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14. ABSTRACT

We use multiscale modeling and computational fluid dynamics to examine the stability of a swimming organism in the face of perturbations, with and without sensory feedback. We focus on the lamprey, the most basal living vertebrate, and hence a model organism for studying the neural control of locomotion. We investigate how the coupling among forces due to passive tissue properties, active muscular forces and the forces from the external fluid environment contribute to the dynamics and stability of swimming. Using our integrative computational model, we can impose external perturbations to the fluid environment as well as internal perturbations to the neural

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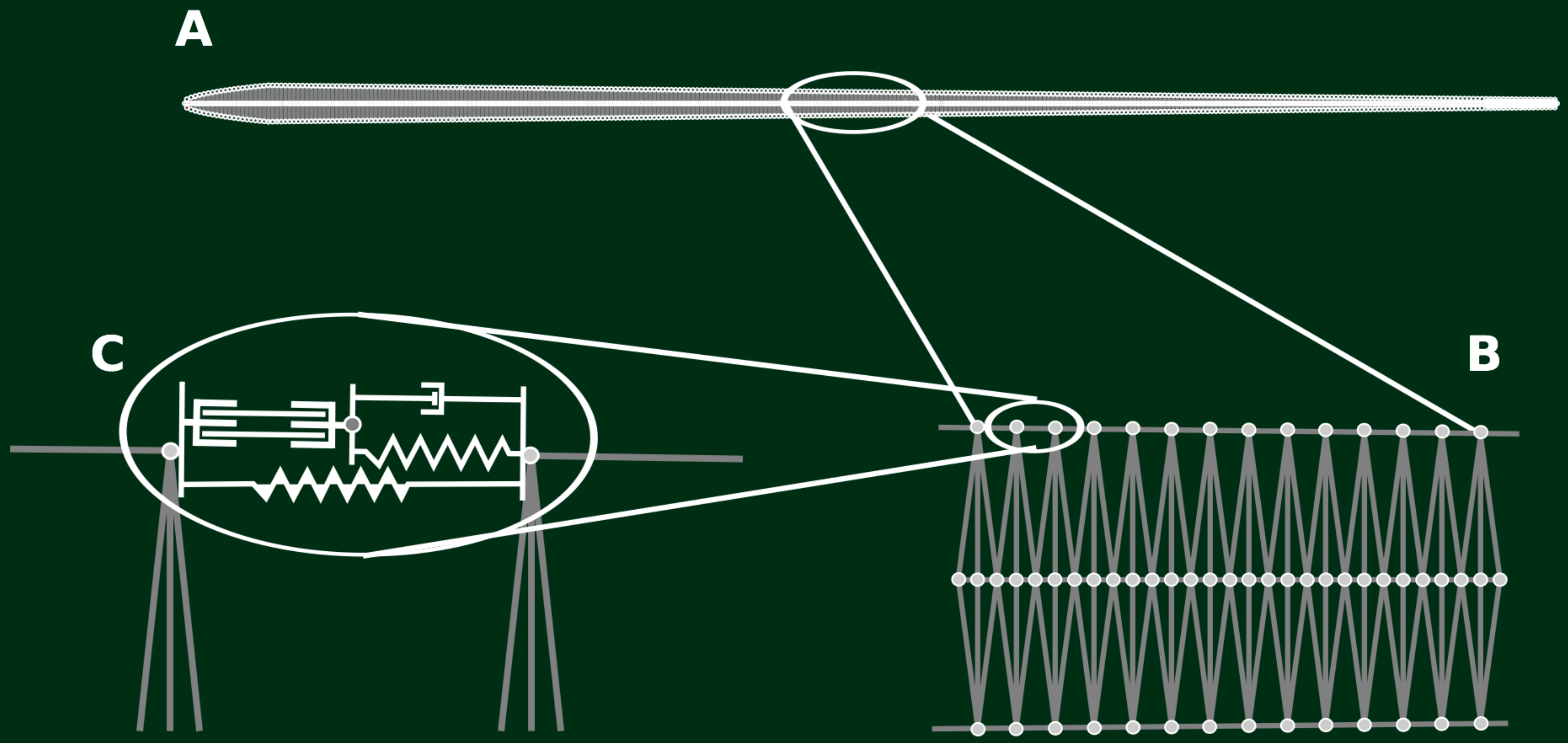


This is a schematic of the computational body. (A) The initial configuration of the material points. (B) The gray lines show elastic springs which resist deformation. (C) Inset that shows the position of the muscle segments.

