

Supplementary Material

Data sources and related sensitivity analysis

The analysis in this study is based on the data collected from previous literatures, as shown in the Table 1-3. These data are either from the authors' previous studies, such as those for hummingbirds [1, 2] and hawkmoth [3], or from other studies, such as those for fruit fly [4-6]. These data (e.g., the measured closed-loop time constants and wingbeat frequency) serve as a reliable basis for the analysis since they are obtained in comparable experiments (i.e., for escape manoeuvres or perturbed flights) and also have relatively low variability within each study. To authors' best knowledge, there are no other available data obtained in similar experiments of escape manoeuvres or perturbed flights for the animals studied here.

Although lacking of additional data might hamper us to deliver a comprehensive sensitivity analysis, in the following, we will provide some preliminary evaluation on the sensitivity of our results to potential variations in two types of data used.

Closed-loop time constants: The experimentally measured closed-loop time constants τ_{CL}^m (Table 3) determine the performance regions (3.3) and consequently affect the estimations of allowable delays (3.3-3.4), stability margins (3.5) and muscle mechanical power (3.6). The sensitivity of the estimated allowable delays relative to the measured closed-loop time constants can be assessed in part by changing the reference closed-loop time constant τ_{CL}^r . For example, as the closed-loop time constant τ_{CL} is changed from $\tau_{CL}^r = 30$ ms to $\tau_{CL}^m = 33$ ms for magnificent hummingbird (Fig. 3A), the difference in the allowable delay T_a is about 2 ms (Table 3), which results in a sensitivity $S = \frac{\Delta T_a}{\Delta \tau_{CL}} = 0.67$. Similar values of sensitivity can be found for other cases as well. Therefore, this indicates that even when there are some variations in the data, the changes in our estimations will not be significant. In addition, our conclusions, such as inter-axis and interspecific similarities and differences and the effects of position and velocity delays, are based on using a common reference closed-loop time constant, and therefore will not be affected by the variations in the measured closed-loop time constants.

Wingbeat frequency (biomechanical delay). It is reported in Fry et al. [7] that fruit flies use wingbeat frequency around 218 Hz in hovering, higher than the 189 Hz used in this study (Table

2). This difference would barely affect our results since the effects of biomechanical delay is negligible for fruit fly (see section 3.2). Wingbeat frequency around 25 Hz for hovering flight is reported for hawkmoth in Willmott and Ellington [8]. This would lead to slightly decreased allowable delay T_a (Table 3, Fig. S3). For example, T_a will be around 27 ms instead of 28 ms for hawkmoth. Nonetheless, our conclusions for inter-axis and interspecific comparisons will remain unchanged (see 3.2-3.3).

