Kinematics of linear accelerations in fishes

Running title: Swimming acceleration kinematics

Kara L. Feilich, Valentina di Santo, and George V. Lauder

Harvard University, Dept. of Organismic and Evolutionary Biology, 26 Oxford Street,

Cambridge, MA 02138 USA

Author for correspondence, email: [kfeilich@gmail.com](mailto:kfeilich@gmail.com)

Key words:

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**Acknowledgements**

**Competing Interests**

The authors declare no competing interests.

**Author Contributions**

G.V.L. and V.D.S. collected fish swimming trial videos. K.L.F. digitized the video, designed and wrote programs for all analyses, ran all analyses, and wrote the first draft of the manuscript.

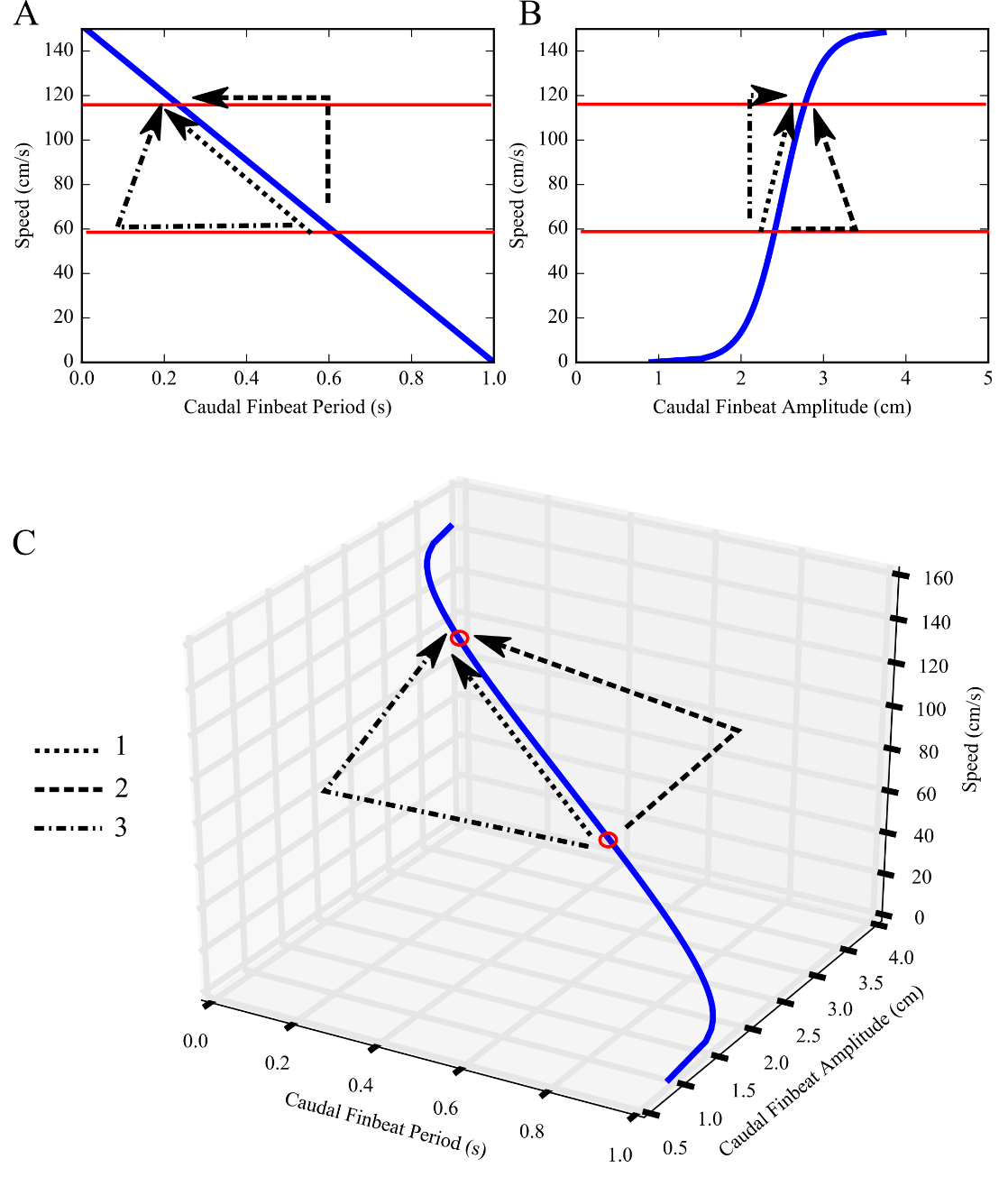
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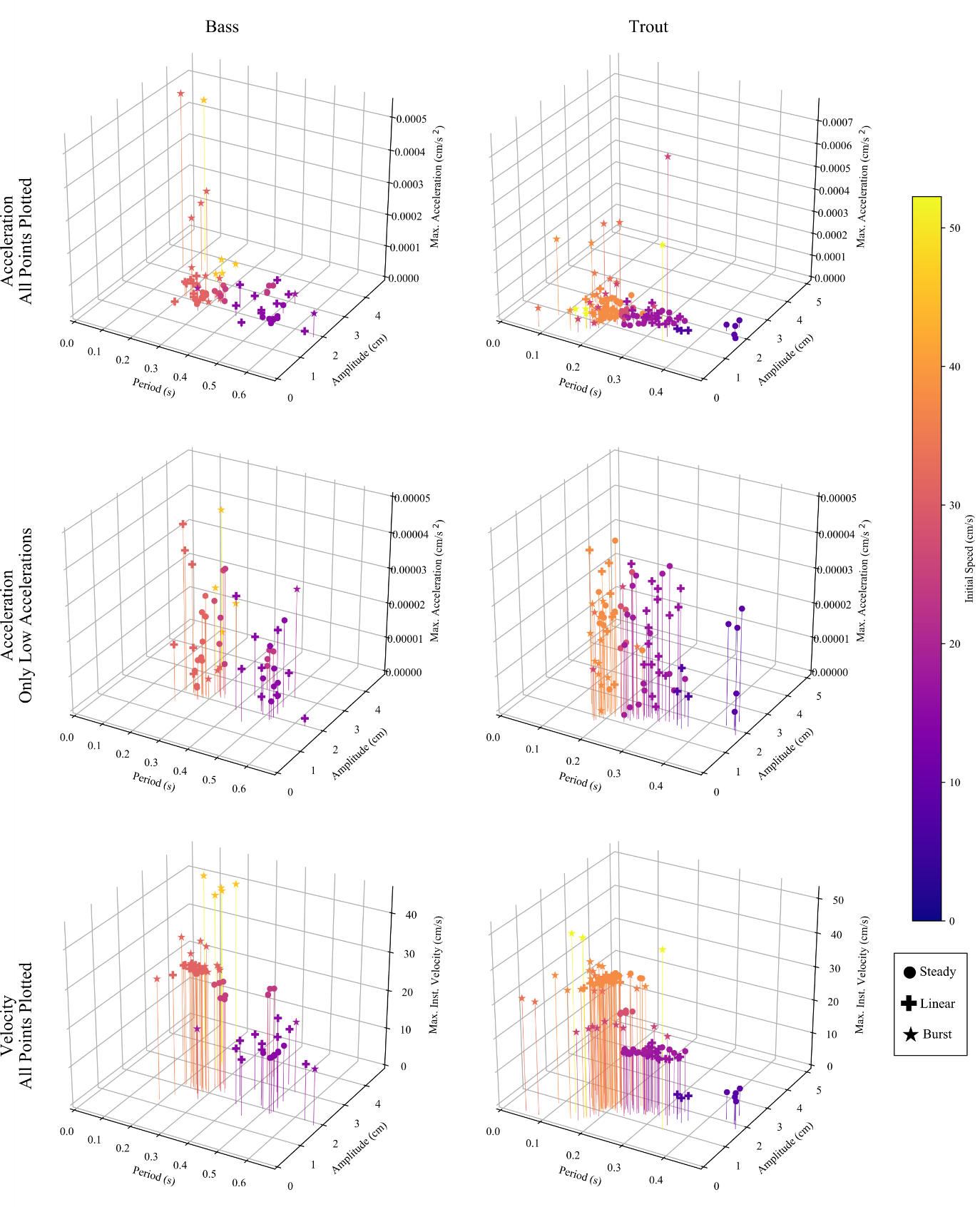
**References**

