Sawing Efficiency in Elasmobranch Teeth

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INTRODUCTION

Previous research has shown little effect of tooth shape on puncturing ability (Whitenack & Motta, 2010), and though the concept of shark teeth as a saw blade has been explored, it has not been manifested beyond mathematical models and hypotheses (Frazzetta, 1988). Frazzetta's analysis covered many aspects of shark teeth in the context of sawing but lacks physical data of their effect when applied. Thus, this project set out to answer several questions about efficiency of shark teeth at sawing prey items: effect of tooth morphology on sawing efficiency, which varied strongly by species; sawing efficiency by trial, to test whether or not teeth are designed for a single use; and, in concept, to see if I can extrapolate feeding ecology from these factors.

MATERIALS & METHODS

ACQUISITION OF SPECIMENS

Teeth were chosen to represent a multitude of tooth morphologies, as opposed to a phylogenetic range.

Teeth were acquired in a variety of ways. Teeth from *Carcharhinus falciformis* were removed by hand from a dried jaw after soaking and short boiling in water. Teeth from *Carcharhinus plumbeus* were removed from a frozen, thawed, and boiled specimen. *Galeocerdo cuvier* teeth were acquired from eBay, and *Hexanchus griseus* teeth were extracted with a scalpel from a thawed *H. griseus* jaw for the purpose of this study.

Indiscriminate teeth from *G. cuvier* were used, as they were acquired mixed in a bag. For both *Carcharinus*, only teeth from the second row and those with no nicks or obvious wear from the first row were used. No third row teeth were placed on blades, due to concerns of insufficient calcification. Only first row teeth of *H. griseus* were extracted, but both upper and lower jaw teeth were used.

Preparation of blades

Ace Hardware 12” Bi-Metal Sawzall blades and Milwaukee 12” Bi-Metal Sawzall blades were used as an attachment surface for the elasmobranch teeth. Metal teeth on the blades were ground down until a flat dorsal surface was reached.

Flesh was removed from teeth to a reasonable extent to not interfere with placement on blade. Quick Set Epoxy was used to attach the teeth to the blade and allowed to cure for a minimum of 24 hours in a warm, dehumidified room. Teeth were placed on the side of the blade that corresponded to the side of the jaw, with each blade limited to one direction of teeth.

Three *C. falciformis* blades were made, with 8, 8, and 7 teeth. Three *C. plumbeus* blades were made, with 10, 8, and 8 teeth. Five *G. cuvier* blades were constructed, each with 10 teeth. Three blades used teeth from *H. griseus*’ upper jaw; each had four teeth. Two blades were constructed with teeth from *H. griseus*’ lower jaw, with seven teeth each.

Actuation of saw

A DeWalt 385 Reciprocating Saw was attached to a fulcrum that allowed regulated vertical articulation (Fig 1). The speed of the saw was kept within a limited range, between 2800 and 2900 reciprocations per minute.

Figure 1, Setup for DeWalt 385 reciprocating saw. Weight placed on posterior allows consistent drop and force on blade. Built by Jeff Brash, 2014.

Substrate was secured in blade path. Headless and eviscerated Alaskan chum salmon, *Oncorhyncus keta*, were used as sample prey item.

Most trials were completed with a single weight on the front of the fulcrum providing -25 N on the blade. Select trials strapped an additional ~30 lbs to the front of the fulcrum to provide -114 N.

DATA COLLECTION & STATISTICAL ANALYSIS

High speed video at 420 frames per second (fps) was taken of each cut, using a Casio Exilim EX-FH20 camera. This data was analyzed in ImageJ and R. Additionally, photos were taken before and after each cut.

ImageJ was used to identify reciprocations per unit flesh of prey item, which were then examined as a Distance/Area (cm^{-1}) (D/A) value. Each reciprocation provided 5.715 cm horizontal motion for each tooth. Area cut was taken from each fish to complete the metric.

R was used to make plots and an ANOVA was applied to test for significant differences between the three groups.

RESULTS

The majority of blades cut successfully through the substrate. Many sliced well, stalled visible progress downwards, then returned to relatively high rate of downward motion. See Table 1 for data.

