MEMS BASED BIOELECTRONIC NEUROMUSCULAR INTERFACES FOR INSECT CYBORG FLIGHT CONTROL

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ABSTRACT

This paper reports the first direct control of insect flight by manipulating the wing motion via microprobes and electronics introduced through the Early Metamorphosis Insertion Technology (EMIT). EMIT is a novel hybrid biology pathway for autonomous centimeter-scale robots that forms intimate electronic-tissue interfaces by placing electronics in the pupal stage of insect metamorphosis. Our new technology may enable insect cyborgs by realizing a reliable control interface between inserted microsystems and insect physiology. The design rules on the flexibility of the inserted microsystem and the investigation towards tissue-microprobe biological and electrical compatibility are also presented.

1. INTRODUCTION

When Micro-Air-Vehicles (MAVs) or tiny fliers are considered, the power source required to fly them within the constraint of generating lift, powering flight control sensors and actuators, and collision avoidance has limited their mission time and autonomy. Researchers have greatly benefited from the study of naturally occurring fliers to design individual biomimetic structures as the parts of MAVs [1]. Although, a tremendous effort has been put forth to combine these structures as a complete MAV, there has been no successful demonstration of a system that can takeoff, maneuver and land autonomously for long periods of hours or days [2].

Another idea has been to directly use naturally designed and optimized flyers, namely, insects as MAVs [3-5]. Insects are self-powered, are cm-scaled and operate with highly efficient flight muscle actuators. Man-made electronic systems can be implanted in insects to study and control the insect flight by recording from and actuating either each or combinations of the sensory, neural or muscular systems. However, it is a challenge to implant electronic systems to modulate the insect's flight without disturbing the insect's own efficient flight mechanism. Any artificially attached platform and surgery on the adult insect is not reliable, as the inserted devices on this stage can shift, create mass-balance disturbance and cause performance affecting tissue damage, especially when the inserted electronic systems are rigid.

In our previous work [6], we demonstrated an efficient method to implant structures in tobacco hawkmoth *Manduca sexta*, which we call "Early Metamorphosis Insertion Technology" (EMIT). EMIT involves inserting structures to the pupae at early stages of metamorphosis (Figure 1) such that the body *adapts* the structures *during the development* and *inserted structures emerge as a part of the body* to create insect cyborgs. A reliable biointerface was created by taking the advantage of the rebuilding of the entire tissue system. This hybrid structure enables a platform where CMOS devices and MEMS structures can be used as sensors and actuators not only for insect flight control, but also for biological and environmental sensing. Moreover, this platform can be used to study the probe-tissue interface in general for MEMS based neuromuscular prosthetic systems.

EMIT can benefit from any insect/animal that has metamorphic development (moths, butterflies, beetles, etc.) to create insect cyborgs with different locomotion capabilities. We have selected *Manduca sexta* due to its relatively shorter metamorphic duration of three weeks. With its 1-2 gram carrying capacity, flight range of miles, wingspan of 10cm and lifetime of 2-3 weeks, *Manduca sexta* makes a wide range of applications for these devices possible.

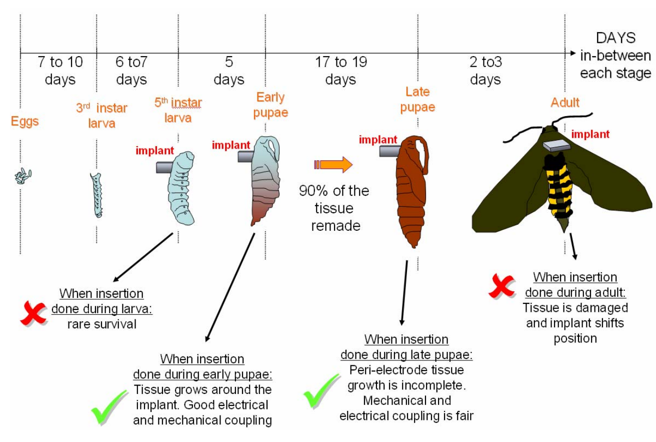


Figure 1: The life-span of Manduca sexta during the metamorphic development and the results of insertions done at various stages of metamorphosis.

