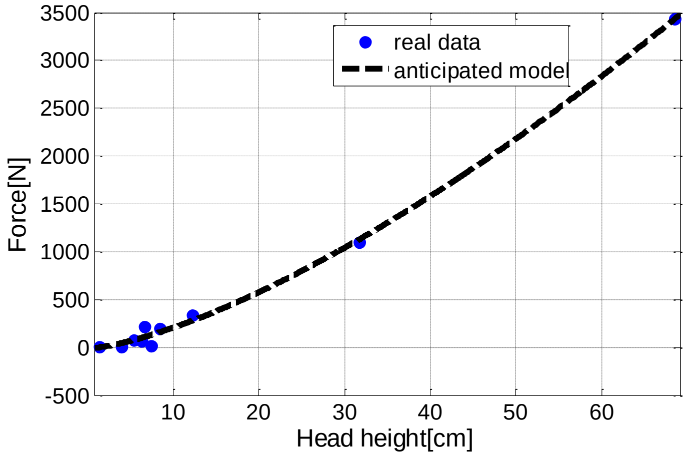

Figure 5. Graph illustrating the scaling of bite force relative to head height

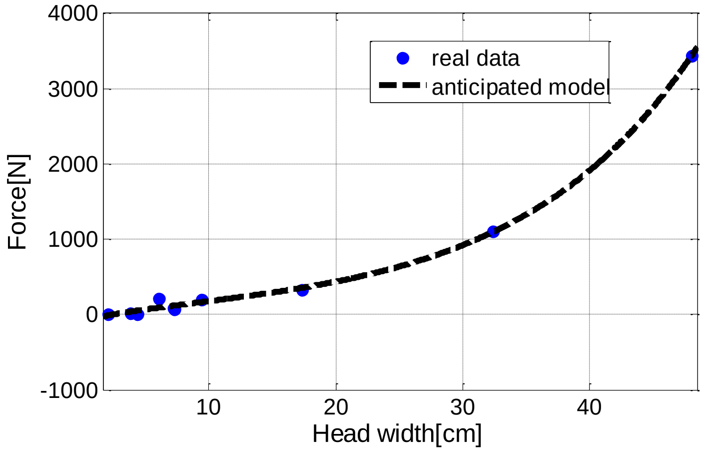

Figure 6. Graph illustrating the scaling of bite force relative to head width

The given data has shown that prebranchial length is another positive effective factor on bite force. Figure 7 shows a significantgrowth between the value of bite force and the prebranchial length.It is estimated that the more the prebranchial length, the greater the bite force.

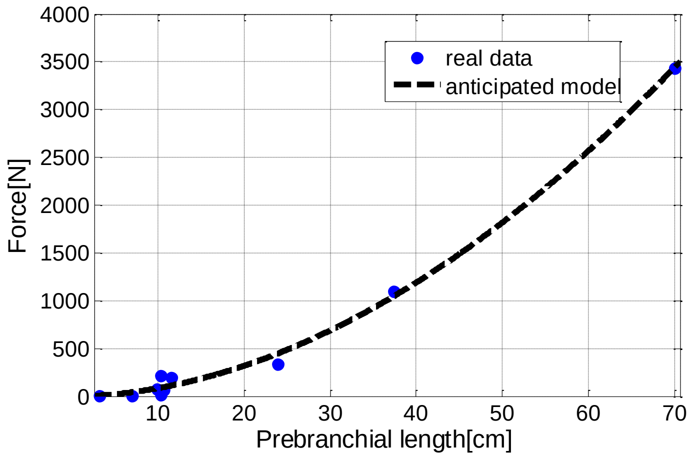

Figure 7. Graph illustrating the scaling of bite force relative to prebranchial length

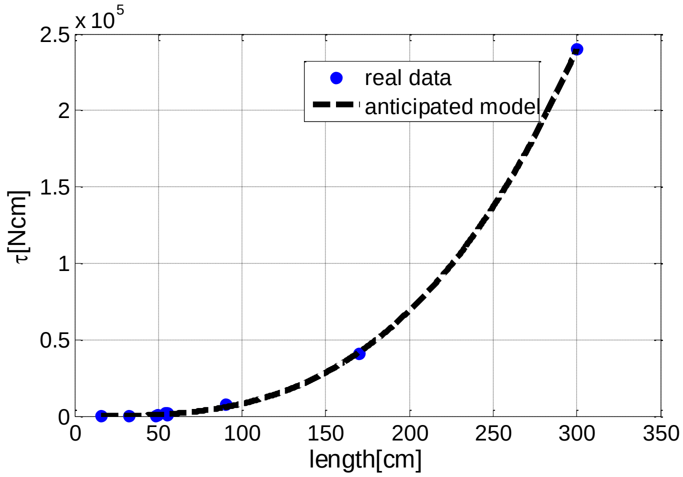

Figure 8. Graph illustrating relationship between torque and length

In addition, theformula below, showing the positive correlation of bite force and prebranchial length, provided an opportunity to estimate how long and short prebranchial length could be influential on bite force and feeding dynamics (no.5 of Table 2).

