A New Metric for Characterizing Swimming Kinematics in Elongate Fishes

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Introduction

Many species of elongate fishes use Anguilliform swimming to propel themselves through the water (Gillis 1996, Long 1998). A fish using this method passes a wave of motion from the head, through the body, to the tail causing thrust. This type of swimming is the only one in which the entire body is used as opposed to just the caudal end such as in Thunniform swimmers (Tytell 2010).

When watching certain species of elongate fishes swim, an interesting rotation in the body can be observed. If the fish is being looked at dorsally as it swims, there is a clear view of the lateral side of the fish as the tail beats back and forth. This view changes as the fish passes the wave from its head to its tail. The current work will describe a new method for measuring this rotation, or wobble, in the fish as it is swimming.

Methods and Materials

Animals used

Trials were run on five species of fish: *Apodichthys flavidus* (n=5), *Lycodes pacificus* (n=3), *Lumpenus sagitta* (n=5), *Xiphister mucosus* (n=3), and *Ptilichthys goodei* (n=5). The fish were caught off the coast of Washington in the area around the San Juan islands and brought back to Friday Harbor Labs. They were kept in sea tables fed by a flow through system which brings in water in from the East side of San Juan Island.

Video Recording and Animal Trials

Tank Setup: A 36” by 7”, 6” deep acrylic tank was constructed from ½” acrylic using marine grade epoxy and sealed with aquarium grade sealant. One end of the tank was the holding chamber (Figure 1). This chamber was 7” x 7” and was separated from the rest of the tank by a removable piece of acrylic. At the end of the tank opposite the holding chamber was the draining plug as well as two rocks and a small piece of 1” pvc pipe. The long sides of the tank were covered with black plastic to reduce the ability of the fish to see outside. For filming, the clear bottomed tank was placed over a white paper to maximize the contrast between the fish and the background. The camera used was a Casio Exilim EX-FH20. It was held over the center of the tank by a tripod (Figure 1). The video taken was high definition and recorded at 30 fps (frames per second).

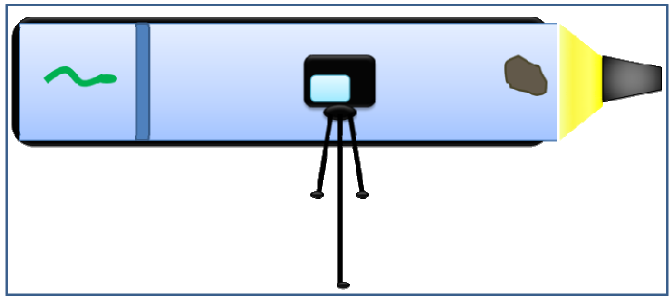


Figure 1: Schematic of described tank set-up.

Desired behavior: The fish were individually netted and placed in the holding chamber. They were allowed adequate time to settle and adjust to the new surroundings. Once ready, the piece of acrylic at the end of the holding tank was removed and the fish was allowed to swim in the direction of the rocks and PVC on the other end. If the fish was stressed, or would not swim across, it would be returned to its sea table and the rest would be repeated either later in the day, or the following day depending on when the first trial was run.

Once the fish completed a trial, they were sacrificed using a 0.5g/L MS 222 (Tricaine mesylate) solution. They sat in the MSv222 for 15 minutes before being removed for photographs. Once photos were taken, the fish were placed in individual bags in the freezer. The photos were uploaded to image-J to get basic meristic data (Table 1, Tables section).

Waveform Data

For each individual, several wave properties were measured (Table 2, Tables section). A single frame was chosen from each trail in which the fish was moving at a steady pace straight through the frame of the camera. Image-J was used to get the coordinates of several points along the fishes body from head to tail. These points were plotted in excel and a best fit line was applied. This like acted like the axis for the wave traveling down the fish's body (figure 2). With this, as well as speed data from each of the videos, maximum amplitude (a, mm), wavelength (λ, mm), period (p, s), wavespeed (C, mm/s), and tail beat frequency (f, hz). All measurements involving mm were also scaled to be in terms of standard length. Maximum amplitude was defined as the maximum distance of any point along the fishes body from the fit line. Wavelength was defined as the distance along the fit line it took to complete one wave cycle. For some fish, the body shape did not complete a full wave cycle in one frame. In this case, ½ wavelength was measured and doubled to get the full wavelength. Period was measured as the time it took to complete one wave cycle. This was measured in image-J by looking at the location of the tail as the fish would swim in a straight line. Tail beat frequency was defined as the inverse of period (1/p). Wave speed was computed using the equation $C = f*\lambda$ (Long 1998).