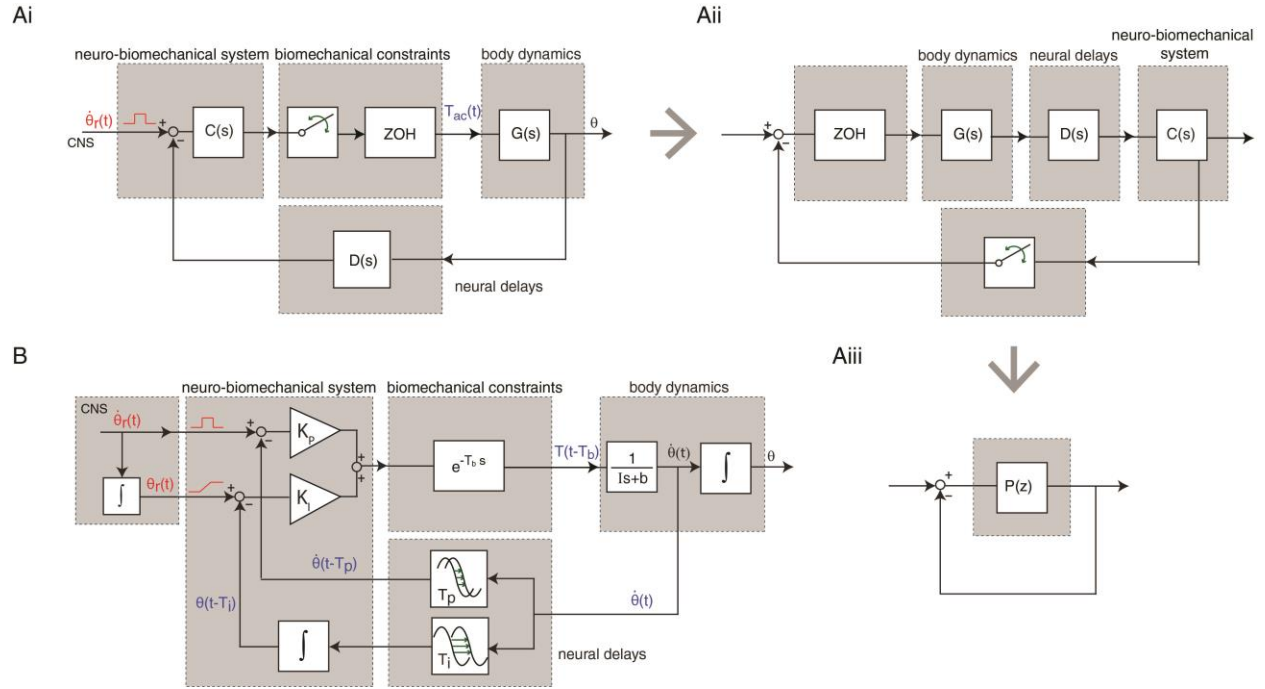


Fig. S1. Two models used to study effects of biomechanical constraint and neural delays. (Ai) The first model uses sampling and zero-order-hold mechanism to model biomechanical constraint, and undistinguished neural delays. (Aii) Sequence of functional blocks is rearranged while characteristic equation is unchanged. (Aiii) The discrete equivalent is then obtained. (B) The second model uses single delay to model biomechanical constraint, and distinguished neural delays.

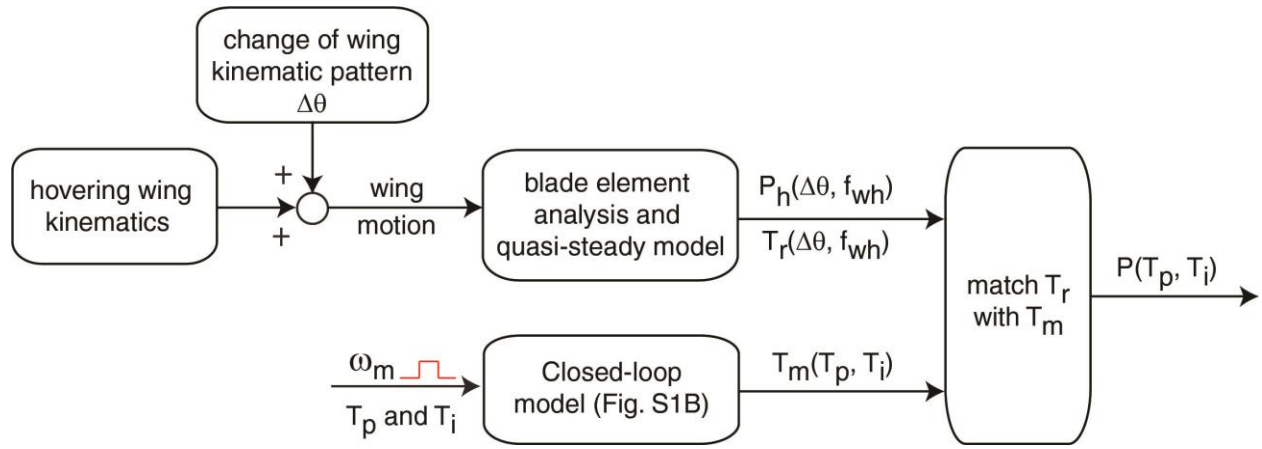


Fig. S2. Outline of estimating muscle mechanical power. In the first step, the muscle mechanical power $P_h(\Delta\theta, f_{wh})$ and corresponding moment $T_r(\Delta\theta, f_{wh})$ is obtained based on blade element analysis and quasi-steady model. In the second step, the closed-loop model is set to respond to a step angular velocity ω_m and the averaged moment $T_m(T_p, T_i)$ is recorded. By matching T_r with $T_m(T_p, T_i)$, the muscle mechanical power $P(T_p, T_i)$ corresponding to different proportional T_p and integral delays T_i is calculated.