Species	Blade	Trial	Slices per Cut	Distance	Area (Prey)
C. falciformis	7	1	524	2994.66	64.5
C. falciformis	7	3	2889	16510.635	80.248
C. falciformis	7	4	4876.09091	27866.8596	132
C. falciformis	7	6	1085.53846	6203.85231	35.8
C. falciformis	5	1	253.555556	1449.07	49.67
C. falciformis	5	2	105	600.075	52.04
C. falciformis	5	4	5537.71429	31648.0371	47.26
C. falciformis	5	5	2289.33333	13083.54	28.8
H. griseus	13	1	1019.8	5828.157	14.7
H. griseus	13	2	331.25	1893.09375	88.68
H. griseus	13	5	487.333333	2785.11	57.28
H. griseus	13	6	166.625	952.261875	17.818
H. griseus	14	1	1394	7966.71	51.497
H. griseus	14	2	1022.875	5845.73063	57.71
H. griseus	14	3	338.666667	1935.48	34.877
H. griseus	14	4	1393.28571	7962.62786	56.414
H. griseus	14	5	548	3131.82	27.139
H. griseus	14	6	4444.72727	25401.6164	48.16
H. griseus	15	2	288.7	1649.9205	62.114
H. griseus	15	3	189.818182	1084.81091	76.317
H. griseus	15	4	3161.1	18065.6865	50.92
H. griseus	15	5	61.9090909	353.810455	42.89
G. cuvier	8	1	856.5	4894.8975	53.44
G. cuvier	8	2	553.5	3163.2525	32.3
G. cuvier	8	3	4743.875	27111.2456	63.991
G. cuvier	8	4	489.333333	2796.54	53.204
G. cuvier	8	5	795.625	4546.99688	57.626
G. cuvier	8	6	109.625	626.506875	39.28
G. cuvier	9	1	2194.66667	12542.52	67.67
G. cuvier	9	3	3630.18182	20746.4891	63.34
G. cuvier	9	4	388	2217.42	51.8
G. cuvier	9	5	1315.66667	7519.035	50.176
G. cuvier	9	6	114.25	652.93875	40.723
G. cuvier	16	1	105.272727	601.633636	48.63
G. cuvier	16	2	512.857143	2930.97857	54.58
G. cuvier	16	4	3520.9	20121.9435	57.04
G. cuvier	16	5	113.545455	648.912273	33.93

Table 1: Primary data.

Some cuts did not make it through the entire fish, as the saw angle to the board intersected with the board. (See Fig. 3) These cuts were stopped and the blade removed as soon as the collision occurred, and the data provides evidence of the incomplete cut. However, the cut is included in the data, as it was a valid and standard cut up to the point of interference with the vertical descent.

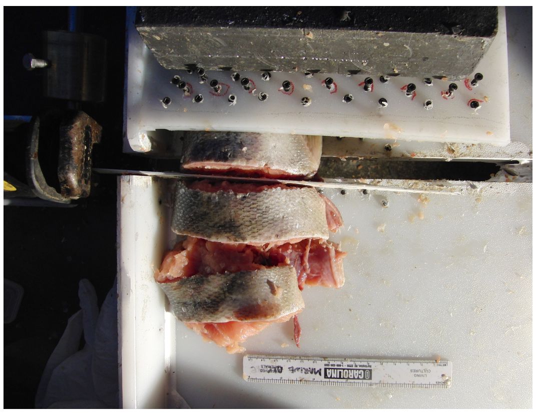


Figure 3: Interfered vertical descent by cutting board supporting substrate.

In four trials, a tooth broke during the cut (Fig. 4, Table 2). Time of tooth breakage within the cut was not identifiable.

Species	Blade	Breakage Trial	Broken Tooth	Total Teeth on Blade
C. falciformis	7	2	6	9
G. cuvier	8	1	7	10
G. cuvier	9	2	6	10
G. cuvier	16	1	4	10

Table 2: Broken teeth during trials. Tooth numbering starts with "1" most dorsally located on prey.

The ANOVA applied in R yielded an F-Value of 0.909 for first trial data by species. The ANOVA applied to all data by species yielded an F-Value of 2.829.

DISCUSSION

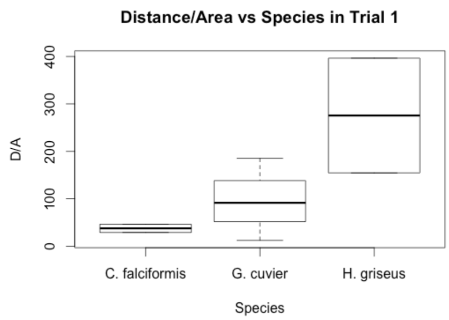
The primary performance metric used was Distance Traveled by Blade/Area of Prey (cm^{-1}). See Table 3 for application to data.