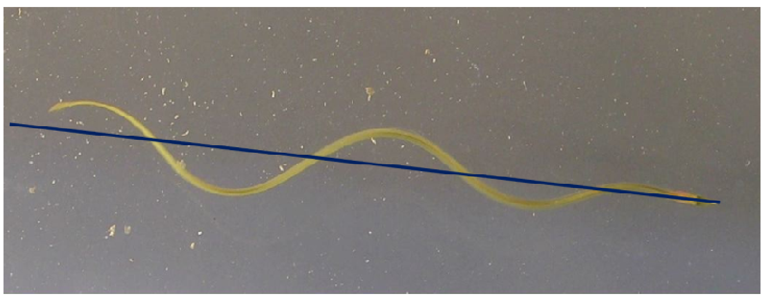


Figure 2: Example of applying a best fit line to one frame of a fish as it swims. This is P. goodei III.

Video Analysis

Videos and photographs were processed and analyzed using MATLAB R2013b. Original code was written for each step in the analysis. First the images and the video were translated into purely black and white images, essentially assigning each pixel a value of 0 or 1. For each individual, the user needs three files: an image of the dorsal view of the fish, an image file of the lateral view of the fish, and a high contrast video file taken from a dorsal view of the fish swimming at a consistent speed in a straight line. After both of the images were converted, another MATLAB script computed a midline down the length of the fish as well as the w (dorsal width) and h (lateral height) for each point along the midline. These points were plotted, and a MATLAB function, polyfit(), was used to get a 3rd degree polynomial equation for both the w and h values (figure 3). This equation was saved for use in calculating wobble later.