2. EXPERIMENTAL PROCEDURE AND RESULTS

Microprobe Design

In the case of flight muscle actuation, the main flight powering muscles are located in the dorsal-thorax of the *Manduca sexta* (Figure 2) where electronic implants can be located. The dorsovental and dorsolongitudinal muscle groups move the wings by changing the conformation of the thorax, which supplies the mechanical power for up- and downstrokes. The alternating relaxation and contraction of these muscles create the alternating up- and down-strokes hence the flight. Therefore, the designed probe should target actuating these muscle groups.

Probe flexibility is a required design property for wider probe geometries, since the probe has the potential to affect the biomechanics of muscle contraction. Conversely, muscle contraction can cause impact and high strain damage to the probe. We had previously demonstrated a microsystem with all-silicon probes [7]. Here, polyimide was selected as the base material of the probe due to its flexibility and biocompatibility. Moreover, fragility and delicacy of the probes while handling during the insertion and throughout the experiments is less of a concern with a flexible polyimide probe.

The aimed experimental protocols consist of tethered setups where insect flight muscle is actuated through the flexible wires, as well as non-tethered setups where there are no attached wires and free-flight of insect can be realized. We designed and manufactured a flexible probe that can work with both setups (Figure 3B). The microsystem for autonomous control of the probe electronics can be seen in the same figure and consists of three parts: power, probe and control layers. The power layer (Figure 3D) is comprised of two coin batteries and a slide-switch positioned on a printed circuit board (PCB). Each battery has an energy capacity of 8mAh and weighs 120mg. Conductive adhesive was used to attach the batteries to the platform. The control layer (Figure 3A) is-

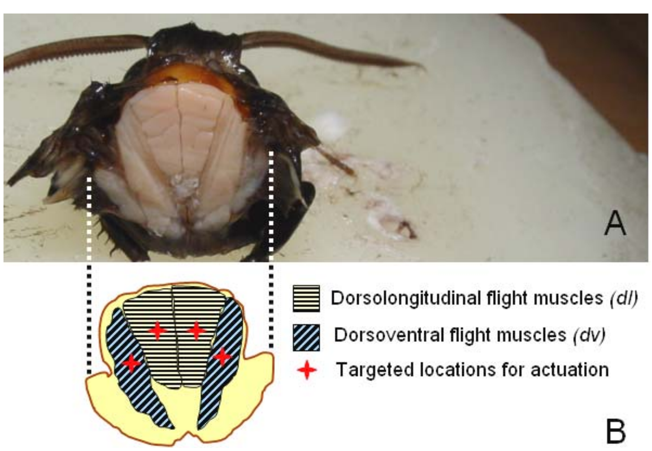


Figure 2: Cross-section (A) and illustrated diagram (B) of the flight muscles powering the up- and down-stroke of Manduca sexta wings.

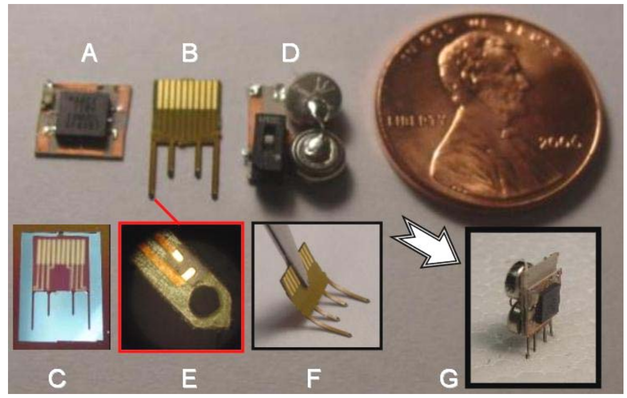


Figure 3: The microsystem including microprocessor (A), flexible probe (B), silicon probe (C) and battery unit for power (D), the close-up view of the tip in (E) with the hole for muscle growth, the flexibility of the probe (F) and the assembled system (G).

an 8×8mm^2 PCB holding the microcontroller (Atmel Tiny13V) and an LED. The microcontroller was electrically connected to the PCB via flip-chip bonding. Wire-bonding was used to connect the PCB to the probe layer. The microfabricated silicon probe is sandwiched between these two layers (Figure 3G). The overall system has dimensions of 8×7mm^2 and total mass of 500 milligrams.