Species	Blade	Trial	Slices per Cut	Distance	Area (Prey)	D/A
C. falciformis	7	1	524	2994.66	64.5	46.43
C. falciformis	7	3	2889	16510.635	80.248	205.75
C. falciformis	7	4	4876.09091	27866.8596	132	211.11
C. falciformis	7	6	1085.53846	6203.85231	35.8	173.29
C. falciformis	5	1	253.555556	1449.07	49.67	29.1739481
C. falciformis	5	2	105	600.075	52.04	11.5310338
C. falciformis	5	4	5537.71429	31648.0371	47.26	669.658001
C. falciformis	5	5	2289.33333	13083.54	28.8	454.289583
H. griseus	13	1	1019.8	5828.157	14.7	396.47
H. griseus	13	2	331.25	1893.09375	88.68	21.35
H. griseus	13	5	487.333333	2785.11	57.28	48.6227305
H. griseus	13	6	166.625	952.261875	17.818	53.4438138
H. griseus	14	1	1394	7966.71	51.497	154.70241
H. griseus	14	2	1022.875	5845.73063	57.71	101.294934
H. griseus	14	3	338.666667	1935.48	34.877	55.4944519
H. griseus	14	4	1393.28571	7962.62786	56.414	141.146309
H. griseus	14	5	548	3131.82	27.139	115.399241
H. griseus	14	6	4444.72727	25401.6164	48.16	527.4422
H. griseus	15	2	288.7	1649.9205	62.114	26.5627797
H. griseus	15	3	189.818182	1084.81091	76.317	14.2145382
H. griseus	15	4	3161.1	18065.6865	50.92	354.785674
H. griseus	15	5	61.9090909	353.810455	42.89	8.24925285
G. cuvier	8	1	856.5	4894.8975	53.44	91.5961359
G. cuvier	8	2	553.5	3163.2525	32.3	97.9335139
G. cuvier	8	3	4743.875	27111.2456	63.991	423.672792
G. cuvier	8	4	489.333333	2796.54	53.204	52.5625893
G. cuvier	8	5	795.625	4546.99688	57.626	78.905301
G. cuvier	8	6	109.625	626.506875	39.28	15.9497677
G. cuvier	9	1	2194.66667	12542.52	67.67	185.35
G. cuvier	9	3	3630.18182	20746.4891	63.34	327.54
G. cuvier	9	4	388	2217.42	51.8	42.81
G. cuvier	9	5	1315.66667	7519.035	50.176	149.85
G. cuvier	9	6	114.25	652.93875	40.723	16.03
G. cuvier	16	1	105.272727	601.633636	48.63	12.3716561
G. cuvier	16	2	512.857143	2930.97857	54.58	53.7005968
G. cuvier	16	4	3520.9	20121.9435	57.04	352.768995
G. cuvier	16	5	113.545455	648.912273	33.93	19.1250301

Table 3: Basic data with D/A. Higher values imply more work to cut through the same area; lower values imply higher efficiency.

Given that the three teeth have such dramatically different tooth morphologies, it is not unexpected that a comparison between species would yield significantly different successes. However, upon running an ANOVA on the data Figure 5a, Distance/Area vs

Species in Trial 1, shows that the data is non-significantly different. The data in Figure 5b is also non statistically significant. Thus far, these data show that tooth morphology variation between species has not the primary role in any difference in sawing.



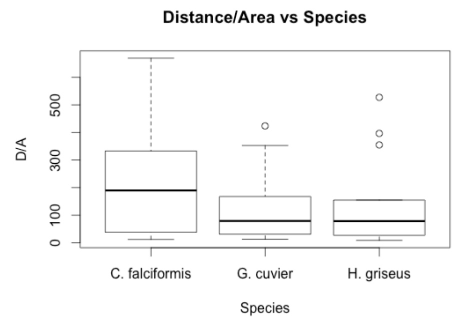


Figure 5a*,* D/A by species in the first trial. F=2.829

Figure 5b*,* D/A by species through all trials. F=0.909

Additional examination was done by trial per D/A for each of the three species. Little can be distinguished from Figure 6a, as this needs to be fleshed out with additional data. However, it is certainly worth noting that trials beyond Trial 2 with a particular blade have higher D/A values than the first two, which is as we expect.

Figure 6b shows very little evidence to support the hypothesis of single-use teeth, however. Perhaps this is indicative of a higher rate of feeding than of tooth replacment, as Figure 5c may show.

G. cuvier's voracious appetite is well documented (Randall 1992). Given that tooth replacement in *G. cuvier* could not possibly match this rate, their teeth must continue to be effective beyond the initial two uses. Under the small sample size available, this seems to be a reasonable assumption. (Figure 5c). Most fascinating is the spike at Trial 3 and collection at Trial 4. With more data, would that be a cyclical pattern or simply chance?

