Bluegill Sunfish Kinematics: How Gaits Affect Swimming Efficiency

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Locomotion is vital to the survival and fitness of animals and dominates daily energy budgets. The main energy consuming process of locomotion is the muscle activity needed to maintain stability or generate propulsive forces. In fish, the speed of swimming is thought to depend on the gait type, which may reflect an energetically efficient locomotory behavior. Bluegill Sunfish (Lepomis macrochirus) exhibit either steady or intermittent (burst-coast) gaits when swimming in the field, but whether these gaits differ in their energetic efficiency is unknown. We analyzed the electromyography (EMG) of oxidative muscle in Bluegill swimming at low velocities to determine if steady swimming is more or less energetically efficient than intermittent swimming. EMG data were acquired using bipolar fine wire electrodes implanted into oxidative musculature at 2/3 tail length. Steady swimming EMGs were recorded in a flume (fish treadmill) at incrementally increasing speeds relative to body length, until nonoxidative muscle was recruited. As speed increased, EMG intensity increased, which corresponds to increased muscle recruitment. Fish reached maximum EMG intensity (100% oxidative muscle capacity) between 1.75 - 2.25 BL/s. Intermittent swimming EMGs were recorded while the fish swam volitionally in a pool. The burst phase consisted of 2-3 tailbeats, followed by a coast phase duration of 1 second or less. Based on preliminary results, fish in the pool swam at an average of 62.1% (n = 10) of their maximum oxidative capacity. When intermittently swimming, muscle activity was 37.9% more efficient than steady swimming at similar speeds. This demonstrates that when swimming volitionally Bluegill choose the most energetically effective gait. However, further analysis is needed to determine how individual variation affects swimming performance. Continued comparison of these methods of locomotion will broaden the understanding of energy decisions that fish make. These results suggest that intermittent swimming is the more energetically efficient form of aquatic locomotion. This work is supported by NSF grant award number 2135851.