Figure 3: Fit lines

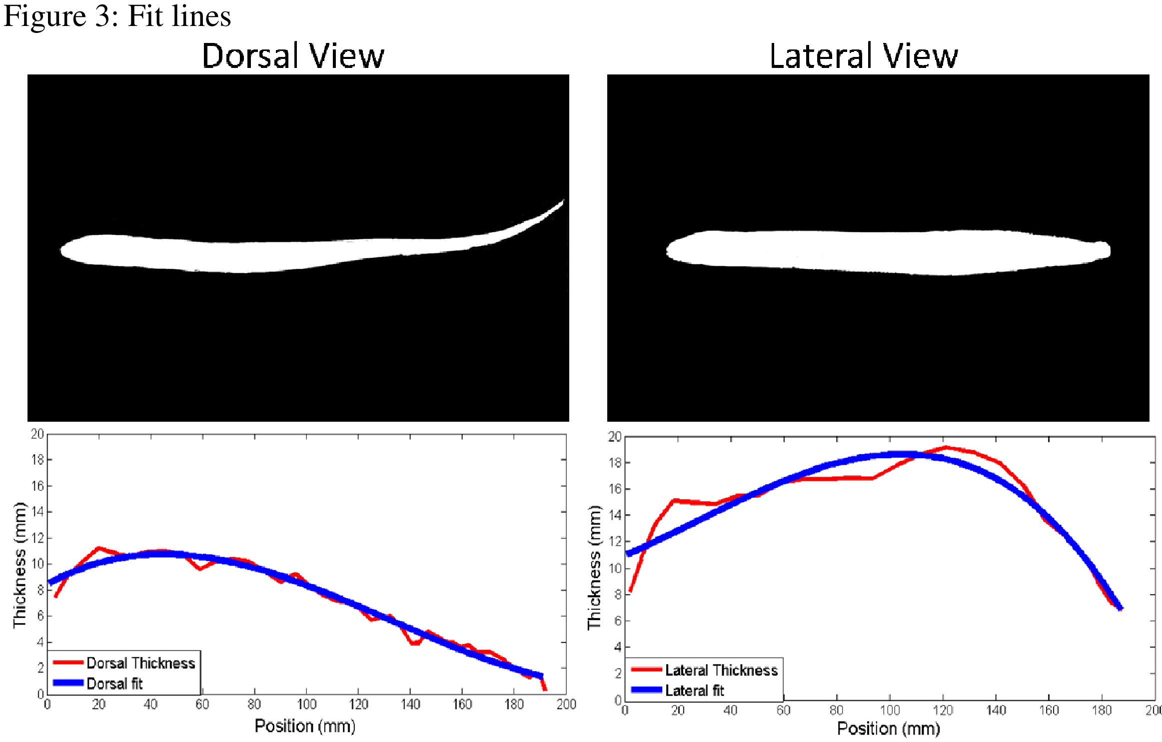


Figure 3: Fit lines computed with the MATLAB function polyfit(). The red lines are the thickness measured by the program and the blue likes are the fit lines.

The video file was broken up into .tif files (one .tif per frame of the video), and each file was converted to a black and white image. A midline was computed for each frame and the D values (the measured dorsal-lateral width) were computed for each point along each new midline. With the computed D, h, and w values, wobble could be calculated for each point along the length of the fish. The script plotted mean wobble and maximum wobble for each point along the fish's body.

Metric for Measuring Wobble

Wobble (W) was defined by the equation below:

$$W = \frac{(D - w)}{(h - D)(D - w)}$$

where W is wobble, D is the thickness of the fish at a particular point along the body while it is swimming, w is the dorsal width at that same point, and h is the lateral height at that point. When W = 0 (D = w), the fish is perfectly dorsal and when W = 1 (D = h), the fish is perfectly lateral.

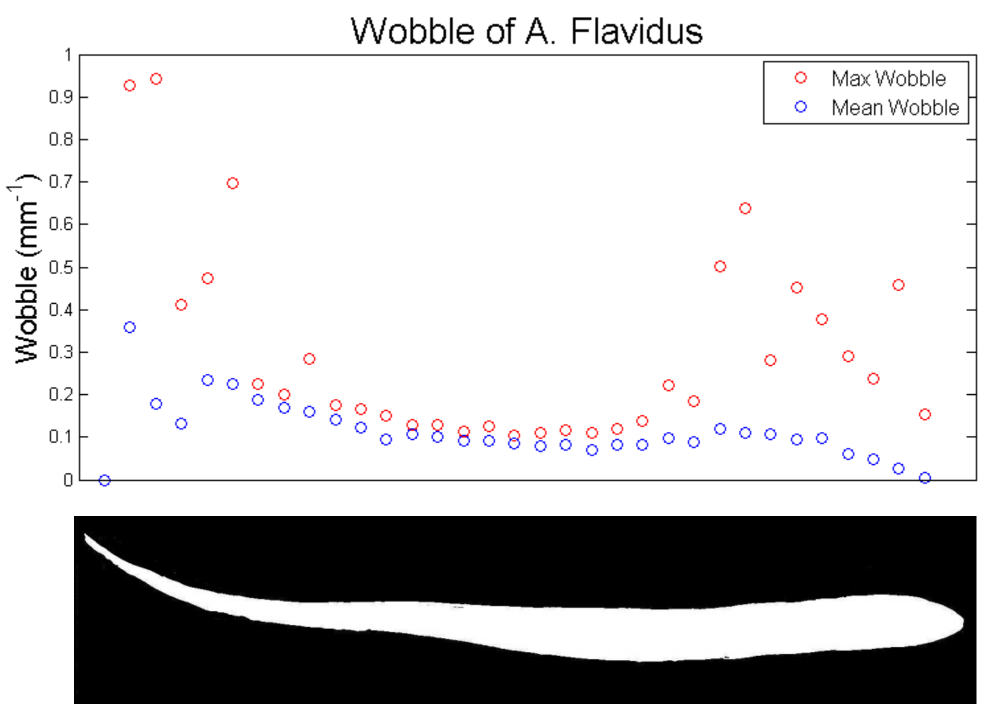
Discussion of results

The wobble software was used to analyze the swimming kinematics of five individuals, all of the same species (A. flavidus). The graphs produced (figure 4) were compared to the videos yielding interesting results. For example the graph of the wobble of A. flavidus IV showed a peak of wobble at the head end, very little wobble in the middle of the body, and a very high wobble at the tail end. When watching the video[1], it can be observed that the pectoral fins are visible near the head. The fins are not computed as a part of the original w (dorsal width) of the fish. As a result, when the program saw them and they were counted as a spike of wobble. Another interesting example is A.

flavidus V. The graph shows a wave-like pattern in the maximum wobble. The video clip[1] reveals a wave of wobble which begins at the head and travels to the tail.