**Feilich, K. L.** (2017).

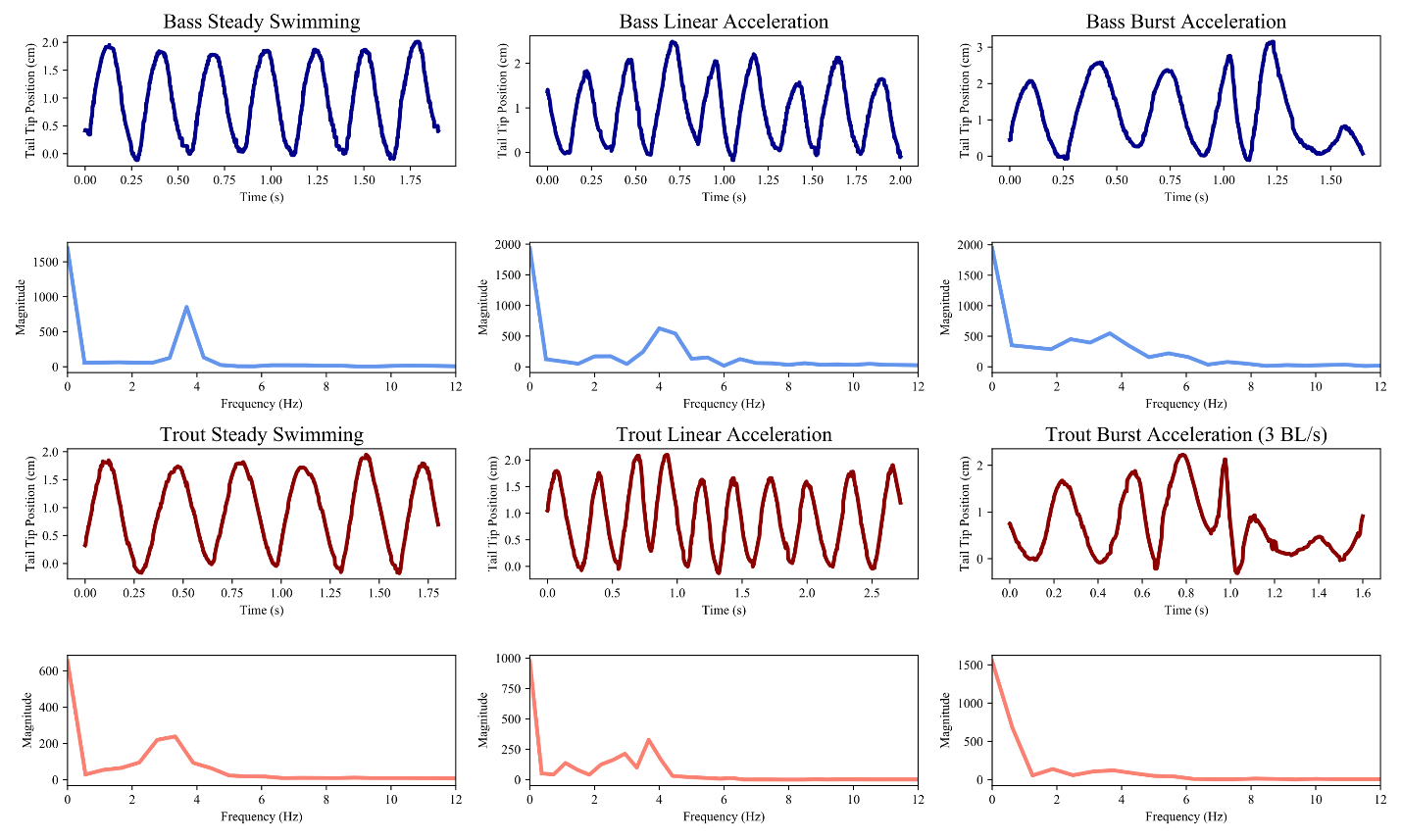
**Figures and Tables**

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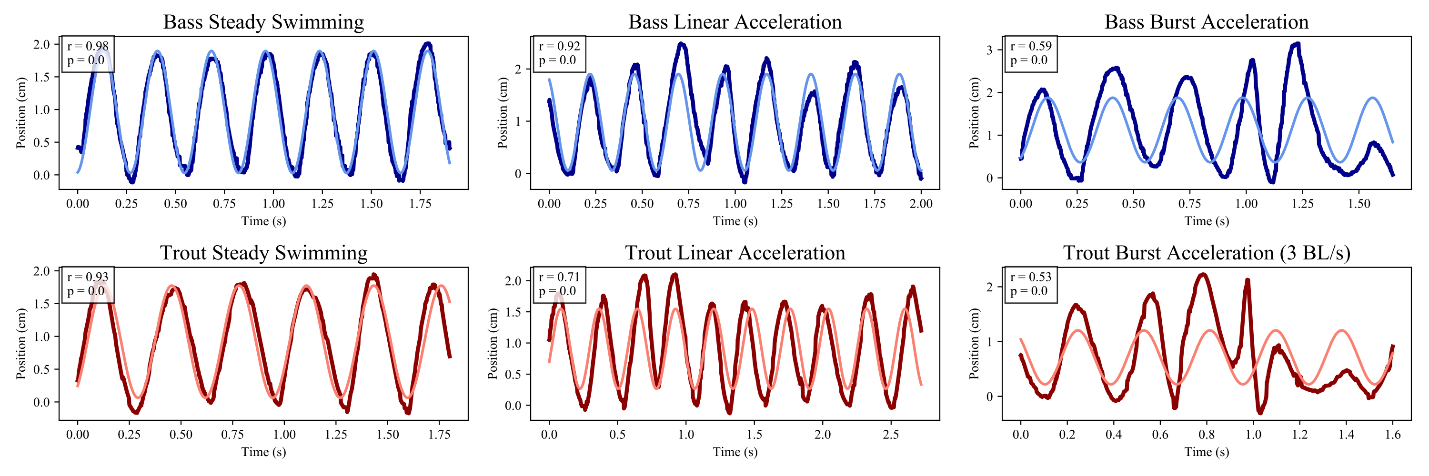
**Figure 1. Schematic diagram with simulated data showing multiple kinematic pathways to accelerate to the same final speed, assuming caudal fin propulsion only**. A. Relationship between steady swimming speed and caudal finbeat period. B. The relationship between steady swimming speed and caudal finbeat amplitude. C. A three-dimensional representation of a caudal steady swimming gait trajectory. Paths 1, 2, and 3, are a few of infinitely many different kinematic possibilities for accelerating between the two speeds highlighted in red. Path 1 represents a gradual kinematic transition where acceleration kinematics mirror the kinematics used during steady locomotion at the intermediate speeds. Path 2 represents acceleration by keeping period constant, jumping to a larger caudal fin beat amplitude to speed up, before decreasing amplitude slightly to settle in to the new steady swimming speed. Path 3 represents acceleration by keeping finbeat amplitude constant, jumping to a shorter fin beat period to accelerate, before increasing period slightly to settle into the new steady swimming speed. Data are simulated such that finbeat period has an inverse linear relationship with swimming speed, and amplitude has a sigmoidal relationship with speed. These hypothesized relationships are in keeping with the experimental observations that speed varies linearly with finbeat frequency (i.e. 1/period), and amplitude is mostly invariant with speed.