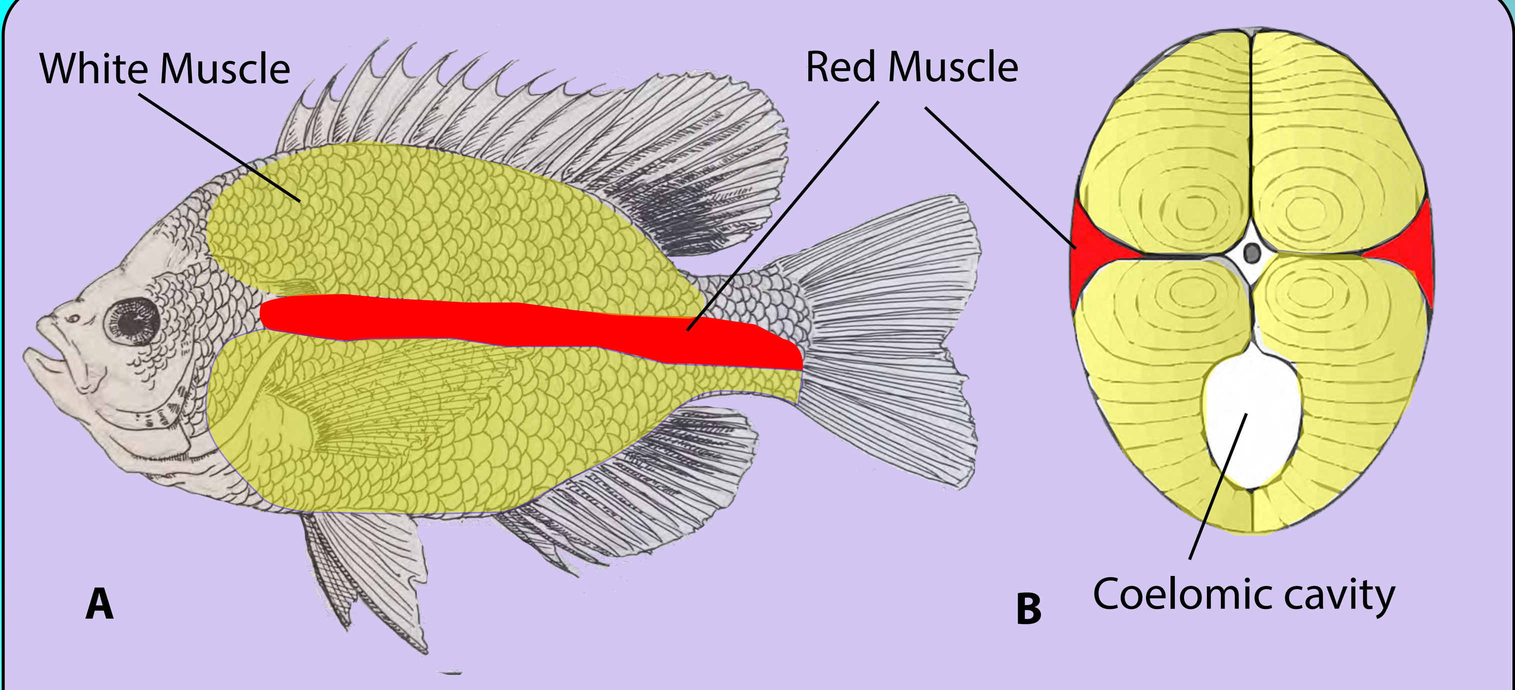

Figure 1: (**A-B**) A thin band of red muscle (oxidative) lies superficially along the mid lateral line, where the mechanical advantage is highest, and is used for prolonged swimming. White muscle (glycolytic) encompasses the rest of the body and is used for power.