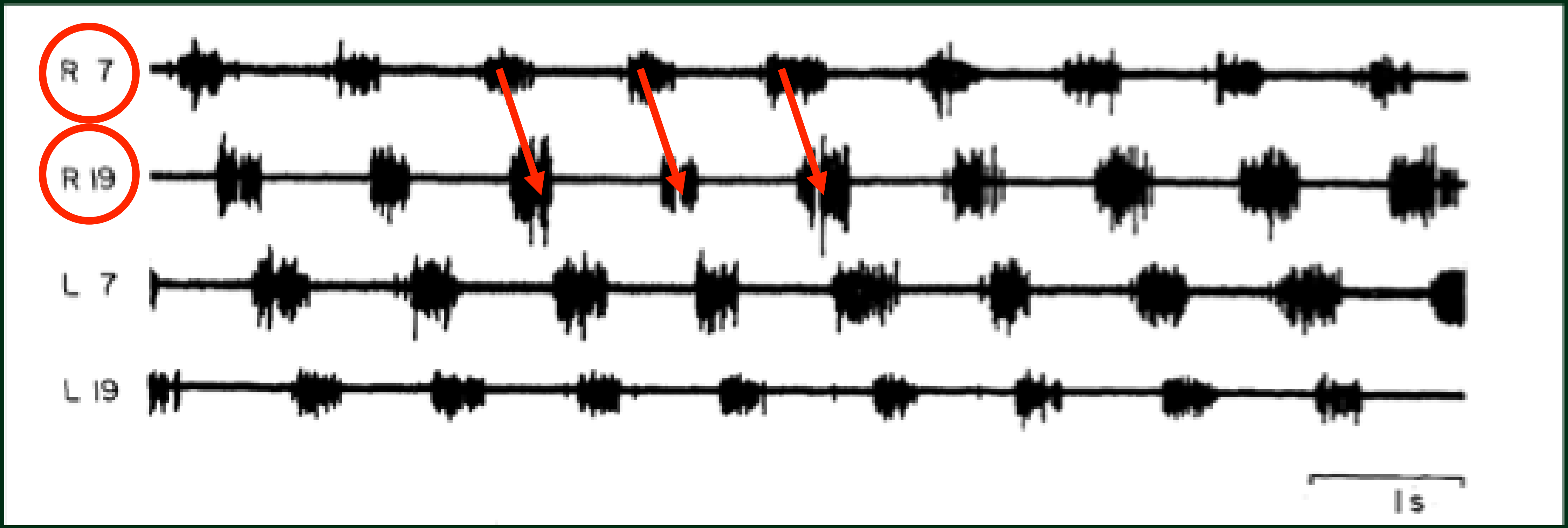
Hamlet, Fauci, Tytell, J.Theo. Bio 2015

A representative plot of bursting signals at different positions on the lamprey body. The “R” and “L” on the left side indicates right and left, respectively. The numbers are the segment number, labeled from head to tail.

Cohen, Holmes, Rand, J. Math Biol. 1982

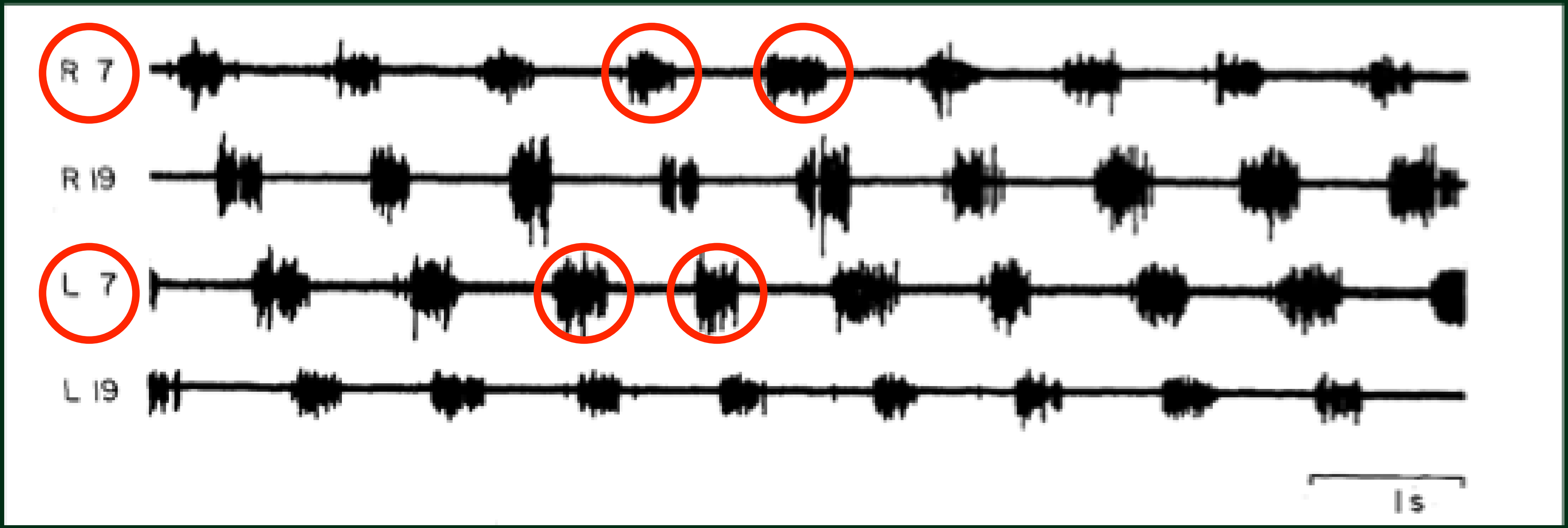
The signals are periodic.

Cohen, Holmes, Rand, J. Math Biol. 1982



From head to tail there is a phase lag on each side.