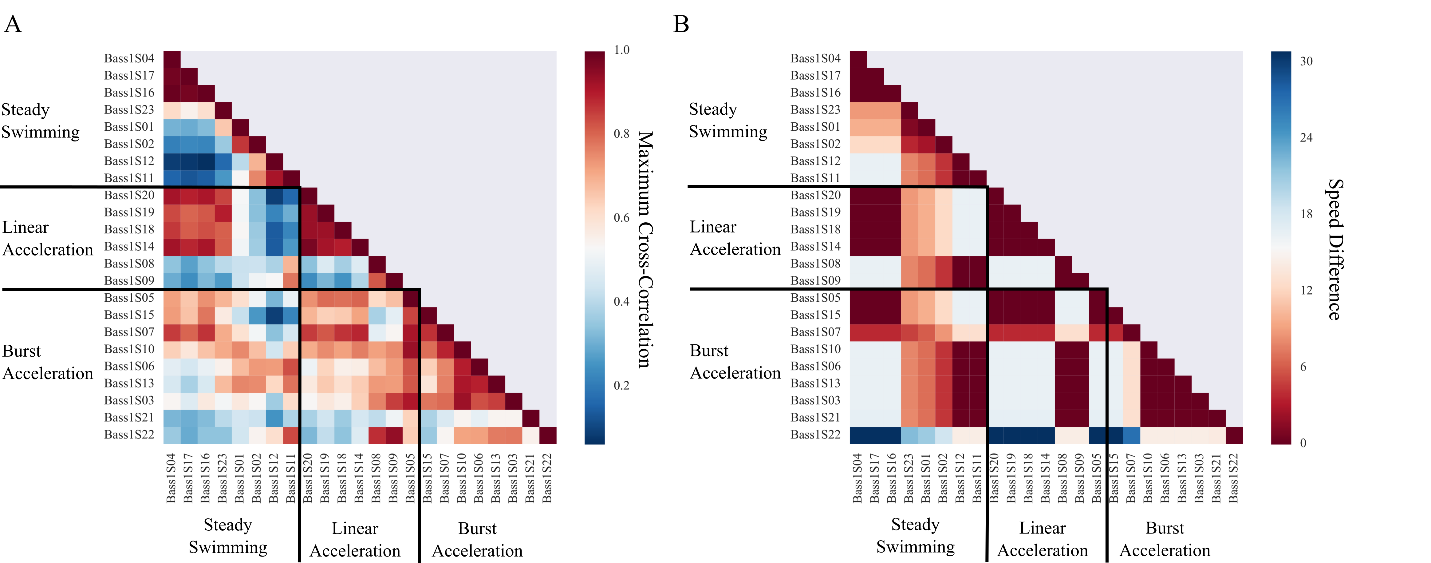
**Figure 2. Observed caudal finbeat kinematics for steady swimming, linear accelerations, and burst accelerations as encoded by the observer.** Left Column: Largemouth Bass (n=1, SL =15 cm, n\_trials = 23), Right Column: Rainbow Trout (n = 2; SL = 9 cm, 8.5 cm, 8 cm; n\_trials = 21). Top: All finbeats against maximum instantaneous acceleration. Middle: Finbeats with maximum instantaneous accelerations < 5x10-4 cm/s2, to show variation. Bottom: Finbeats against maximum instantaneous velocity. (Circles: steady swimming trials, +: linear acceleration trials, Star: burst acceleration trials. Points are colored by initial speed of trial.)