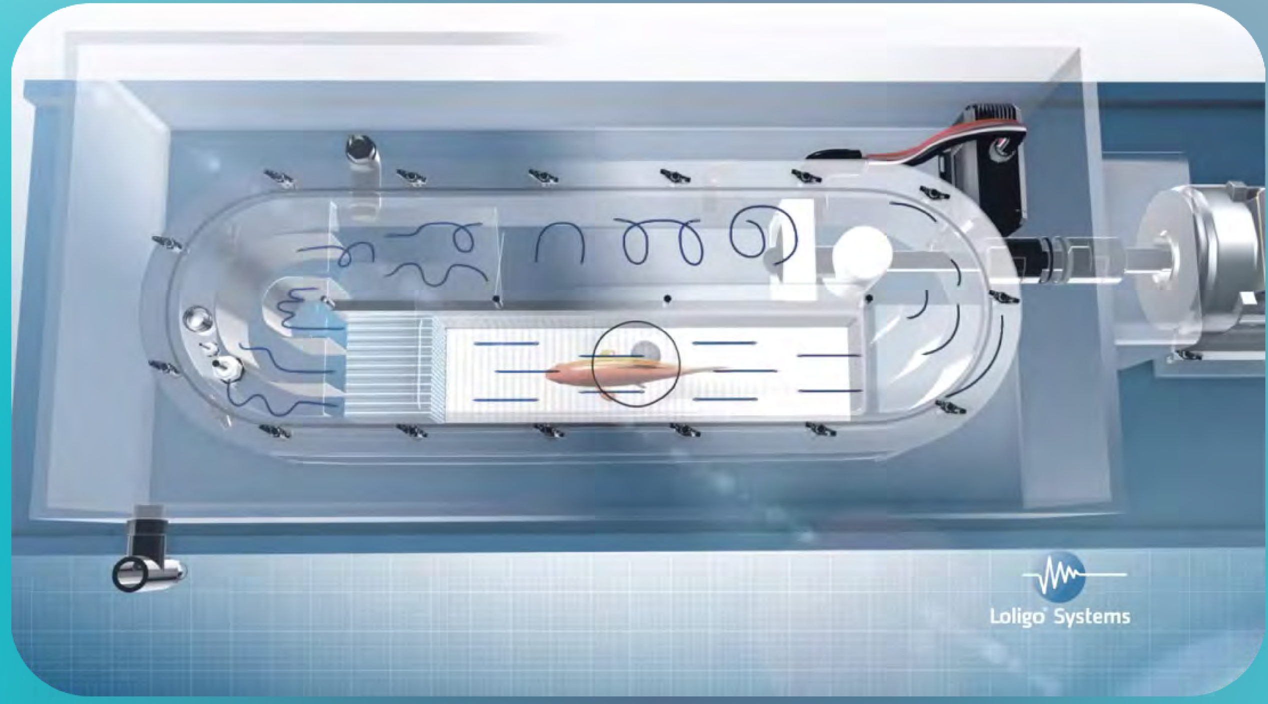

Figure 3: The flume produces laminar flow in the swimming chamber when the turbine pushes water through flow straighteners at a steady speed. Speeds can be precisely controlled relative to the fish's body length.