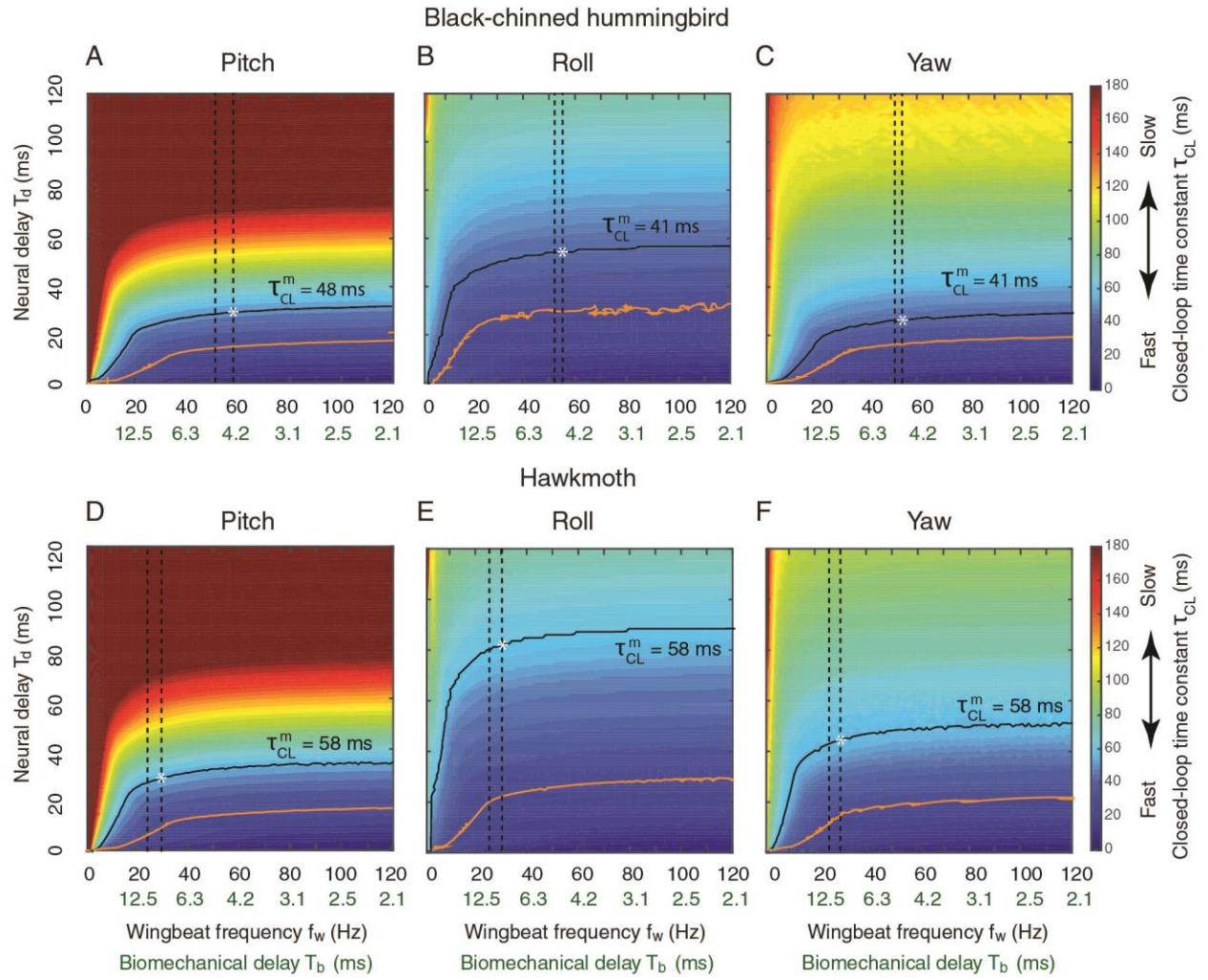


Fig. S3. Effects of biomechanical constraints and neural delay on closed-loop response time τ_{CL} for black-chinned hummingbird and hawkmoth. The definitions of black and orange lines are the same as Fig. 3.