Hammerhead poses both higher mass and bite force than Bull shark. But, it is recommended that other factors such as movement speed, and habitat might be more effective to make Bull shark dangerous. In this paper, we crossed bite force in prebranchial length and named moment or torque. Surprisingly, the fitted graphs below are highly precise, which shows the effect of this parameter. In all cases, an increase in length, mass and head width caused a growth in moment quantity. As a result, a similar trend can be easily seen in Figures 8 to 10. However, it is obvious that the moment increased much rapidly regarding to the head width rather than length. In contrast, Figure 9 experienced a dramatic rise, which demonstrated a close relationship between moment and mass in sharks. It seems an increase in length of sharks shorter than 1m, with weight less than100 kg, and head width shorter than 20cm would not necessary result in the shark being much dangerous. It is worth mentioning that, all the calculated results were based on previous laboratory observations.

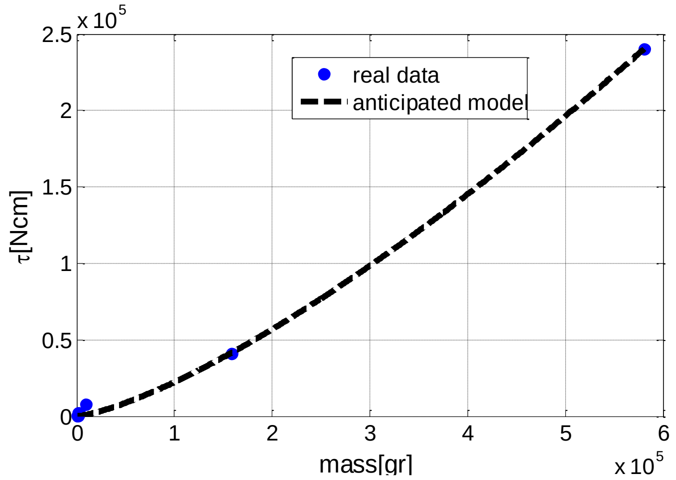

Figure 9. Graph illustrating relationship between Moment and Mass

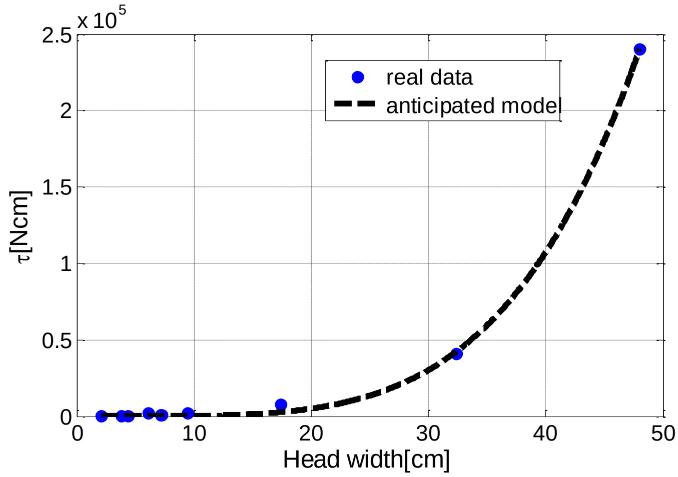

Figure 10. Graph illustrating relationship between moment and head width

Conclusion

There exist a correlation between behavioral ecology and morphology of sharks. As illustrated in Table 2, the R- squared value for all the mentioned relations were above 99.5%. In fact, the functional morphology resulted in much more effective behavioral ecology. Sharks experience morphological changes in order to have diverse habitat and diet, through evolution. Bite force and teeth shape are two effective factors in feeding dynamics and also, studies have shown a straight correlation of mass, length, width and height of the head as well as prebranchial length with bite force. In this study, it was discovered that in addition to the aforementioned factors, biting energy and more influential biting depended on another factor such as moment (torque) which had a positive correlation with prebranchial length. As shown by the results, one of the reasons for sharks as a top predator, despite less applied force, was an increase of moment which resulted from an increase in mass and prebranchial length. With the aid of the formula derived from the curve fitting toolbox in MATLAB and available morphological data such as length, height and width of the head, the quantity of bite force in different sharks can be estimated.

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