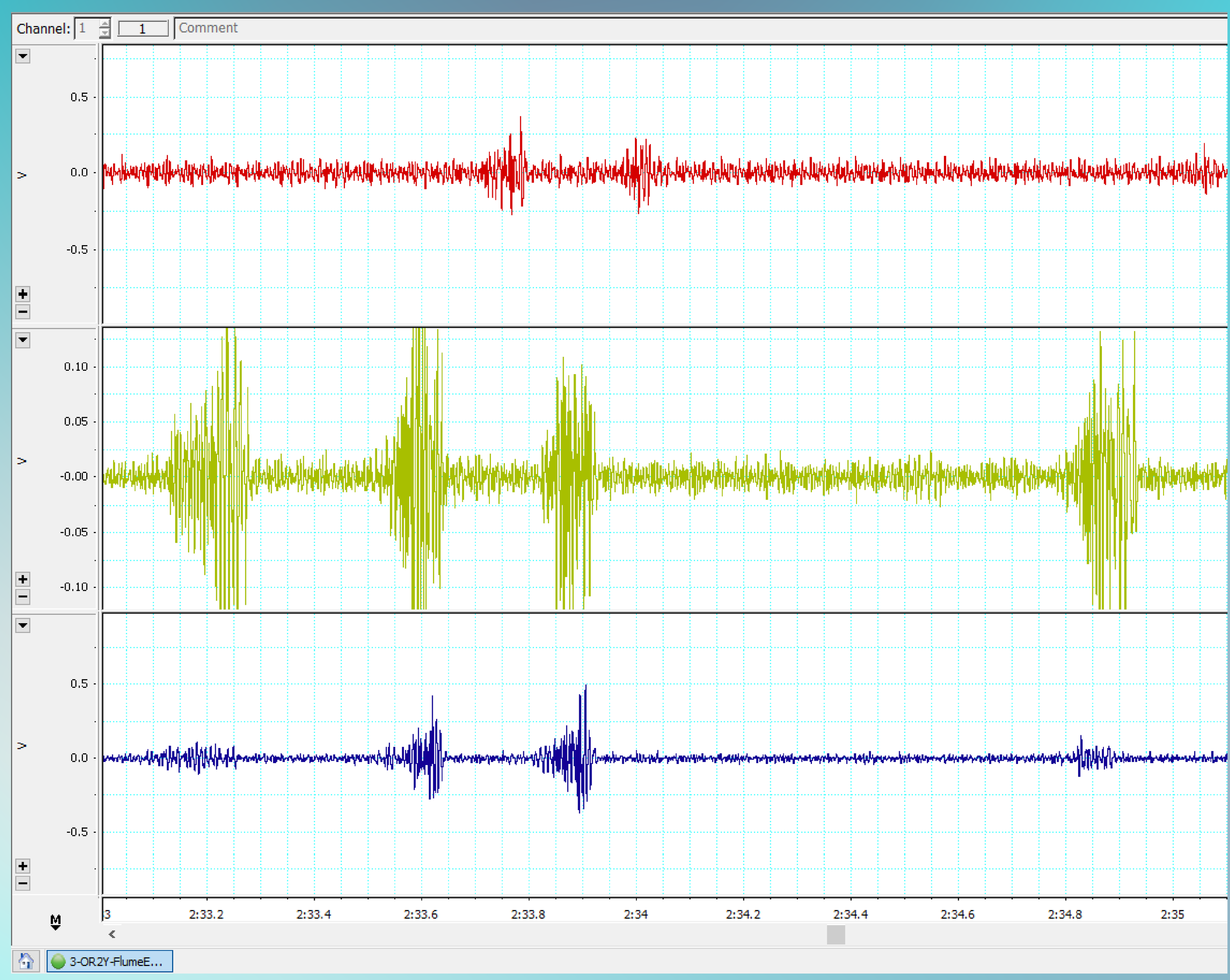

Figure 4: EMGs were recorded by using Labchart version 7. Red corresponds to the red muscle on the right side, yellow to the red muscle on the left side, and blue to the white muscle on the left side.