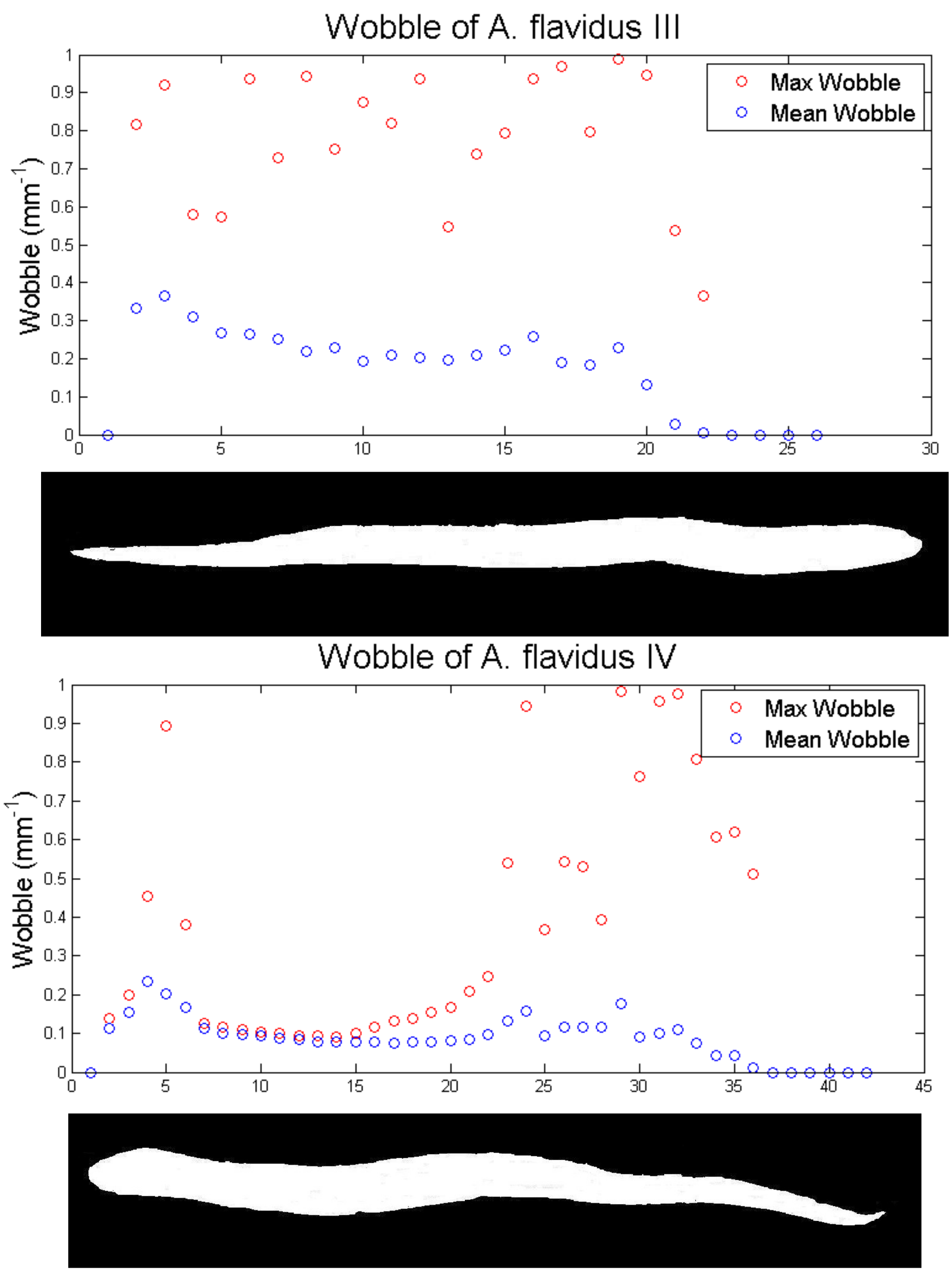
It should be noted that a high quality video is essential to making this code run. The fish needs to stand out from the background, and there can be no debris in the tank otherwise the program could accidentally measure that as part of the fish. This issue can be seen with A. flavidus III (figure 4). The wobble appears to be random. When the video is played, artifacts from debris and lighting can be seen skewing the outline of the fish.