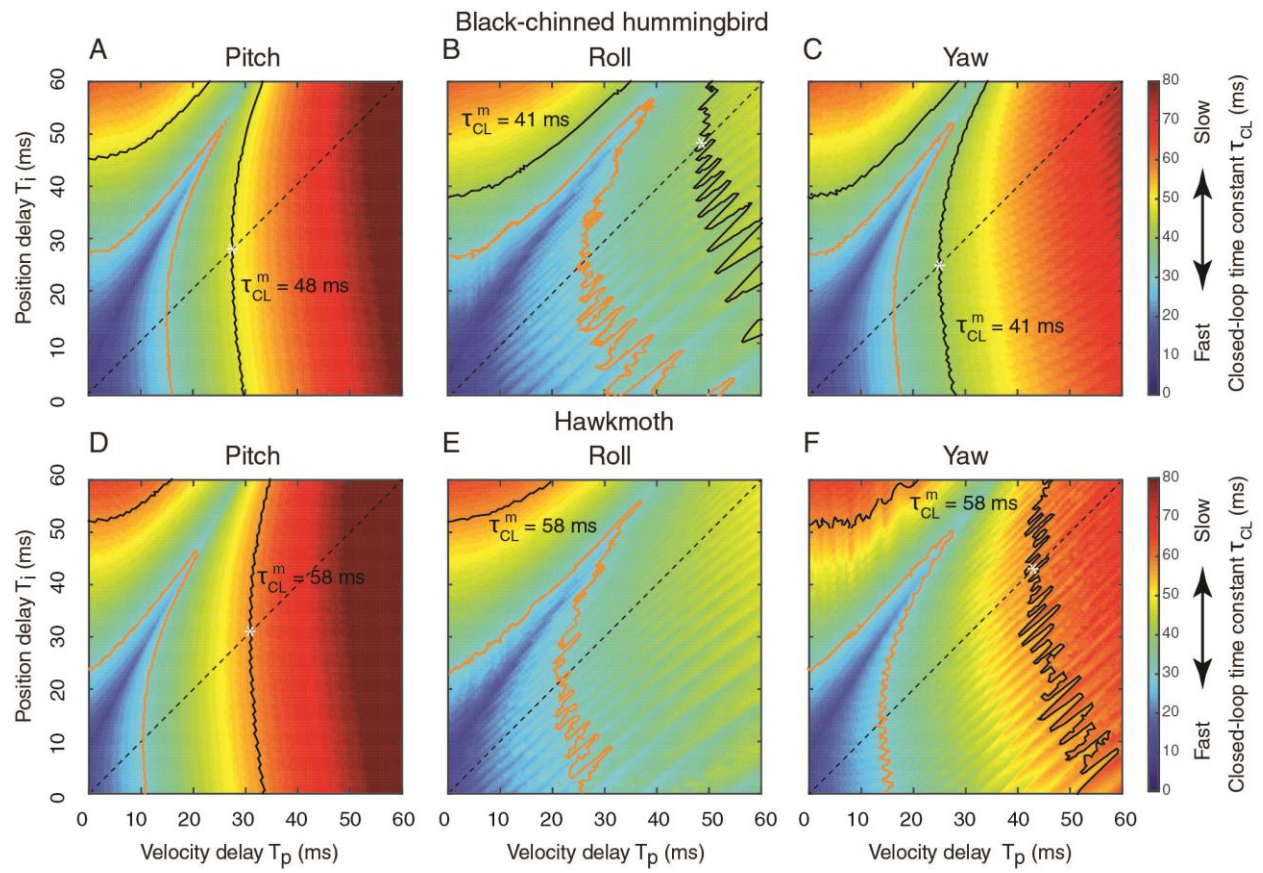


Fig. S4. Effects of velocity (T_p) and position (T_i) delays on closed-loop time constant τ_{CL} for black-chinned hummingbird and hawkmoth. The definitions of black and orange lines are the same as Fig. 4.