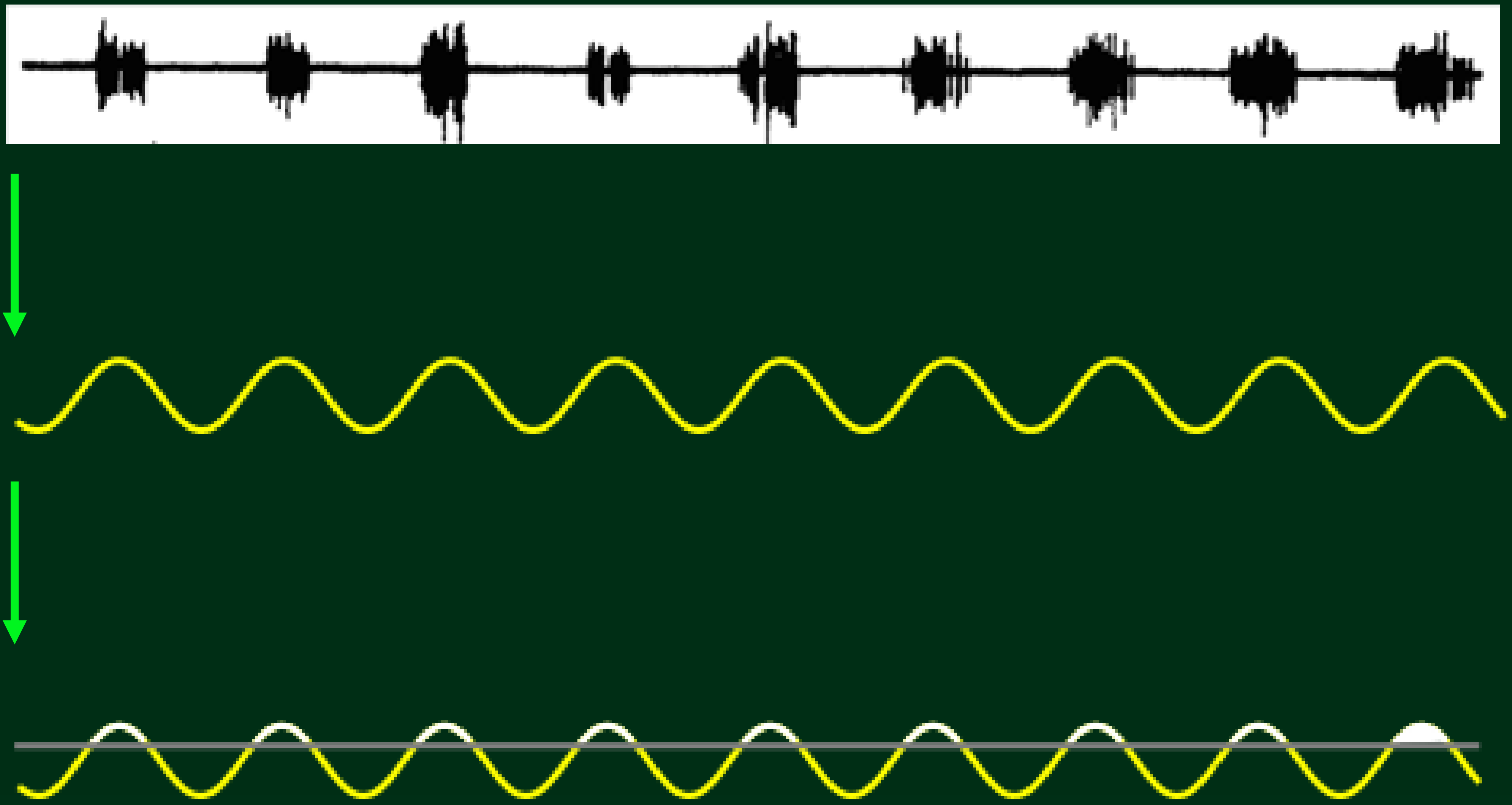
Cohen, Holmes, Rand, J. Math Biol. 1982



On a given segment, the signals are in antiphase.