Figure 4: Wobble of A. flavidus



[1] If .avi files of the video are desired for observation please feel free to contact the author at cassandra.donatelli@gmail.com or (207)-838-0021

Figure 4 continued.



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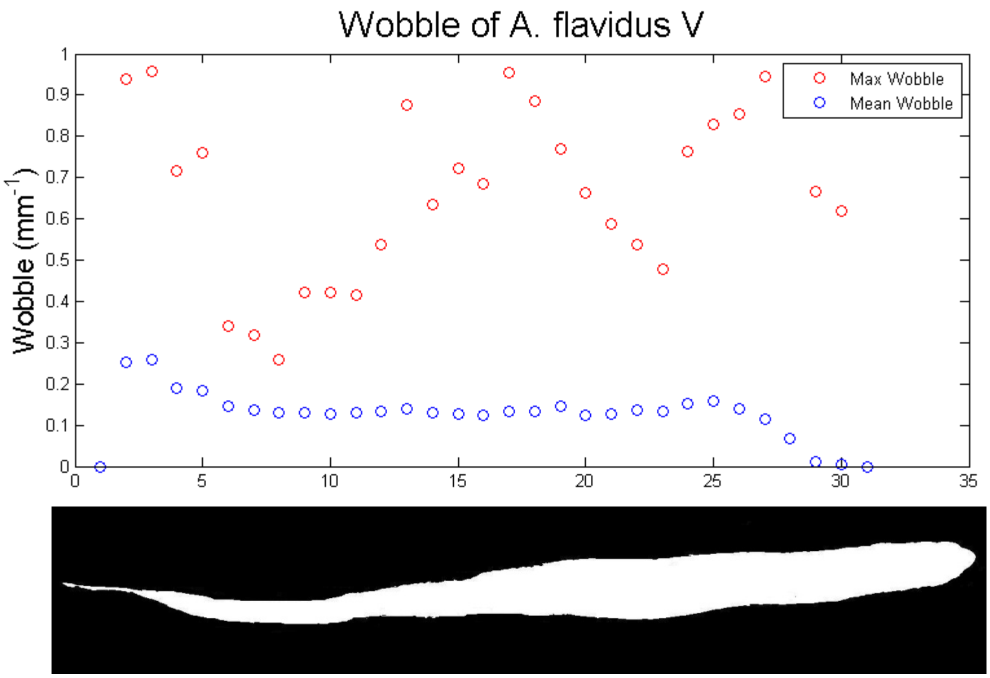

Figure 4: Wobble plots of A. flavidus I, III, IV, and V. II was omitted due to video processing errors. The x-axis is position on body (depicted by a black and white dorsal view of the fish) and the y-axis is wobble. The blue points are mean wobble (the mean of each value for wobble at one point across all framed of the video) and the red points are maximum wobble.

Applications of metric

With all of the waveform data collected, it would be interesting to see how wobble interacts with values such as speed and tail beat frequency. Hypothesis can be formed, based on observations, that wobble may decrease with speed and increase with amplitude. Also, the direction the fish is traveling could have an effect on the amount of wobble.

Another interesting project would be to look at the effect of fin shape on wobble. The fins on L. sagitta, for example, are much larger than the fins on A. flavidus. I would hypothesize that the larger the fin size, the less wobble there would be. This hypothesis is based on the fact that a greater fin size would lead to greater resistance to rotation as the fish pushes laterally through the water. A good way to test this would be to create models of fish with different fin shapes, actuate them with a servo motor, and record the motion as they actuate. The same software can be used to quantify wobble in the models, and these data could be compared to the data from live fishes.

This software is not limited to the study of elongate fishes. Once fully developed, it can be utilized to study swimming kinematics in any species of fish. The user would simply need to have video taken from the dorsal view of the fish in question, as well as pictures of the dorsal and lateral views. This new metric has many uses and the software will make collecting data on it quick and fairly simple.