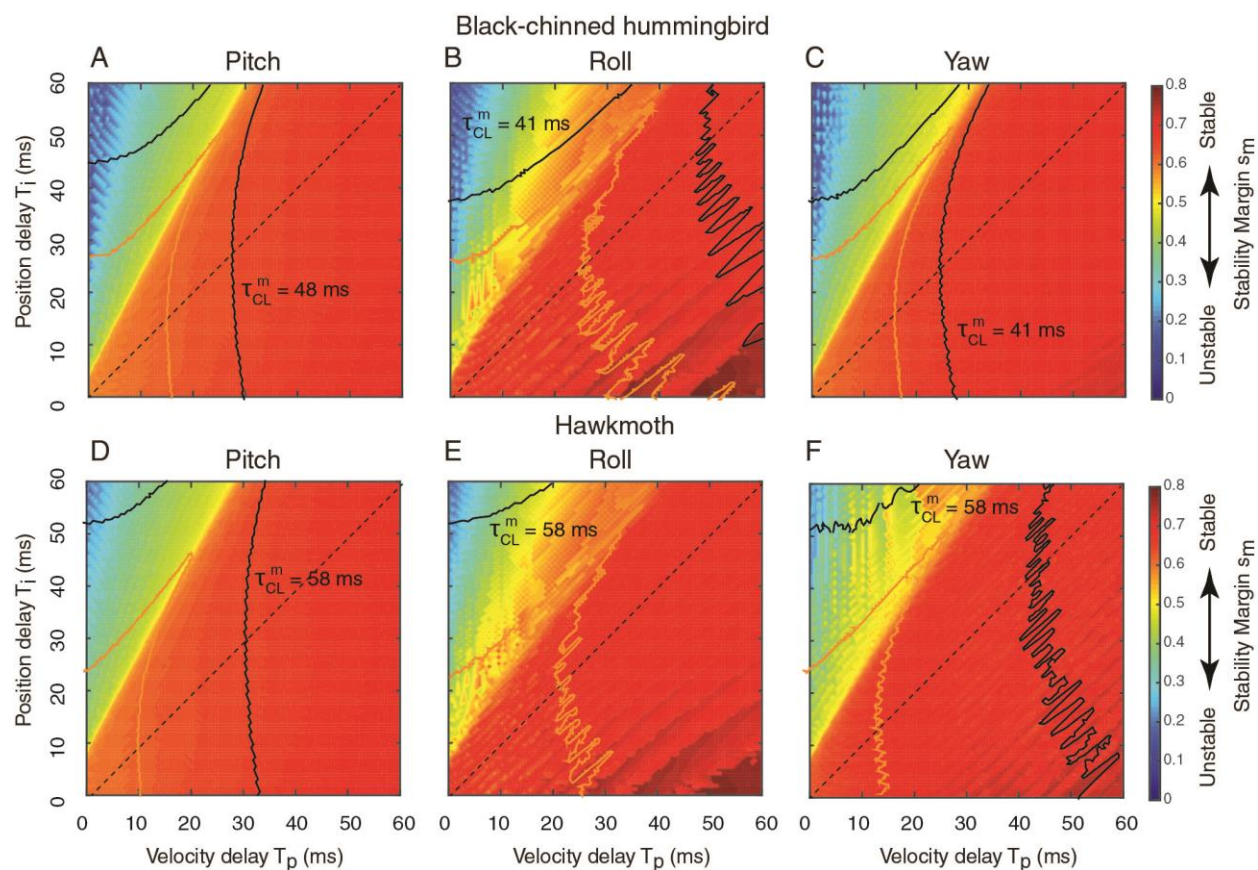


Fig. S5. Effects of velocity (T_p) and position (T_i) delays on stability margin s_m for black-chinned hummingbird and hawkmoth. The definitions of black and orange lines are the same as Fig. 5.