However, an important factor to recall when examining Figure 6c is the tendency for teeth to break on Trials 1 and 2. Yet the blade remains effective post loss of a tooth, contrary to my expectations.

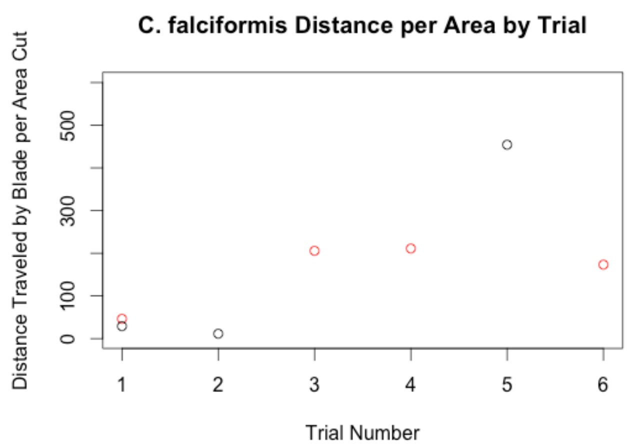


Figure 6a: *C. falciformis* D/A. At the very least, an increase in D/A required appears after the first two cuts.

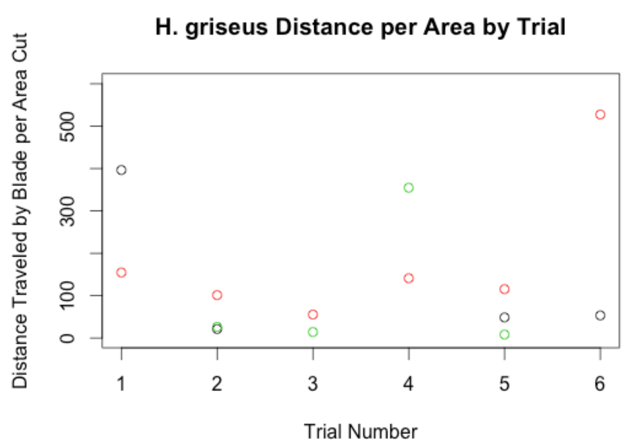


Figure 6b: *H. griseus* D/A. Worth investigating is whether teeth of *H. griseus* require minor wear to achieve maximum effectiveness.

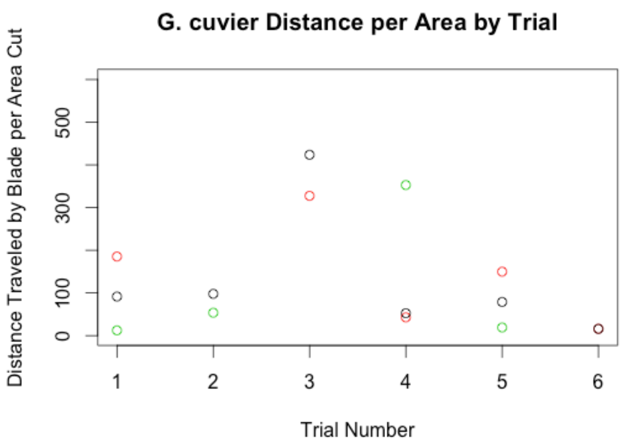


Figure 6c: *G. cuvier* D/A. Worth investigating further to clarify possible patterns of wear and effect on teeth.

Were this data significant, it would provide evidence for the ability to extrapolate feeding characteristics from tooth morphology and function.

When watching the sawing action it was difficult to avoid noticing the affect of the spine on the saw, as the saw often stalled visibly along the cut. However, some sharks may remove a bite in the feeding process (Motta and Huber, 2004) unlikely to intersect with the spine. In this the case, much of the difficulty and the risk of the bite are reduced. Future research on this should examine more closely the effect of the spine on the saw.

CONCLUSIONS

Little support is here for the hypothesis that tooth shape has significant impact on sawing efficiency in sharks. However, I am confident that the effect of tooth shape on sawing is greater than can be seen in this preliminary examination of tooth morphology and cutting. With further research, examining with more variety in tooth shape, biomimetic force on the blade, and increased substrate variety, a trend will appear.

These data were inconclusive or simply did not hold up my hypothesis regarding single or multiple uses of teeth. It is my expectation that these, too, will benefit from increased sample size. I anticipate a plateau from loss of efficiency from use of the same teeth to develop within the data.

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