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Title: A neural network model of the wing hinge reveals the control logic of fly flight

Abstract: All flight behavior in flies is controlled by the activity pattern of just 24 neurons. Each wing is actuated by 12 steering muscles and each muscle is innervated by one motor-neuron. Despite this sparsity of information, flies can modulate their wings over a large dynamic range, a desirable control characteristic that is encoded mechanically in the wing hinge. The steering muscles act on the wing hinge and can alter this mechanical encoding. Due to the complexity of the wing hinge, an accurate model of how the steering muscles actuate wing motion has remained elusive, despite more than a century of research.

We avoided the complexity of the hinge by simultaneously measuring its input, the activity of the steering muscles, and its output, the wing motion. Muscle activity was imaged through the cuticle via the genetically encoded calcium indicator, GCaMP. Using a neural network, we performed non-linear regression between GCaMP fluorescence and recorded wing kinematics. The trained network accurately predicts wing motion from the fluorescence traces and was used to infer how the steering muscles affect wing motion. With a flapping wing robot, we measured the aerodynamic forces generated by the corresponding wing motion of various muscle activity patterns. We incorporated the measurements into a state-space system of fly flight and used this system to simulate various flight maneuvers.

Our simulations show that relatively subtle changes in wing motion cause rapid body rotations, an observation that is corroborated in free flight. The neural network model of the wing hinge has allowed us to model how the activity of 24 neurons controls flight behavior in flies.