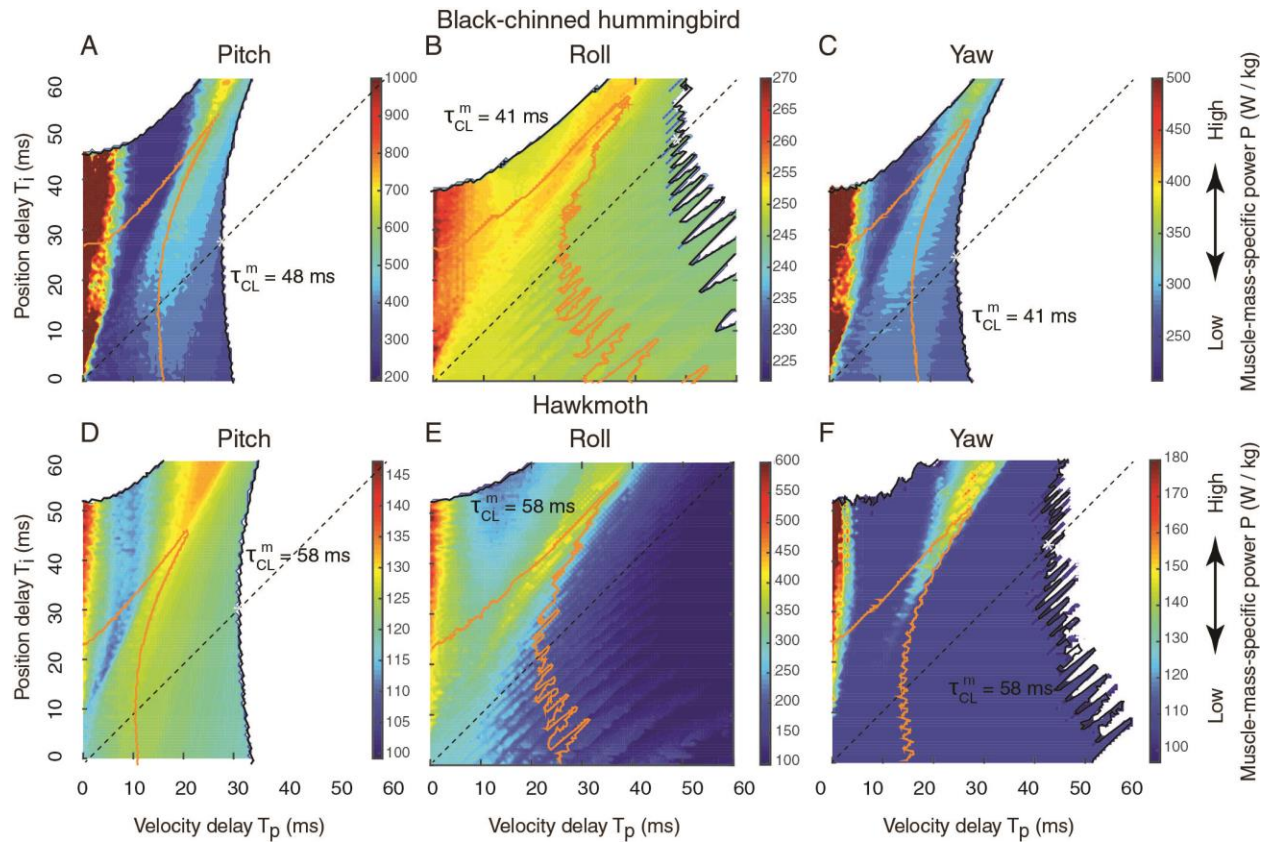


Fig. S6. Effects of velocity (T_p) and position (T_i) delays on muscle-mass-specific power for black-chinned hummingbird and hawkmoth. The definitions of black and orange lines are the same as Fig. 6.