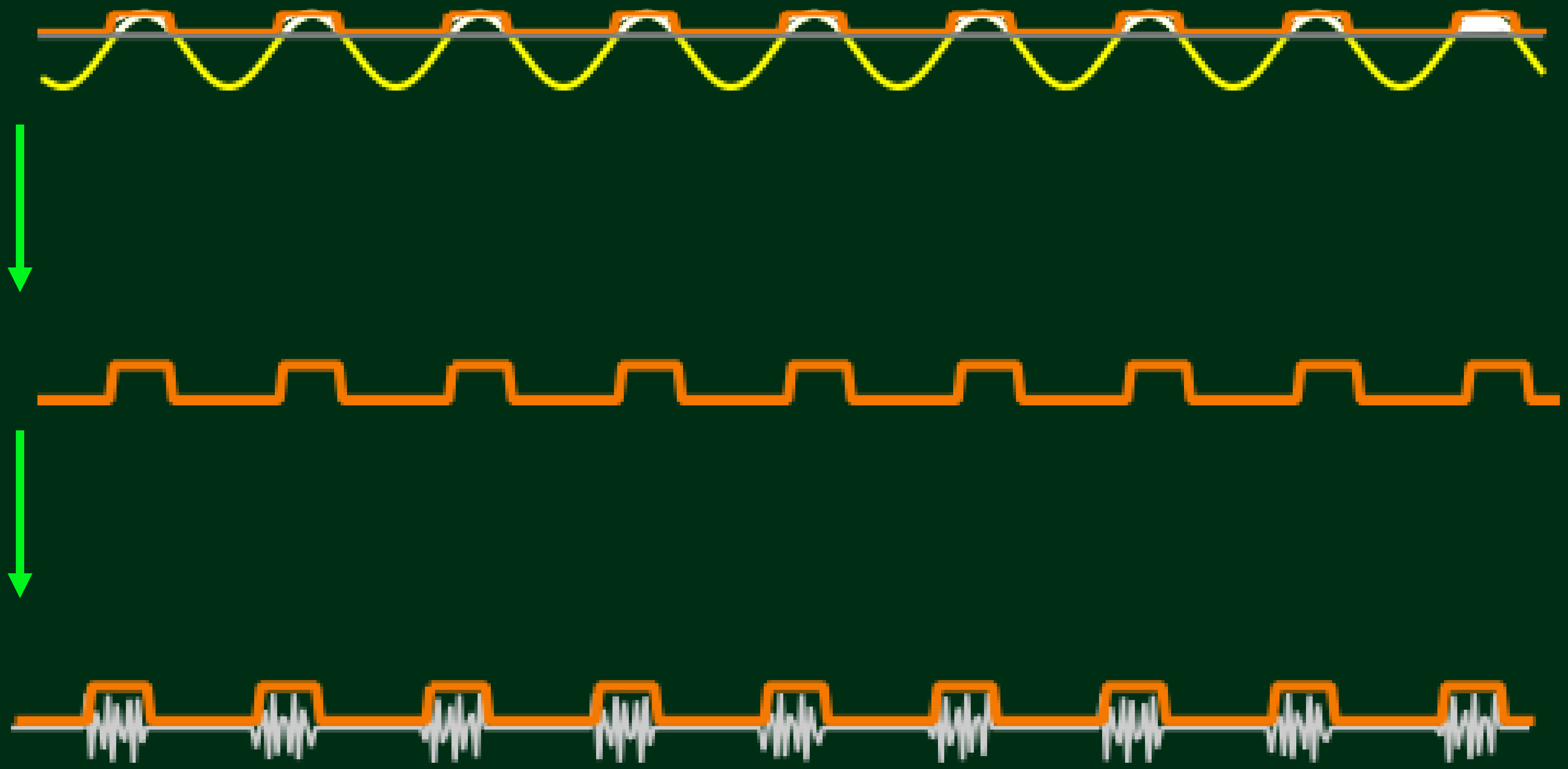
Cohen, Holmes, Rand, J. Math Biol. 1982

Periodic nature of CPG motivates modeling by an oscillator

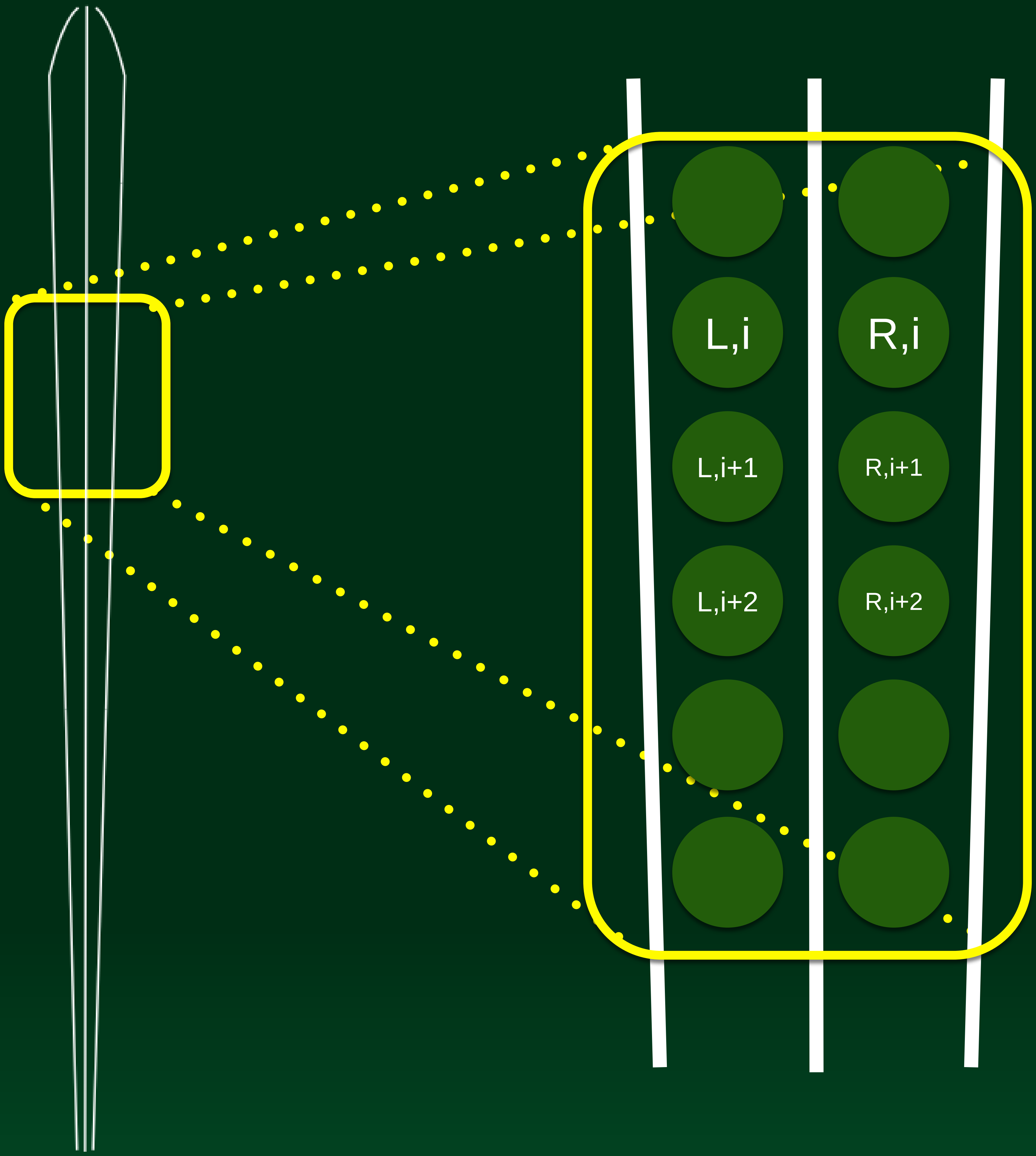


Using one signal as a representative example, we define an oscillator described by its phase that generates a signal. Then a threshold is applied based on experimental data.

