Journal of Physics Special Topics
An undergraduate physics journal

A5 7 Big mantis

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December 12, 2024

Abstract

In this short study we investigated the difference in energy imparted by the striking arm of a regularly sized Peacock mantis shrimp and a hypothetical version of this shrimp that was scaled to the size of a human. The mechanical energy involved in producing a blow from the striking arm was found to be 9.3 mJ for the smaller crustacean and 13.1 kJ for the larger one.

Introduction

The Peacock mantis shrimp is a marine crustacean known for its complex vision, as well as its striking arm (also referred to as its dactyl or club), an appendage capable of striking with a speed of 31 ms^{-1}, accelerating faster than a 0.22 calibre bullet [1]. Although these little creatures already pack a punch, we decided to investigate how much more energy would be produced by a strike from their club if they were scaled to the size of a human.

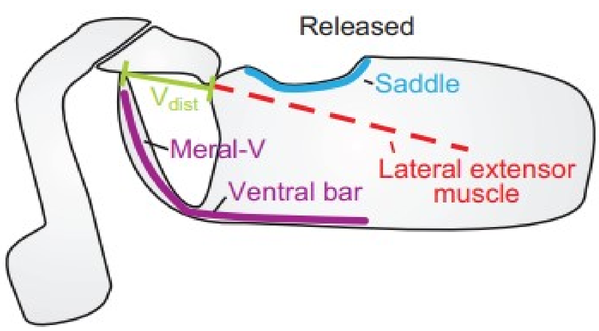

Figure 1: Schematic of the unloading phase of a dactyl strike [1]

The part of the striking arm responsible for producing its extreme acceleration is referred to as the 'saddle' [1]. This saddle behaves similarly to a spring in that in the moment just before a strike, the shrimp's muscles compress it and hold it back with a latching mechanism comprised of four main components [1]. As soon as it is ready to strike, the latching mechanism relaxes, releasing the potential energy stored in the saddle, and hence propelling the club forward. Just after the impact of the club, the rebound speed of the club creates a small area of low pressure, instantly vaporising the water around it, creating a cavitation bubble. The outward pressure from the water surrounding the bubble causes it to collapse, thus releasing energy in the form of heat and light. Due to the complexity of the calculation of the cavitation energy, we chose to exclude it from this paper with the potential of investigating it in future works.

Calculations and Discussion

When considering a human sized mantis shrimp, the first step in our calculation is to calculate the size of its appendage when scaled. The average length of an adult Peacock mantis shrimp is ≈ 13 cm with its average striking arm length being 26.5 ± 3.6 mm, and the mass of this arm being 5.6 ± 0.9 g [2]. In order to scale this to human size, the ratio of the average human height to the average length of the shrimp is needed. Assuming an average male human height of 1.7 m [3], the scaling factor is found to be ≈ 13, indicating an arm length of ≈ 0.34 m. Modelling the striking arm as a cuboid of length 0.34 m and width and height of 0.2 m, hence a cross sectional area 0.04 m^2, the scaled mass of the club can then be deduced. The composition of the club is known to be an assortment of minerals, however to reduce complexity of calculations, we assumed it is primarily composed of the mineral apatite, with a density of $\rho_a = 3400$ kg m^{-3} [4]. Therefore we can say that the mass of the scaled club is ≈ 46 kg

Rotational energy - The first step in quantifying the rotational energy of the striking arm being released is to consider its inertial moment, using:

$$I = \frac{L}{\omega} = \frac{Lr}{v} \tag{1}$$

with I being the moment of inertia (kgm^2), L being the angular momentum (kgm^2 s^{-1}) and ω being the angular velocity of the arm ($rads^{-1}$). Using eq(1) the torque produced by the rotating arm can also be considered using:

$$\tau = I\alpha = \frac{Lr}{v}\frac{d\omega}{dt} \tag{2}$$

with τ representing the torque produced by the arms rotation (Nm) and α the angular acceleration ($rads^{-2}$) with all other variables as previously stated. Using the fact that the angular momentum of the arm will be given by
$L = mvr$, where v is the tangential velocity of theclub (ms^{-1}) and r is the distance of the tip of the club from the pivoting point (m) (which we assume to be the length of the club itself), eq(2) can be re-written elminating v, the mechanical energy involved in rotating the arm be computed using:

$$E_m = \tau\theta = mr^2\frac{d\omega}{dt}\theta \tag{3}$$

Assuming also that the clubs target will be hit after a rotation about the pivot of 90° ($\theta = \pi/2$ rad), and that it rotates this amount within the same amount of time as its smaller counterpart at ≈ 0.001 s [2], plugging in the known values of m ≈ 46 kg and $r \approx 0.34$ m provides us with a mechanical energy of $E_m \approx 13.1$ kJ.

Energy loss due to drag - The mechanical energy lost due to frictional forces will have a significant impact on the efficiency of the striking arm, however due to the short length of the paper we chose to temporarily neglect the effects of drag with the potential of investigating this in future papers.

Big vs Small - When following the same mathematical method described considering the regular sized mantis shrimp instead, the total mechanical energy imparted on the object being struck was found to be ≈ 9.3 mJ. This is of order 10^6 times smaller than the energy imparted by its larger counterpart. The reason why the difference is so large is mainly due to the assumptions we have made about the club of the larger shrimp having the same acceleration as the smaller one.

Conclusion

The energy imparted on an object being struck by the striking arm of the smaller mantis shrimp was found to be ≈ 9.3 mJ, following the same method, the value obtained for the human larger shrimp was calculated to be ≈ 13.1 kJ.

References

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