STUDY OF PROPULSION MECHANISMS IN LEECH ANGUILLIFORM SWIMMING

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INTRODUCTION

The swimming gait of the leech is anguilliform, with rearward traveling waves that propel the animal forward. We analyze this motion with a simple fluid model that combines Taylor's resistive and Lighthill's reactive forces, and fix the drag coefficients by fitting model predictions to trajectory data derived from video recordings. The fluid force on the body, the power supply from the muscle, and its dissipation to the fluid are predicted by the model. Thrust generation and power transmission mechanisms along the body of swimming leeches are investigated. The model for body-fluid interactions developed in this study will be an essential element of our integrated model for anguilliform swimming, comprising the central pattern generator (CPG), muscle activation dynamics, body-fluid interactions, and sensory feedback.

METHODS

The leech body is modeled by a chain of eighteen rigid links on a plane, subject to fluid forces and joint torques generated by muscle contractions. We adopted the equations of motion developed in [3] with a modification on the description of the environmental (fluid) force. Our simple fluid model combines Taylor's resistive force [1] and Lighthill's reactive force [2], and is given, for each link, by

$$\begin{aligned} \gamma_t &= c_t\left(5.4l\sqrt{\rho\mu d|v_n|}v_t\right) \\ \gamma_n &= \text{sign}(v_n)c_p\rho d l v_n^2 + c_a\rho\pi d^2 l a_n/2 \end{aligned} \qquad (1)$$

where γ_t and γ_n are the fluid forces in the body coordinates, the subscripts t and n represent, respectively, the tangential and normal components, ρ and μ are the density and viscosity of the fluid, d and l are the width and half length of the body link, v_t and v_n are the link velocities in body coordinates (the implicit assumption is that the fluid is static), c_p and c_t are the drag coefficients, c_a is the added mass coefficient and a_n is the acceleration of the link in the normal direction.

The model was decoupled as described in [3] into two sets of equations: (Dynamics A) one from the muscle torques to the resulting body shape change, and (Dynamics B) the other from the shape change to the inertial movements of the body. The inertial movements refer to the translation of the center of gravity and the overall rotation, which is defined as $\theta_o := (\sum_{i=1}^{18}\theta_i)/18$, where θ_i are the link angles with respect to the direction of locomotion, which is fixed to the horizontal axis in this study.

The body movements during steady swimming were recorded via a high-speed camera, and the video images were processed to generate time courses of kinematic variables. Fig. 1 illustrates the data processing of the measured joint angles.

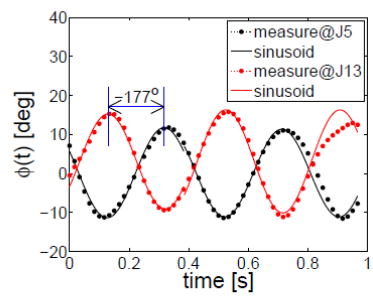

Figure 1: Measured joint angles ϕ_5 and ϕ_{13} during swimming. Joint angles change sinusoidally. The posterior joint ϕ_5 lags anterior joint ϕ_{13}.

We simulated Dynamics B by enforcing the measured body shape change, and determined the fluid drag coefficients c_p, c_t and c_a by minimizing the root-mean-square error between the simulated trajectory of the center of gravity and the video data. The joint torques were then predicted by inverting Dynamics A using the shape change data and the estimated drag coefficients.

RESULTS AND DISCUSSION

The fluid drag coefficients were found to be $c_p = 3$, $c_t = 0.6$ and $c_a = 0$, indicating that the resistive force is dominant over the reactive force in leech swimming (Re=500~1000). Video data of eight swim episodes and simulated swimming were compared in terms of the trajectory of the gravity center (GC) and the overall body rotation (θ_o). The result (see Fig.2 for a sample) shows that the simple fluid force model (1) captures the essence.

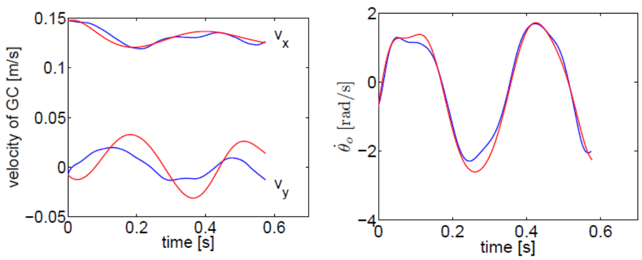

Figure 2: Comparisons of a simulated swimming (blue curves) with the video data (red curves).

We computed the distribution of thrust and drag along the body (Fig. 3), where the thrust and drag on each link are calculated by the projection of normal and tangential fluid forces, respectively, in the direction of swimming averaged over one cycle. Thrust is generated all along the body and increases towards the tail; drags experienced by the links are roughly uniform over the body.

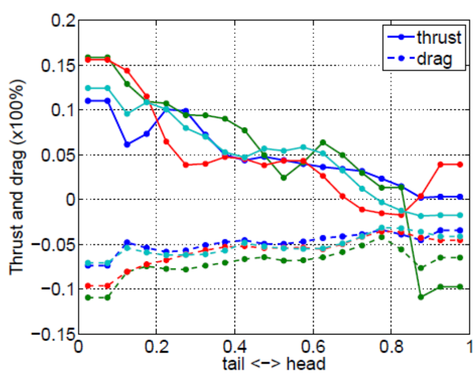

Figure 3: Thrust and drag generated along the body. The values are normalized by total thrust. The abscissa is the body location, "0" denotes the tail tip and "1" denotes the head tip. The colored curves represent four swimming episodes.

We also calculated the energy supplied to the body by muscle in one cycle and its dissipation to the fluid along the body (Fig. 4). The power from the muscle is mainly supplied in the mid-body and is dissipated into the fluid mostly at the tail link.

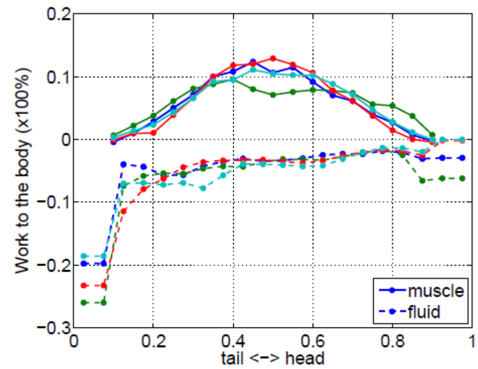

Figure 4: Energy supplied at 17 body joints in one cycle (upper curves) and its dissipation into the fluid (lower curves). The values are normalized by the total work of 17 joint muscles in one cycle.

The time courses of muscle power input at joints show that mid-body muscles always supply power, whereas the muscles near the tail region both supply and absorb power during each cycle. Correlating the negative power stroke with the muscle strain, we found that the energy supplied by the mid-body muscles is transmitted to the elastic energy of the posterior muscles through body kinematics. The elastic energy stored in the muscles near the tail region acts on the fluid and generates large fluid forces.

CONCLUSIONS

A simple static model appears to capture the hydrodynamic forces during leech swimming. More generally, our results suggest that, in anguilliform swimming, thrust is generated all along the body but increases towards the tail. Power from muscles is generated primarily in the mid-body and is dissipated to the fluid at the tail tip.

REFERENCES

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