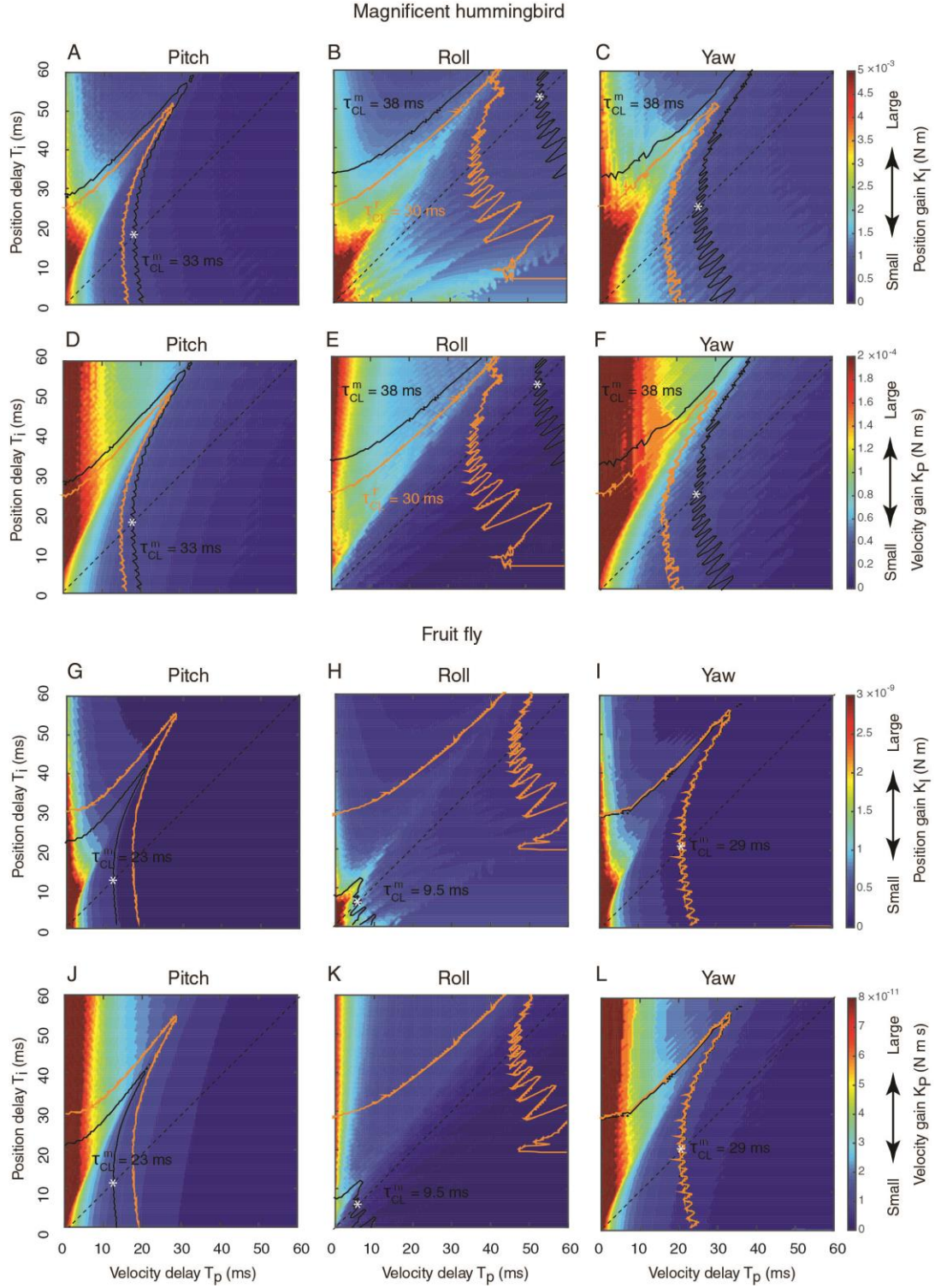


Fig. S7. The position (K_I) and velocity (K_P) controller gains (defined in Eqn. 4) that reach the fastest closed-loop dynamics, i.e. minimize τ_{CL} , for magnificent hummingbirds and fruit flies. The definitions of black and orange lines are the same as Fig. 4.