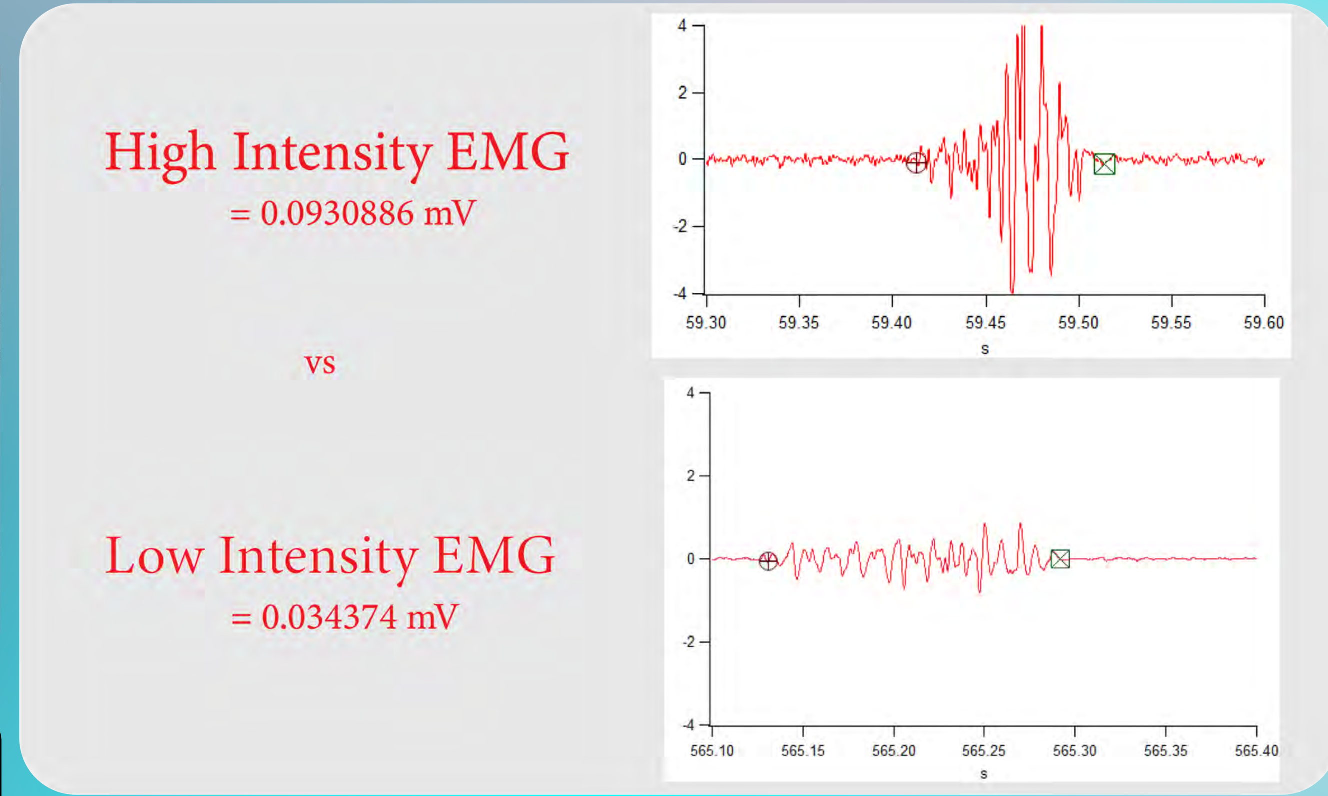

Figure 5: Electromyography (EMG), which measures electrical activity in response to a nerve's stimulation of the muscle, was quantified with a customized macro in IGOR Pro version 8.04. EMG intensity is directly related to how much muscle is activated.