Acknowledgements

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Tables

Table 1: Meristic data

	Standard Length	Head length	Head height	Max Body Height	Caudal-Peduncle width	Head Width	Max Body Width
A.flavidus 1	168	11.58	15.52	18.68	8.42	9	10.1
A.flavidus 2	235	12.22	16.67	29.63	11.17	13	17.5
A.flavidus 3	103	5.94	6.89	11.1	4.84	9.3	9.17
A.flavidus 4	197	9.49	13.24	23.51	11.08	10	13.1
A.flavidus 5	170	8.35	10.94	21.01	9.99	8.1	10.5
L.sagitta 1	183	23.34	12.01	15.67	6.67		
L.sagitta 2	123	22.33	9.78	11.67	4.88	7.2	8.65
L.sagitta 3	171	23.22	11.08	14.03	6.21	9.3	11.4
L.sagitta 4	174	25.16	11.85	16.05	6.36	8.8	12.4
L.sagitta 5	102	18.95	10.61	9.66	4.51	6.5	7.84
P.goodei 1	257	13.53	4.42	4.74	1.21	2.2	1.7
P.goodei 2	129	8.8	2.35	2.45		2.1	2.23
P.goodei 3	147	7.3	2.48	2.98	1.22	2.4	2.09
P.goodei 4	121	7.92	2.46	2.2	0.41	2	1.5
P.goodei 5	127	8.04	2.59	2.41	0.44	1.9	1.47
L.pacificus 1	96.1	20.59	12.08	12.64	1.13	10	7.46
L.pacificus 2	147	34.5	16.55	18.97	1.24	19	13
L.pacificus 3	171	36.85	17.7	24.38	2.29	21	17.3
X.atropurpureus 1	149	13.69	11.06	14.26	5.27	9.3	10.9
X.atropurpureus 2	150	13.57	10.34	14.57	6.11	9.6	11.2
X.atropurpureus 3	89.7	7.94	6.67	8.05	2.76	6	6.55

Table 1: Meristic data for individuals ran in trials. All measurements are in mm.

Table 2: Waveform Data

	v (SL/s)	λ (SL)	p (s)	f (hz)	C (SL/s)	a (SL)
A.flavadus 1	0.65	0.692924	0.566667	1.764706	1.222808	0.062719
A.flavadus 2	0.5	0.781976	1.3	0.769231	0.60152	0.086458
A.flavadus 3	0.51	0.964598	0.766667	1.304348	1.258171	0.120303
A.flavadus 4	0.69	1.195782	0.833333	1.2	1.434939	0.127976
A.flavadus 5	0.49	1.237608	0.766667	1.304348	1.614271	0.138926
L.sagitta 1	--	--	--	--	--	--
L.sagitta 2	1.83	1.005767	0.766667	1.304348	1.31187	0.096072
L.sagitta 3	0.97	0.842965	0.4	2.5	2.107412	0.047816
L.sagitta 4	0.65	0.575378	0.533333	1.875	1.078833	0.033292
L.sagitta 5	0.58	1.135407	0.4	2.5	2.838517	0.049578
P.goodei 1	0.315552	0.244489	0.333333	3	0.733466	0.029502
P.goodei 2	1.22449	0.447151	0.433333	2.307692	1.031888	0.067363
P.goodei 3	0.682268	0.472005	0.7	1.428571	0.674293	0.069258
P.goodei 4	0.330415	0.51173	0.866667	1.153846	0.590457	0.103571
P.goodei 5	0.550607	0.382448	0.466667	2.142857	0.819532	0.060294
L.pacifacus 1	0.88	1.011455	0.366667	2.727273	2.758513	0.058435
L.pacifacus 2	1.23	0.988183	0.266667	3.75	3.705685	0.075044
L.pacifacus 3	0.35	0.770533	0.266667	3.75	2.889499	0.081588
X.atropurpureus 1	0.346199	1.055766	0.566667	1.764706	1.863116	0.054636
X.atropurpureus 2	0.721247	0.806912	0.866667	1.153846	0.931052	0.112769
X.atropurpureus 3	0.266555	1.11592	0.3	3.333333	3.719732	0.060643

Table 2: Wave form data for each individual where v is velocity (standard lengths / second), λ is wavelength (standard lengths), p is period (seconds), f is frequency (hertz), C is wave speed (standard lengths / second) , and a is amplitude (standard lengths).

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