The Breaking Force Required by Specialized Tooth Morphologies to Crush Hard Prey Items

Vera Hoang[1], Andrea Vancil[1]

Marine Ecology Research Apprenticeship

Autumn 2011

[1]Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250

Keywords: Tooth Morphology, Durophagy, Nucella, Mytilus, 3-D Printer, Force

Contact Information:
Vera Hoang
University of Washington
Biology Department
Seattle, WA 98195-1800
vhoang26@uw.edu

Abstract

Teeth are important in the breakdown and digestion of food. They are oftentimes a good indicator of an organism's fitness and survival. Though many have studied durophagous tooth morphologies and prey preference, no study has aimed to understand how crushing teeth work, and if there are prey-specific specializations. To understand tooth-prey interactions, we made two different aluminum tooth models: pointy and cup-shaped. Then, measured the force required by the teeth to initially break plaster snail and mussel shells produced by a 3-D printer. Assuming that the durophagous predator is able to consume its prey after an initial breakage, our results suggest that pointy teeth are more effective at crushing snail shells. However, neither tooth morphology is more effective in crushing mussel shells.

Introduction

An organism's teeth are a good indicator of its fitness and survival because teeth are important in the breakdown and digestion of food. Different tooth shapes or morphologies result in different tooth functions. Despite the fact that tooth morphologies and prey preference have been extensively studied (Gilmore 1912, Massare 1987, Schulp 2004), no study has aimed to understand how crushing teeth work, and if there are prey-specific specializations. Durophagous (hard-shelled) predators which represent a broad range of taxa including teleost fish and crustaceans (Oji, Ogaya, and Sato 2003) will be the focus of our study. Understanding the functional morphology of durophagous teeth will shed light on the comparative tooth-prey specializations and explain how one tooth morphology is more advantageous than another.

In this experiment, we studied how effectively cupped versus pointy teeth crush snail and mussel shells by measuring the initial breaking force (N). If the tooth exerts a lower force to break the shell, the tooth is more effective because less energy was expended to break the shell. If the tooth exerts a higher force to break the shell, the tooth is less effective because more energy was expended to break the shell.

We proposed that a pointy tooth is more specialized at crushing both snail and mussel shells because Evans and Sanson (1998) found that the force necessary to penetrate insect shells was proportional to the surface area of contact between the tooth and shell. Because the pointy tooth has a smaller surface area in contact with the shells, it would require less force to break the shells than the cupped tooth which has a larger surface area. Futhermore, Andersen and LaBarbera (2008) found that by localizing points of contact with blades, the material fails at lower overall strain.We believed that the pointy tooth would also localize the point of contact and, thus, fracture the both shells with a lower force as compared to the cupped tooth.

Comparing between the two prey types, we predicted that a cup-shaped tooth would provide more surface area for contact against a curved snail shell and, thus, the force required to fracture the shell would be higher than the mussel shell.

Methods

Computerized tomography (CT) scans of *Nucella* sp. and *Mytilus* sp. were done to create cross-sectional, three-dimensional images of shells. A 3-D image of the shells were rendered using the program Amira 5.2.2 (Visage Imaging, Germany) and converted into a standard triangulation language (STL) file format using ZPrint Software 7.10.3-7 (Z Corporation, Massachusetts). The STL file was used to print 3-D prototypes of the shells using ZPrinter 310 (Z Corporation, Massachusetts). The 3-D printer created identical prototypes which controlled for life histories of the organisms inhabiting the shells (Whitenack and Motta, 2010).

Nucella sp. with parameters of 2.4 cm long and 1.3 cm wide were printed as well as *Mytilus* sp. shells 5.2 cm long and 2.7 cm wide (Figure 1, C and D). Three-dimensional prototypes of shells were printed in plaster using a binding solution and ZP 150 High Performance Composite Powder (Z Corporation, Massachusetts).

To harden the shells, a ~7:9 ounce ratio of Epson Salt to tap water solution was made and uniformly misted with a spray bottle on the snail shells. The snail shells were left to air dry but were later transferred into an oven. The same Epson salt-water solution was sufficiently hand-syringed, drop-by-drop around the inner oval of the more delicate mussel shells which sat on a small piece of metal mesh. All shells were baked at 80°C for a minimum of 12 hours and left to cool.

Curvatures of teeth were generated using two Gaussian curves. The first curve generated a flat tooth morphology. Adding the second curve to the first created the pointy tooth morphology while subtracting it created the cupped tooth morphology. The following equation was used to generate the curves:

$$y = x^{32} + h * e^{\left(-\left(\frac{x^2}{0.4}\right)\right)}$$

where h was the height. h=1 for the first curve which created a flat tooth, h=+0.5 for the pointy tooth and h=-0.5 for the cupped tooth.