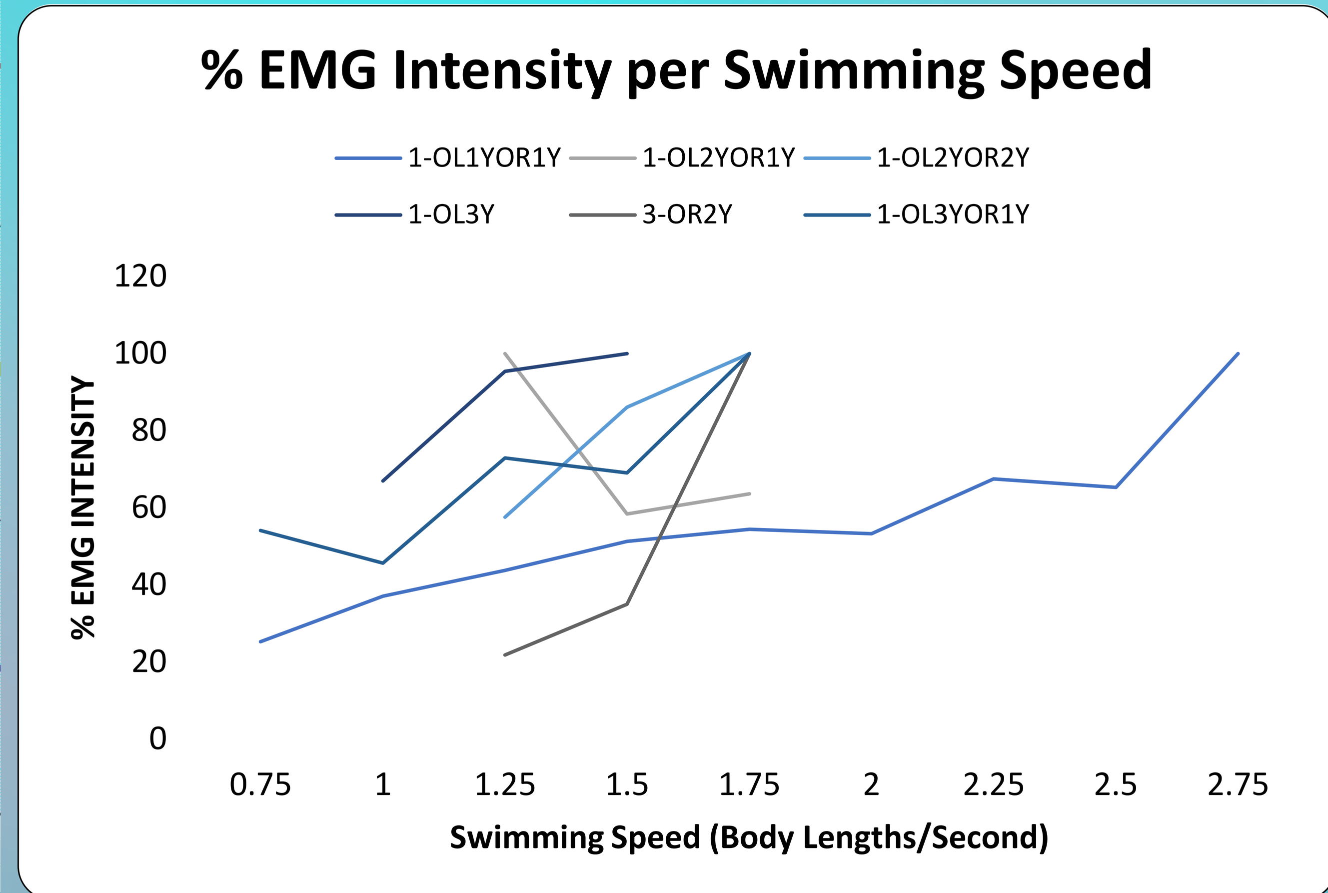

Figure 6: For most fish, percent EMG intensity increased in response to increased swimming speed. This suggests that fish are recruiting additional motor units at higher speeds.