Oscillators generate a signal

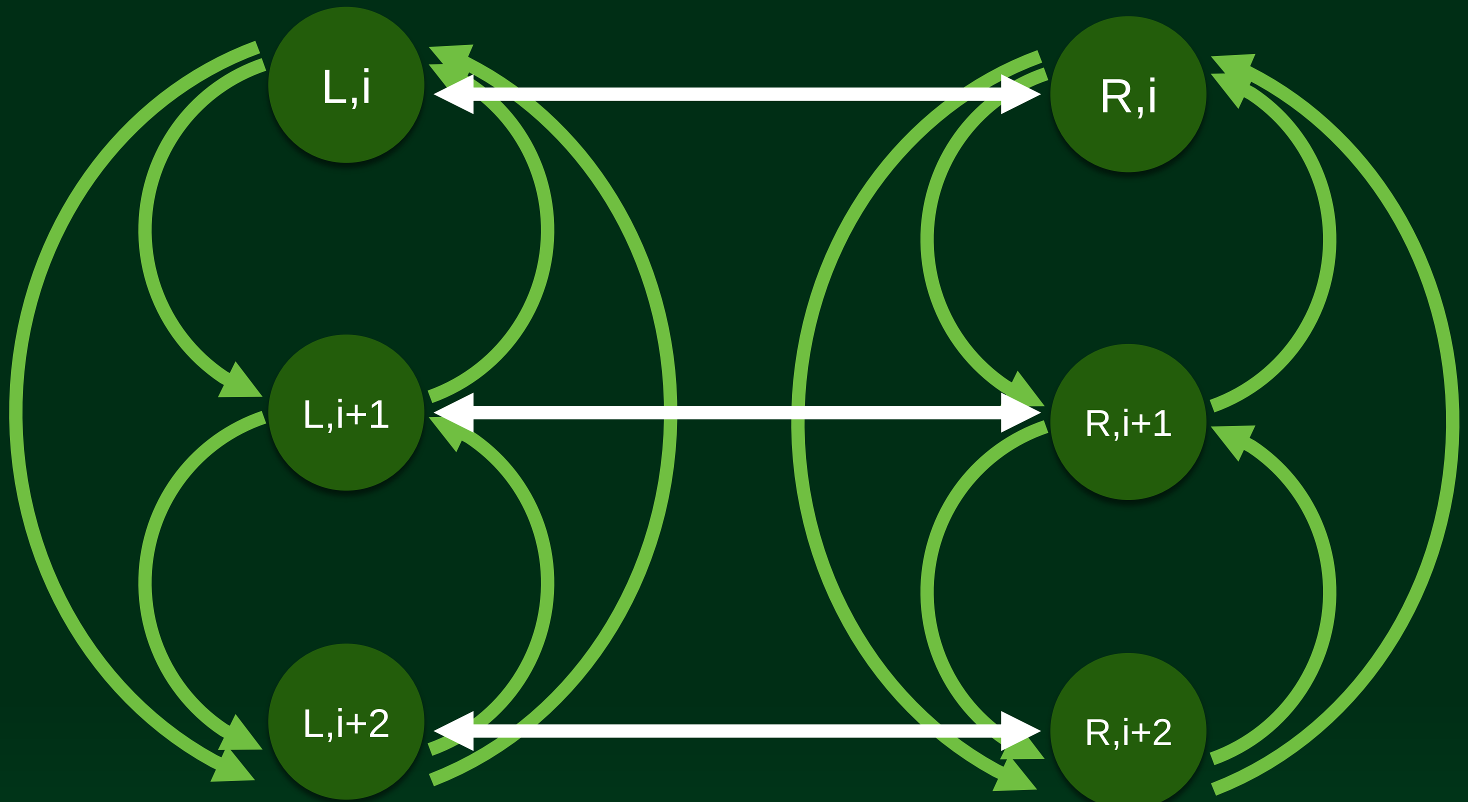


Applying the threshold to define “active” and “inactive” and coarsely approximate the observed experimental signal.