The program SprutCAM (SPRUT Technology Inc., Russia) was used to program the automated mil, Tormach PCNC 1100 (Tormach, Wisconsin), to cut the model teeth. Teeth were cut from 2.5 cm aluminum stock and the diameter of the teeth after cutting was 1.2cm (Figure 1, A and B).

The model teeth were attached to the crosshead of the MTS Synergie 100 (MTS Systems Corporation, Minnesota) and shells were placed on a silicon pad to prevent stress concentrations due to surface irregularities on the testing platform. Test simulations and data collection were run using TestWorks 4 (MTS Systems Corporation, Minnesota): For both prey-types, the crosshead was lowered at a rate of 1.27mm/sec to crush the shells. When testing the mussel shells, the automatic test stop was set to 60% break sensitivity. For the snail shells, the break sensitivity was set to 75%. The break sensitivities measured the relative yield of the material. Thus, this metric was chosen to automatically stop the MTS Synergie because we considered the shells adequately crushed to assume the organism inhabiting it would be dead.

Thirty-six snail and mussels shells were tested on each tooth type, and two metrics were recorded: load at yield (the force (N) at initial breakage) and peak load (the maximum force (N) applied to the shell during the test). However, because the break sensitivity for each shell was pre-set, the peak load was found to be a poor predictor of the force required to break the shells. For some shells, the test would not end and the maximum force increased though the shell had already initially broken. (Figure 2). For most tooth, shell combinations, there were no statistical differences between the peak load and load at yield ($p>0.05$) except when the pointy tooth crushed the cupped shell ($p<0.05$). Thus, we analyzed our data for the load at yield because, from a testing standpoint, shells broke at the load at yield as opposed to the peak load. Trom a biological standpoint, we assumed that the organism living inside the shell would be dead if the durophagous predator was able to initially break the shell.

To analyze our data we used a two-way ANOVA on ranked data performed using SigmaPlot 11 (Systat Software, California). ANOVAs are robust to violations of assumptions (Box and G.E.P. 1954) and the analysis was continued though the equal variance test failed. The Holm-Sidak method was used to make pairwise multiple comparisons.

Results

There ANOVA showed three important relationships. First, there is a significant difference in the force required to initially break the two different shells ($F_{\text{dfshell morphology,dfresid}}$= 678.34, P = <0.01). The mussel shells broke at a lower force than the snail shells. There is also a significant difference in the force required by the two different tooth morphologies to break the shells ($F_{\text{dftooth morphology,dfresid}}$= 52.937, P = <0.01). Generally, the pointy tooth required lower force to break the shells. Finally, there is a significant difference in the interaction between the shell and tooth morphologies ($F_{\text{df shell morphology x tooth morphology,dfresid}}$= 33.615, P = <0.01).

The Holm-Sidak all pairwise multiple comparison showed that there was no difference between the cupped and pointy teeth when crushing the mussel shell (p=0.300). Both teeth crushed the mussel shells at about 40 N. The pointy tooth required half as much force to crush the snail shell compared to the cupped tooth (p=0.001). The cupped tooth required more than five times more force to crush the snail shells than the mussel shells (p<0.001). The pointy tooth required almost three times the force to crush snail shells compared to the mussel shells (p<0.001).

Discussion

The data partially support our hypothesis that the pointy tooth is more effective in initially breaking either shell. This difference in tooth effectiveness is most evident in the snail shell trials ($p \leq 0.001$). The pointy tooth exerted half as much force to initially break the snail shell as compared to the cupped tooth. In contrast, we must accept the null hypothesis that neither tooth is more effective in crushing the mussel shell (p=0.300).

This could be due to the intrinsically more flattened mussel shape. Also, though the Epson salt syringing method deformed the shells less than the spraying method, many mussels had a slightly flattened curvature. If there was a more uniform method in correcting for the deformity, it may result in a significant difference between the pointy and cupped tooth in crushing the mussel shell. In addition, there were quite a few outliers when crushing the snail shells. This may have been a result of uneven Epson salt solution spraying and may be remedied by creating an Epson salt solution bath or by increasing the sample size of shells crushed.

The force required to initially break the shells cannot be predicted without knowing the specific shell and tooth morphologies. Though the interaction between the shell and tooth morphologies does lead to some significant differences, we are unsure of the nature of the interaction ($p<0.001$). Therefore, it would be interesting to explore other factors that might influence the shell and tooth morphology interaction.

Further research of interest includes testing with a wide range of tooth and shell morphologies to more accurately depict the comparative effectiveness of tooth morphologies when crushing a variety of hard-shelled prey items. In addition, testing a row or jaw of teeth as opposed to one tooth would more accurately simulate the feeding habits of durophagous organisms (Schulp 2004).