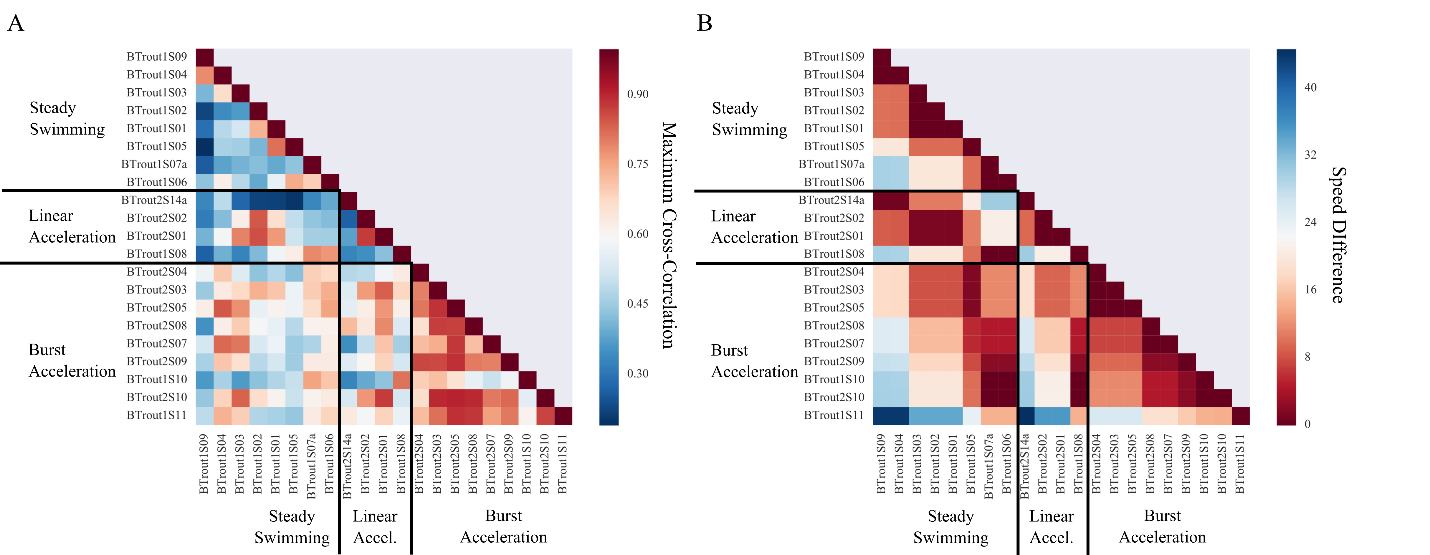
**Figure 3. Representative traces of de-trended tail tip motion during three swimming behaviors with initial speeds of 2 BL/s, and the FFTs of those traces.** Blue: Largemouth Bass (SL = 15 cm), Red: Rainbow Trout (mean SL = 8.75 cm). Top row of each species shows tail tip position in the axis perpendicular to the direction of swimming, with background trend removed. Bottom row for each species shows the FFT of the tail tip trace immediately above. The burst acceleration trace for trout is from a trial at a speed of 3 BL/s, as we were unable to elicit burst accelerations below this speed.



**Figure 4. Representative traces of de-trended tail tip motion during three swimming behaviors with initial speeds of 2 BL/s, and the best fit sine-waves for those traces.** Blue: Largemouth Bass (SL = 15 cm), Red: Rainbow Trout (mean SL = 8.75 cm). The dark curve is the detrended raw data for that trial (as in Figure 3), and the light curve is the sine wave fitted to that trial using least squares optimization. The correlation coefficient between the detrended raw position data and the best fit sine wave is shown in the top left corner of each plot, with its associated p-value. The burst acceleration trace for trout is from a trial at a speed of 3 BL/s, as we were unable to elicit burst accelerations below this speed.



**Figure 5. Heat-map showing maximum normalized pairwise cross-correlations between the Fourier transforms of detrended tailbeat motions for all bass trials, and pairwise initial speed differences between trials.** For each pairwise comparison, the detrended raw tail-tip position data (as shown in Figure 3) for the shorter length of the two trials was padded on either end with its mean value to equal the length of the longer trial before Fourier transform convolution. This made the lengths of the two Fourier transforms suitable for the purposes of cross-correlation. A: Maximum cross-correlations of FFTs. B: Pairwise speed differences between trials. The correspondence between A and B indicates that swimming speed is a major factor driving the shape of the finbeat frequency distribution.