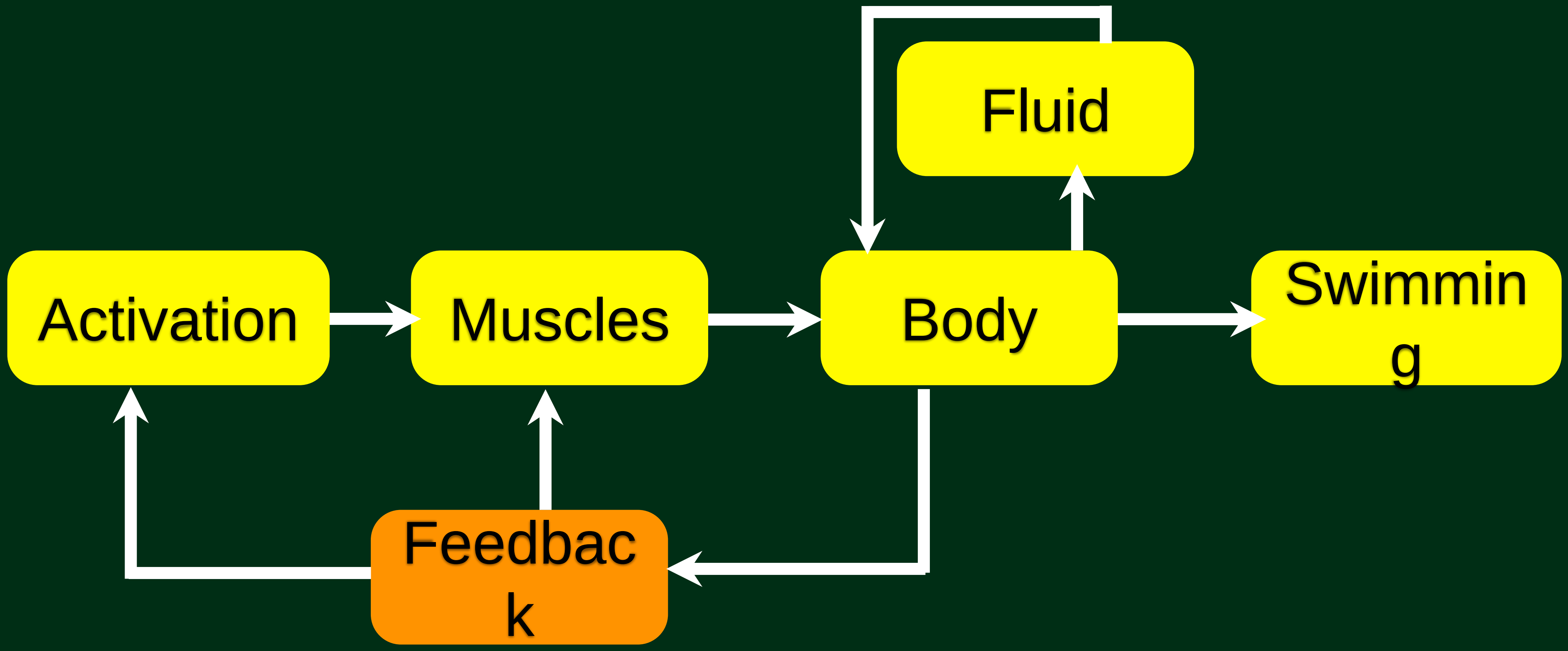


Oscillators are assigned one-to-one to the muscle segments and coupled according to experimental guidance.

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right) + \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$

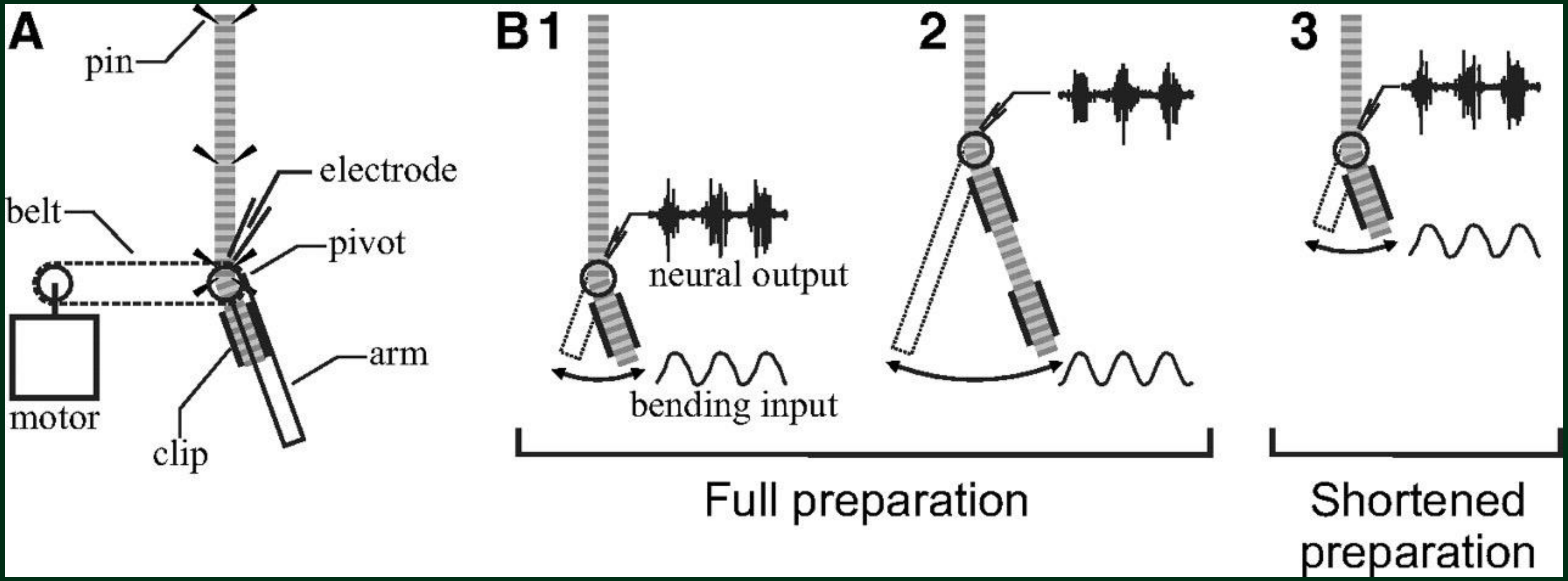


The oscillators are coupled all-to-all one each side (green arrows showing example) and across a segment (white arrows show examples). For each oscillator ω represents the natural frequency, θ is the phase, Φ is the phase lag down the body, ψ is the phase lag across a segment.



Feedback diagram. Feedback added though curvature sensing.