Because teeth have an obvious role in the processing of food, more research is needed to further explore tooth-prey specializations. This study, however, shows that pointy teeth are more specialized in crushing snail shells.

Figure 1. (A) Side and (B) top views of aluminum cupped and pointy teeth. (C) Top and (D) lateral views of printed mussel and snail shells.

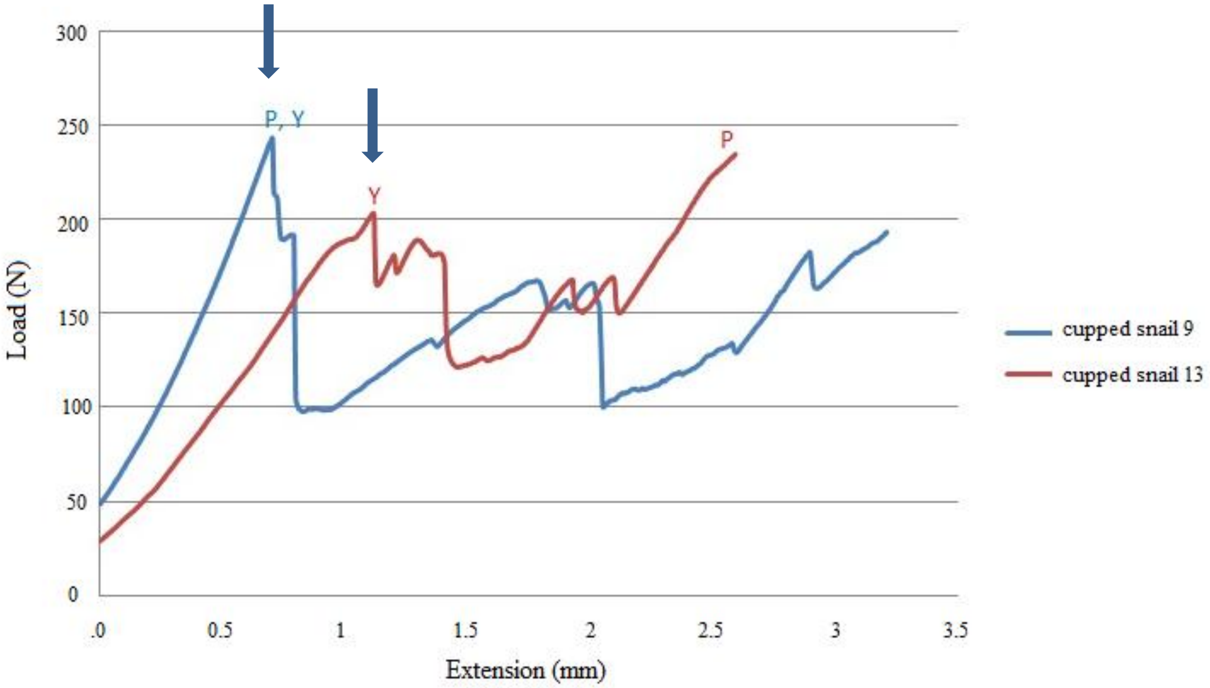

Figure 2. Shells broke at load at yield (Y) versus the peak load (P) The load (N) on examples of two snail shells that were crushed by the cupped tooth. The yield at load metric was chosen to measure the force required by the tooth to crush the shells as opposed to the peak load metric. Snail shell 9 yielded the same value for both metrics and the MTS automatically stopped when it detected a breakage of at least 75%. Snail shell 13 yielded different values for the load at yield and peak load because it did not detect the 75% breakage and continued the test though the shell was obviously crushed. Arrows indicate when the shell was crushed.