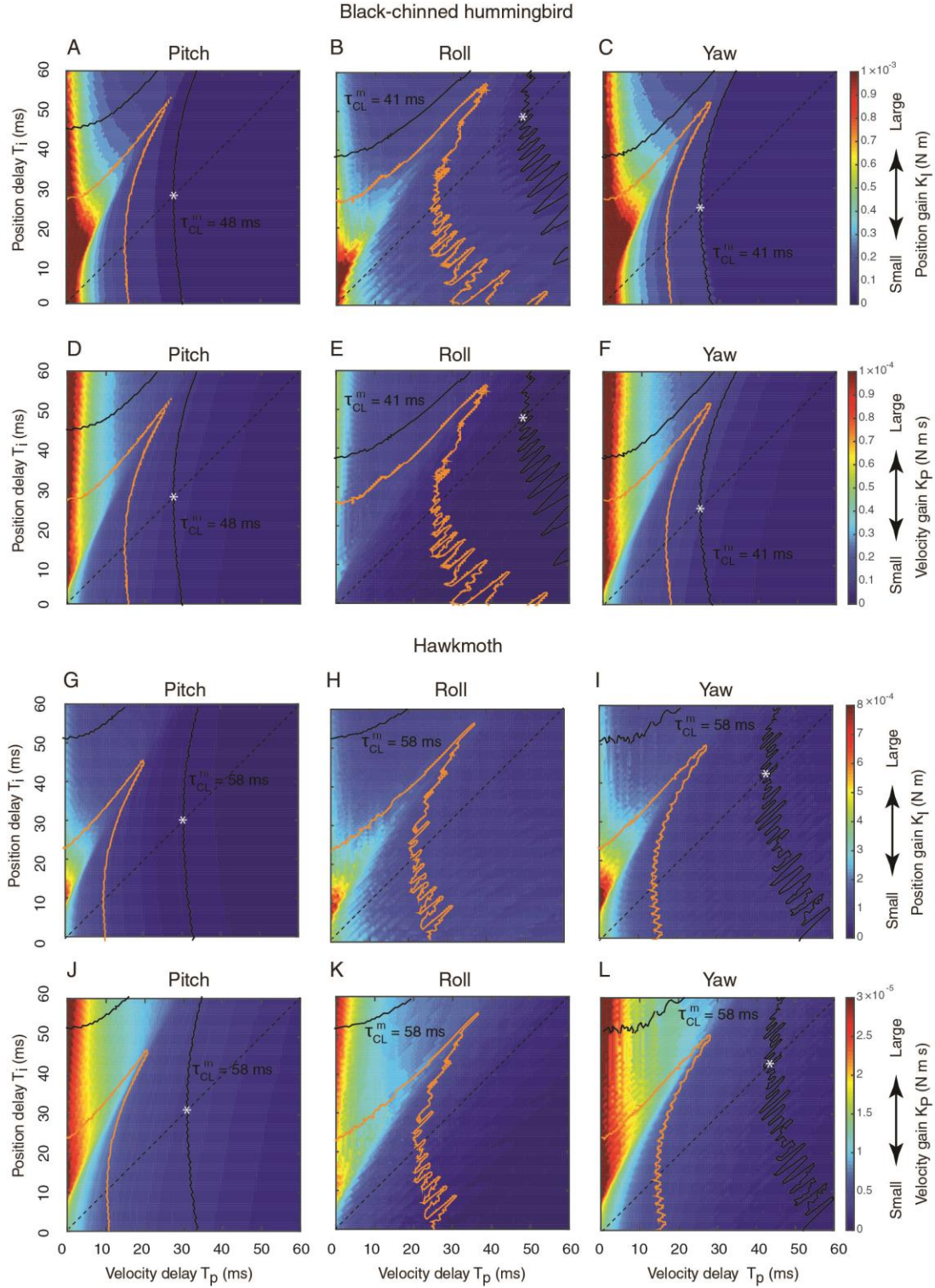


Fig. S8. The position (K_I) and velocity (K_P) controller gains (defined in Eqn. 4) that reach the fastest closed-loop dynamics, i.e. minimize τ_{CL} , for black-chinned hummingbirds and hawkmoths. The definitions of black and orange lines are the same as Fig. 4.

References

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