Edge cells and sensory feedback



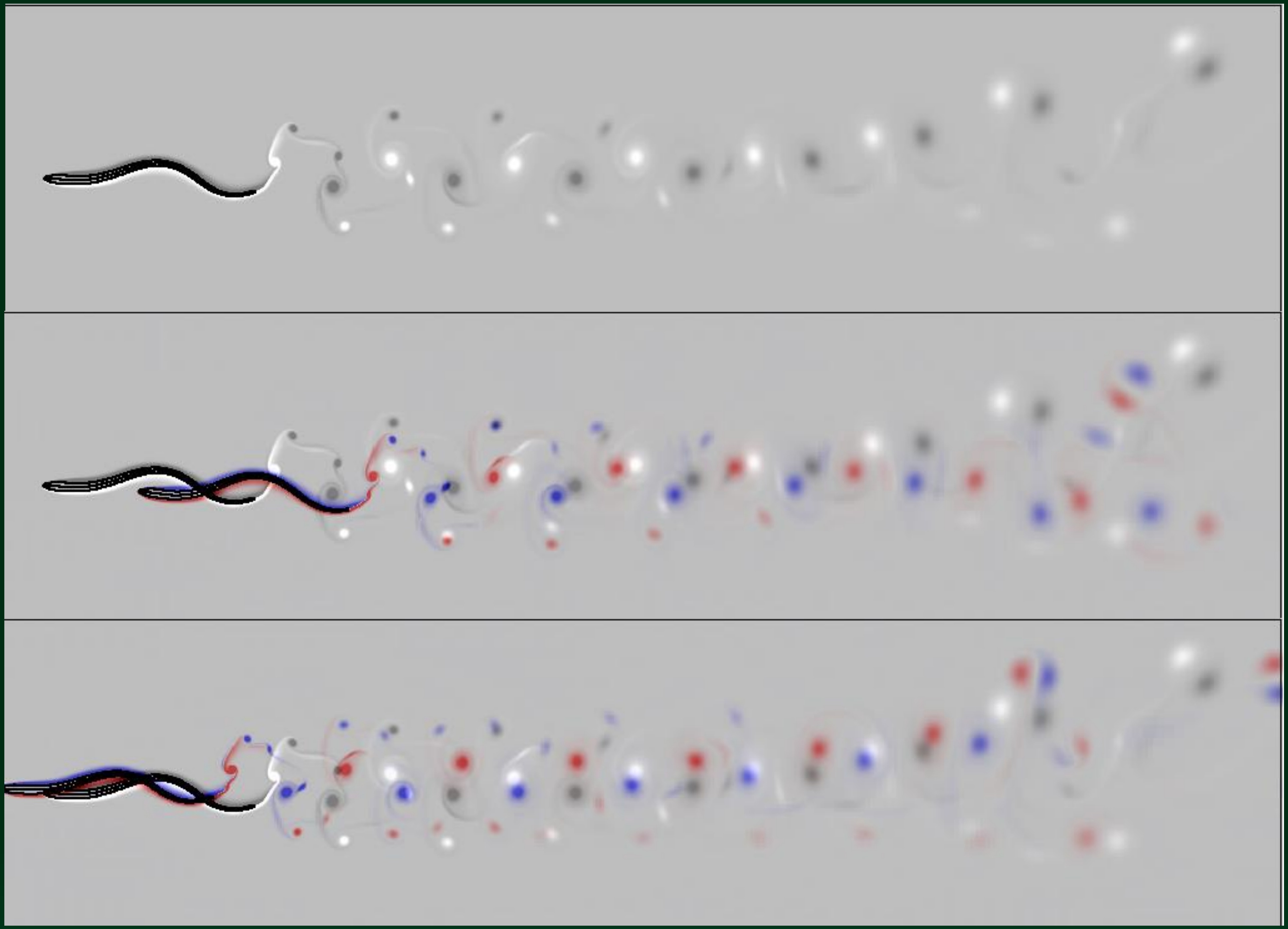
Schematic of Eric’s experimental set up.

Tytell and Cohen, J. Neurophysiology 2008

Connect sensory feedback to oscillators

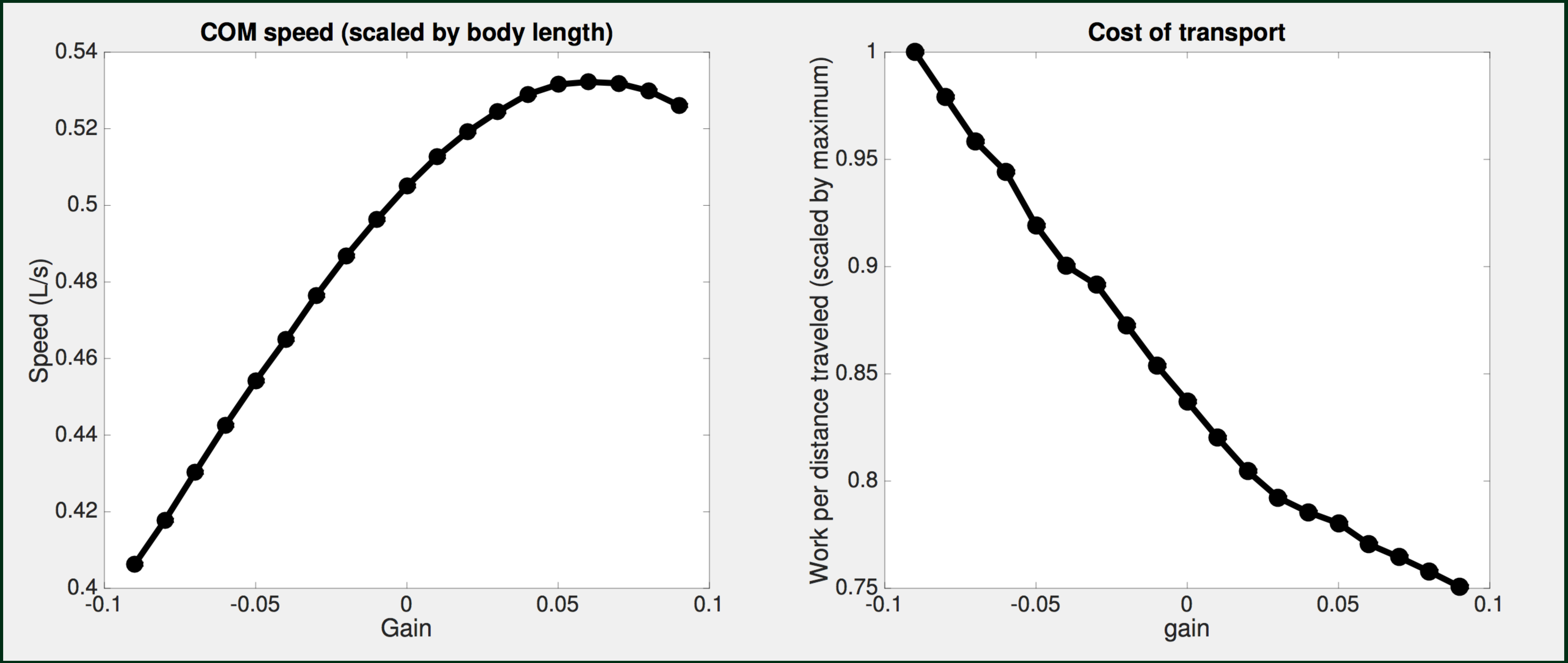
$$\begin{aligned}\dot{\theta}_{k,i} &= \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right) \\ &\quad + \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right) \\ &\quad + \boxed{\eta_{k,i}\left|\bar{\kappa}\right|} \longleftarrow \eta_{k,i}\left|\kappa\right| = g\left|\kappa\right|\end{aligned}$$