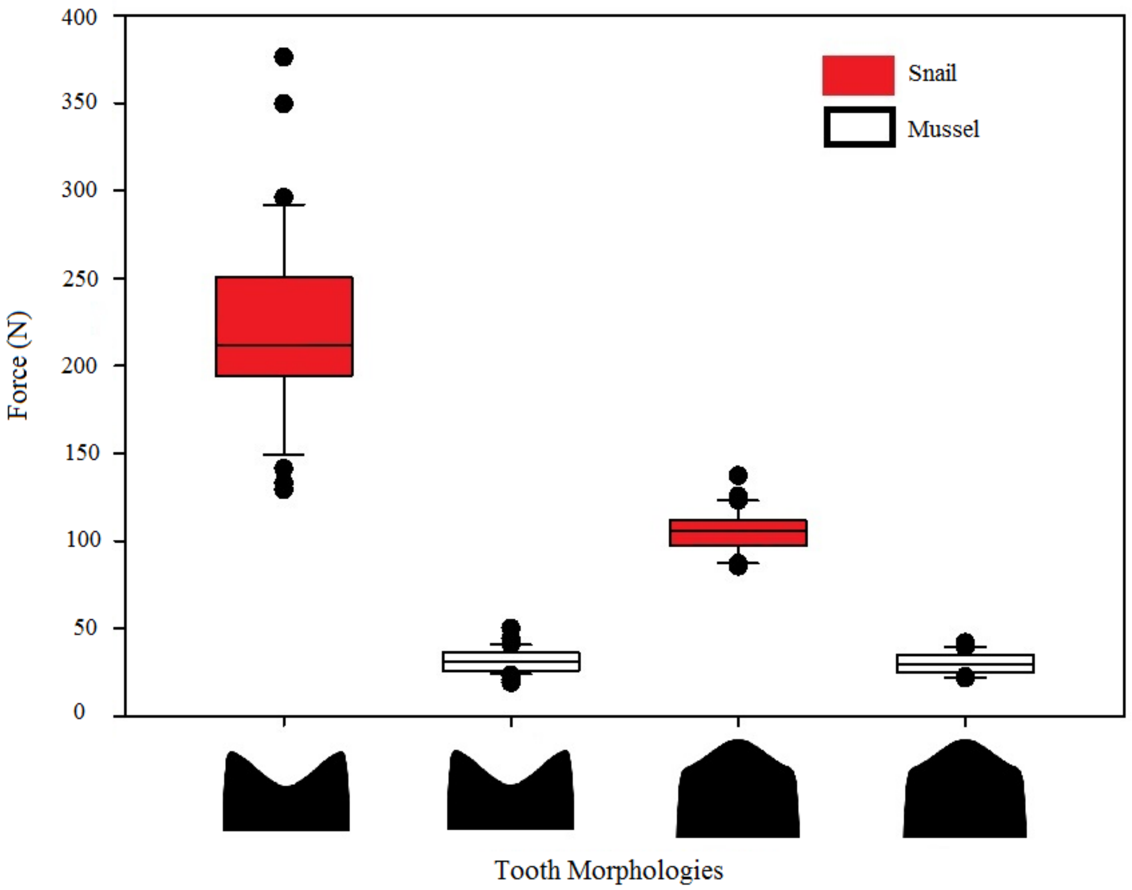

Figure 3. Load at yield forces, in Newtons, required to initially break mussel and snail shells by pointy and cupped tooth morphologies. n=36 for each shell-tooth combination. Medians and two quartile ranges are shown, dots represent outliers. A two-way ANOVA run on ranked data showed no difference between the cupped and pointy teeth in crushing the mussel shell (p=0.300) while there was a significant difference between the cupped and pointy teeth in crushing the snail shell (p=0.001). Similarly, there were highly significant differences between the snail and mussel shells being crushed by the cupped tooth (p<0.001) and the snail and the mussel shells being crushed by the pointy tooth (p<0.001).

Acknowledgements

Sincere thanks to our fantastic research mentor, Stephanie Crofts. In addition, thanks to Friday Harbor Labs, Chris Neufeld, Mike Nishizaki, Adam Summers, and FHL maintenance. Finally, thanks to Henry and Holly Wendt for their generous support for the FHL research apprenticeship program.

Literature Cited

Anderson, P.S and M. LaBarbera, 2008. Fuctional consequences of tooth design: effects of blade shape on energetics of cutting. *The Journal of Experimental Biology,* 211:3619-3626.

Box, G. E. P, 1954. Some Theorems on Quadratic Forms Applied in the Study of Analysis of Variance Problems: II. Effects of Inequality of Variance and of Correlation Between Errors in the Two-Way Classification. *Ann. Math. Statist.*, 25: 484-498.

Evans, A. R. and G. D. Sanson, 1998. The effect of tooth shape on the breakdown of insects. *Journal of Zoology*, 246 (4): 391-400

Gilmore, C.W., 1912. A new Mosasar reptile from the Cretaceous of Alabama. Proceedings of the United states National Museum, 41: 479-484.

Massare, J. A., 1987. Tooth morphology and prey preference of Mesozoic marine reptiles. *Journal of Vertebrate Paleontology*, 7(2): 121-137.

Oji, Tatsuo, C. Ogaya, and T Sato. Increase of Shell-crushing Predation Recorded in Fossil Shell Fragmentation. *Paleobiology* 29(4): 520-526.

Schulp, A.S., 2004. Feeding the mechanical Mosasaur: what did *Carinodens* eat? *Netherlands Journal of Geosciences*, 84(3): 345-357.

Turner, C.H. and D.B. Burr, 1993. Basic Biomechanical Measurements of Bone: A Tutorial. Bone, 14(4): 595-608.

Whitenack, L.B and P. J. Motta, 2010. Performance of shark teeth during puncture and draw: implications for the mechanics of cutting. *Biological Journal of Linnean Society*, 100: 271-286.