Modulation of Fore-Hind Wing Overlap in the Moth *Manduca sexta*

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INTRODUCTION

Moths and butterflies are four-winged animals. Most studies of their flight, however, focus primarily on the fore wing and treat the insects as functionally two-winged fliers. Previous studies in which the hind wings of a variety of moths and butterflies were removed showed that they retained the ability to fly, but lost some maneuverability. Nevertheless, it is not yet known how the interactions of the fore and hind wings generate this increased mobility. We hypothesized that one way the moths could increase maneuverability would be by modulating the amount of overlap between the fore and hind wings. By changing the overlap of the wings, a moth could alter the total area of its flight surface, which could afford it greater control over the forces produced in flight.

Photos taken from scanning electron and optical microscopes were used to qualitatively assess the wing structures long thought to serve as linkage mechanisms, which differ markedly between male and female moths. We then marked both male and female moths on the thorax, fore, and hind wings to measure the change in angle between the fore and hind wing before and after take-off. This angle served as an indication of increase or decrease in overlap between the fore and hind wings.

We conducted this experiment to determine:

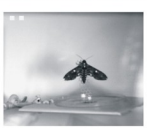
1. The physical characteristics of the frenulum, retinaculum, and overlapping scale patches of the fore and hind wings
2. If moths modulate the amount of overlap between fore and hind wing during take-off.

Change in angle between points on the fore and hind wings correspond with a change in overlap.

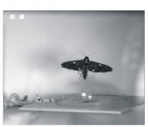
Increased overlap, decreased angle between fore and hind wing

Decreased overlap, increased angle between fore and hind wing

We placed white dots on the wings and thorax of each moth. We then set the moth on a stand and recorded its behavior during take-off with two high speed video cameras. Each trial was then digitized and analyzed to determine how the three-dimensional angle between the fore wing, thorax, and hind wing changed over time.



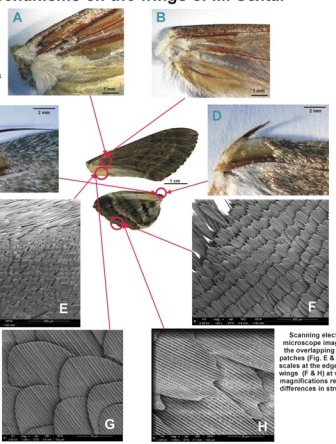
Still image from high speed video recordings showing decreased overlap



Still image from high speed video recordings showing increased overlap

Wing overlap may be maintained by linking mechanisms on the wings of M. Sexta.

The frenulum (Fig. C & D) is a small spine or set of stiff hairs on the lower wing which (in males) is held by the retinaculum, a curled piece of cuticle on the fore wing (Fig. A). Female fore wings lack a retinaculum (Fig. B).



Scanning electron microscope images of the overlapping scale patches (Fig. E & G) and scales at the edge of the wings (F & H) at varying magnifications revealed differences in structure.

Modulation of wing overlap may afford M. sexta increased maneuverability in flight.

Increased overlap

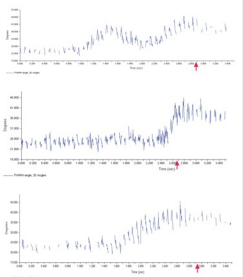
Decreased wing area
Increased flexural stiffness
Decreased lift & thrust

Decreased overlap

Increased wing area
Increased flexural stiffness
Increased lift & thrust

Previous studies have shown that butterflies and moths are capable of flight without hind wings. However, the insects are unable to turn as quickly or as sharply as they could with hind wings intact. Adjustments in the amount of overlap between the fore and hind wings could allow moths to alter flight forces via changes in the total surface area of the combined wings, and/or in flexural stiffness (degree to which the wings bend in flight).

Wing overlap decreases during take-off.



- ***Each graph represents the change in angle between the fore and hind wing over time for a single moth.***
- ***The red arrows mark the point at which the moth lifted away from the platform in flight.***

Summary and Future Directions

- **Although we have yet to analyze the data from the wing overlap experiments, it seems that *M. sexta* moths decrease the overlap between fore and hind wings as they prepare for take-off.**
- **Various treatments will be necessary to conclude if moths are capable of modulating flight forces by altering fore-hind wing overlap. These include experiments such as flying moths in varying wind speeds.**
- **If moths do alter wing overlap in flight, it will become important to determine which structures serve as the primary mediators of wing overlap (i.e. the frenulum/retinaculum complex, scale patches, etc.)**
- **The noticeably different structure of the overlapping scales in comparison to the scales on the other surfaces of the wings suggests that these scale patches function in some way related to wing overlap.**
- **Additional experiments must be carried out to determine if these scales serve to link the fore and hind wing, decrease friction between the two wings, or do something else entirely.**

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