Propose forms of functional feedback. The one shown here will advance the activation wave if the gain (g) is positive proportional to the curvature (κ), and will slow the activation wave if the gain is negative.

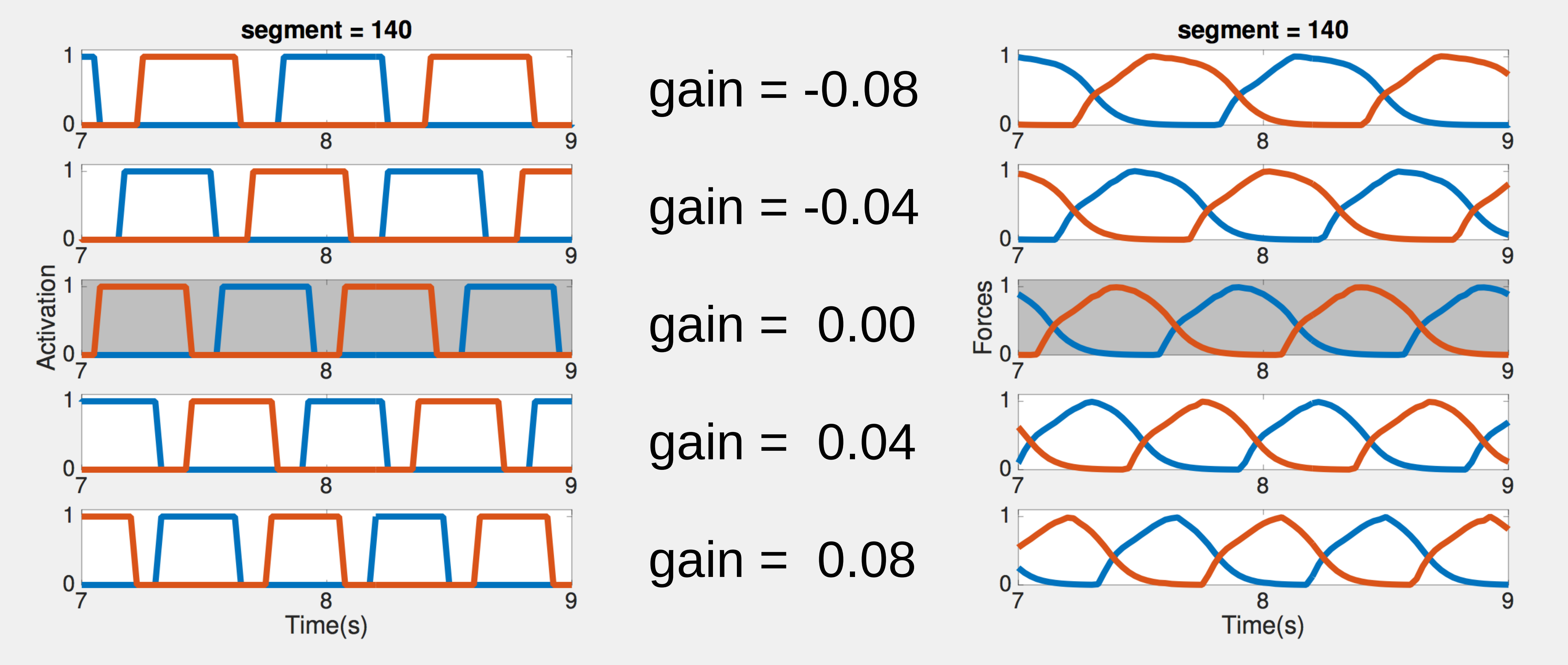


Top: No feedback
Middle: Negative gain
Bottom: Positive gain

Changing the feedback term changes the behavior of the swimming lamprey (see the next slides)



Left plot shows the swimming speed at the center of mass of the swimmer in each simulation in (L/s) where L=body length). Right plot shows the work per unit distance (cost of transport) scaled by the maximum value.



Plots to illustrate the effect of the feedback term (g|κ|), left plot shows that at a given segment, the feedback increases the tail beat frequency as the gain increases. The right plot shows that the area under the force curve during each cycle is decreased, reducing the achieved amplitude.