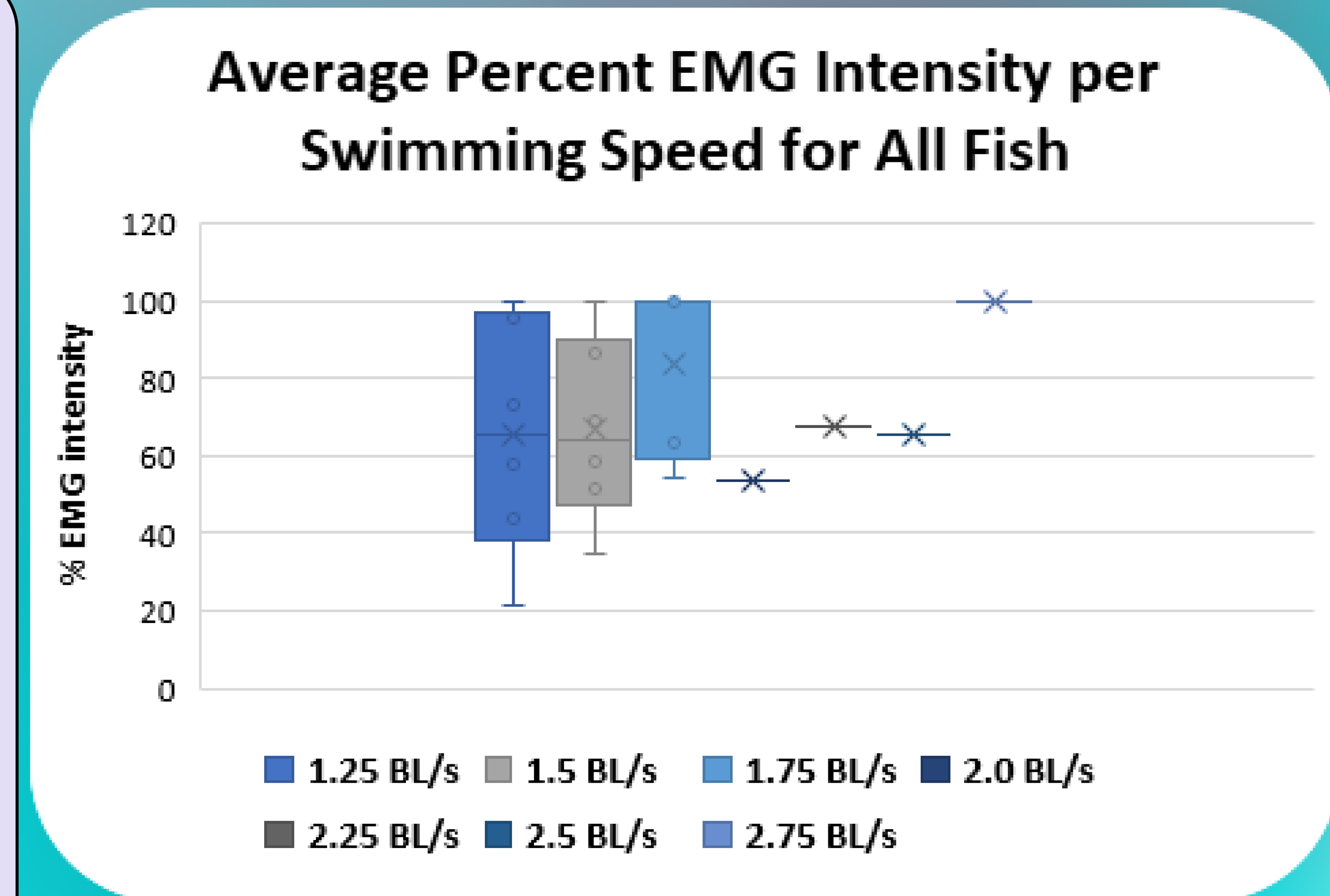

Figure 7: Total percent EMG intensity relative to the maximum oxidative capacity, showing that as speed increases fish use more of their muscle capacity to swim. As fish are forced to increase speed, their percent EMG intensity approaches maximum.

Figure 8: Steady swimming is characterized by continuous tail beats that produce rhythmic EMGs. Red fish represents maximum curvature, which occurs immediately after muscle activation.

Figure 9: Intermittent swimming (burst-coast) is characterized by several rapid tail beats followed by a gliding phase sans tail beats. The red fish represents maximum curvature (burst phase), whereas the blue fish represents no muscle recruitment (coast phase).

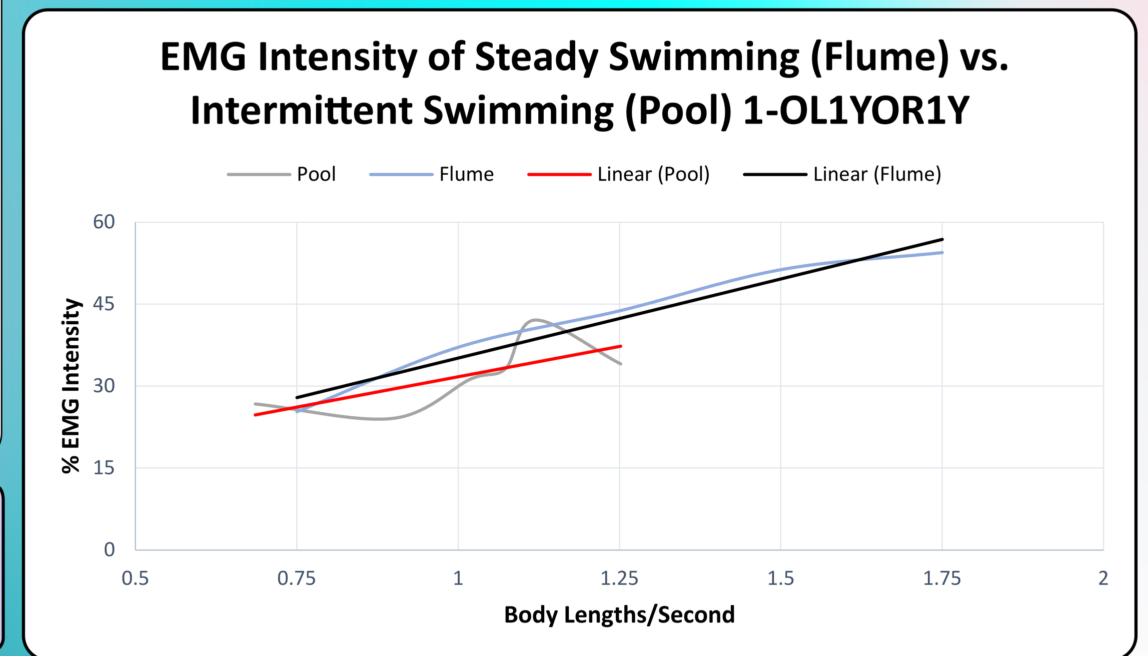

Figure 10: Percent EMG intensity for a single fish when swimming in the flume and the pool. When relativized to the same speed, percent EMG intensity when intermittently swimming (pool trend line) is lower than when steady swimming. Therefore, intermittent swimming is a more efficient gait than steady swimming.