**Figure 6. Heat-map showing maximum normalized pairwise cross-correlations between the Fourier transforms of detrended tailbeat motions for all trout trials and pairwise initial speed differences between trials.** For each pairwise comparison, the detrended raw tail-tip position data (as shown in Figure 3) for the shorter length of the two trials was padded on either end with its mean value to equal the length of the longer trial before Fourier transform convolution. This made the lengths of the two Fourier transforms suitable for the purposes of cross-correlation. A: Maximum cross-correlations of FFTs. B: Pairwise speed differences between trials. The correspondence between A and B indicates that swimming speed is a major factor driving the shape of the finbeat frequency distribution.

**Table 1. Pearson’s correlation coefficients and associated p-values for each trial when correlated with its best fit sine wave, grouped by speed and behavior.**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bass** | | | | | | | | |
| **Steady Swimming** | | | **Linear Acceleration** | | | **Burst Acceleration** | | |
| **Trial** | **Initial Speed** | **r** | **Trial** | **Initial Speed** | **r** | **Trial** | **Initial Speed** | **r** |
| Bass1S04 | 14.7 | 0.91 | Bass1S19 | 14.7 | 0.94 | Bass1S05 | 14.7 | - |
| Bass1S16 | 14.7 | 0.93 | Bass1S20 | 14.7 | 0.88 | Bass1S15 | 14.7 | 0.82 |
| Bass1S17 | 14.7 | 0.98 | Bass1S14 | 14.7 | 0.85 | Bass1S07 | 18.5 | 0.60 |
| Bass1S23 | 23.5 | 0.98 | Bass1S18 | 14.7 | 0.69 | Bass1S03 | 31.4 | 0.49 |
| Bass1S01 | 24.6 | 0.96 | Bass1S08 | 31.4 | 0.92 | Bass1S06 | 31.4 | 0.70 |
| Bass1S02 | 27.1 | 0.99 | Bass1S09 | 31.4 | 0.77 | Bass1S10 | 31.4 | 0.32 |
| Bass1S11 | 31.4 | 0.98 |  |  |  | Bass1S13 | 31.4 | 0.59 |
| Bass1S12 | 31.4 | 0.99 |  |  |  | Bass1S21 | 31.5 | 0.65 |
|  |  |  |  |  |  | Bass1S22 | 45.6 | 0.74 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Trout** | | | | | | | | |
| **Steady Swimming** | | | **Linear Acceleration** | | | **Burst Acceleration** | | |
| **Trial** | **Initial Speed** | **r** | **Trial** | **Initial Speed** | **r** | **Trial** | **Initial Speed** | **r** |
| BTrout1S09 | 8.2 | 0.99 | BTrout2S14 | 7.5 | 0.97 | BTrout2S03 | 26.3 | 0.53 |
| BTrout1S04 | 8.37 | 0.97 | BTrout2S02 | 17.0 | 0.84 | BTrout2S04 | 26.3 | 0.33 |
| BTrout1S01 | 18.2 | 0.91 | BTrout2S01 | 17.0 | 0.71 | BTrout2S05 | 26.3 | - |
| BTrout1S02 | 18.2 | 0.97 | BTrout1S08 | 37.9 | 0.78 | BTrout2S07 | 33.5 | 0.37 |
| BTrout1S03 | 18.2 | 0.93 |  |  |  | BTrout2S08 | 33.5 | 0.49 |
| BTrout1S05 | 28.0 | 0.97 |  |  |  | BTrout2S09 | 35.7 | 0.49 |
| BTrout1S06 | 37.9 | 0.84 |  |  |  | BTrout1S10 | 37.9 | 0.80 |
| BTrout1S07 | 37.9 | 0.83 |  |  |  | BTrout2S10 | 38.0 | 0.50 |
|  |  |  |  |  |  | BTrout1S11 | 52.2 | 0.26 |