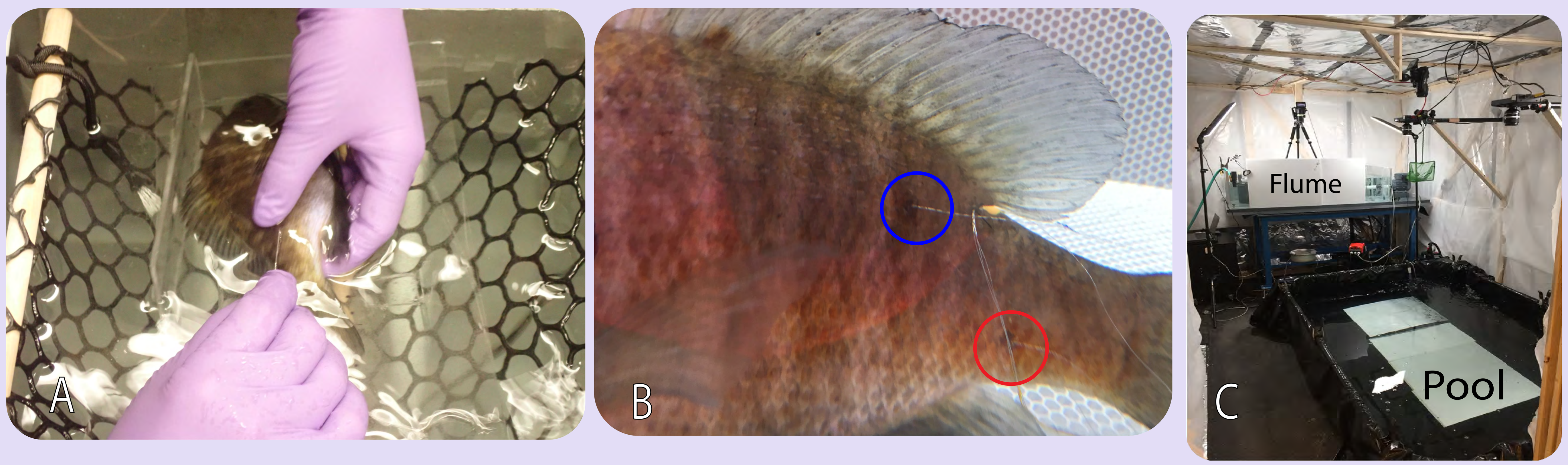

Figure 2: Electromyography (EMG) experiments were performed on fish captured from Lake Waban, Massachusetts. (**A**) Fish were sedated by using electronarcosis to enable implantation of 3 pairs of electrodes. (**B**) 2 pairs of electrodes were implanted contralaterally in the red muscle (red circle), and 1 pair of electrode were implanted in the white muscle, on the left side (blue circle). (**C**) For each experiment, EMGs were recorded while fish were filmed swimming steadily in the flume with current speed starting at 0.5 Body Lengths per second (BL/s), increasing 0.25 BL/s every 15 minutes, until reaching thier maximum oxidative capacity. Fish were then placed in the pool and allowed to swim freely while EMGs were recorded and the fish were filmed.

Conclusions

- Burst coast swimming is more efficient than steady swimming
- These results will be used in *in vitro* muscle mechanics experiments (i.e., work loop experiments), to determine the impact of intermittent muscle activation on power production.
- These data could be extrapolated to other aquatic vertebrates that use unique gaits to locomote at different speeds.