The flexible probe can also be used in tethered setups by utilizing a FFC/FPC connector (Figure 10). All-silicon rigid probes, which provide higher stiffness for narrower cross-section enabling higher density probing, were also fabricated and tested (Figure 3C).

Microprobe fabrication

Flexible PCB technology was used to deposit 18µm of Cu layer on 100µm thick Kapton-polyimide base material (Figure 5). Cu traces were coated with 20µm of LPI soldermask for insulation, except for the locations of the excitation/recording pads. 3µm of Electroless Nickel and Immersion Gold (ENIG) layer was deposited on the pads for biocompability. Each probe has a width of 400µm and each actuation pad is 75×75µm^2 (Figure 4).

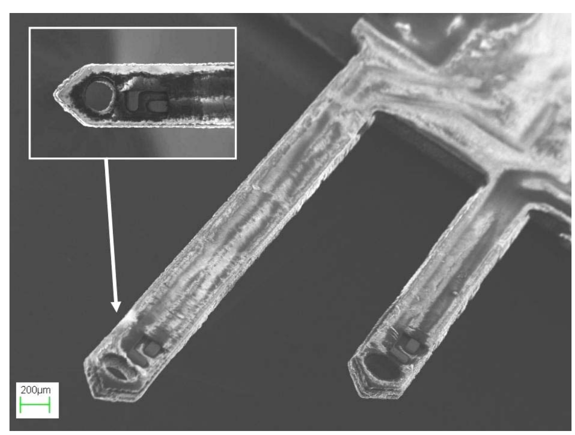
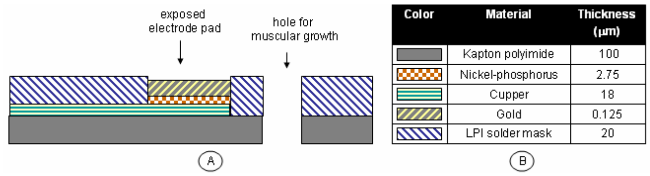


Figure 4: SEM image of the flexible-probe tip with expanded image of the ground and actuation pads



Color	Material	Thickness (μm)
	Kapton polyimide	100
	Nickel-phosphorus	2.75
	Cupper	18
	Gold	0.125
	LPI solder mask	20

Figure 5: Cross-section (A) and description (B) of the layers used in the fabrication of the flexible probe

The relative stress between the implant and the tissue was minimized by matched flexural rigidity (37.5N/m). For an all-silicon probe with a similar stiffness to the flexible probe, a silicon thickness of 30 μm would be required.

Insertion results

The probe based microsystem platforms were inserted to the pupae 7 days before emergence (Figure 6). At this time, a thin thoracic skin is formed under the cuticle of the pupae. If inserted in earlier stages, the fluidity of the tissue prevented adequate sealing around the insert. When inserted later, some of the preformed muscle was damaged, leading to an inefficient bioelectronic interface. In addition, the flexible probes buckle and cannot be positioned to the targeted muscle groups when the thoracic skin is thicker.

Adaptation of probes by the muscle was highly maximized as the muscle grew around and through the hole of the probes (Figure 7iii), as observed under the microscope. Cuticle healing, therefore sealing, at the insertion points can be seen in the same figure (Figure 7i), both of which are indications of structural integration during metamorphosis.

When the probes were extracted, considerable tissue was also removed in pupae-inserted probes, in contrast to adult inserted probes. Moths with inserted probes emerged with a success rate of 90% and have been electrically actuated.

Testing the tissue-probe coupling

The electrical coupling between the probe and the tissue was inspected before actuating the wing muscles using two

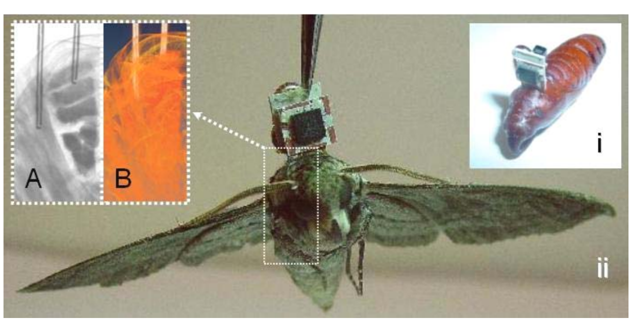


Figure 6: Pupal stage insertion (i) and successful emergence (ii). The microsystem platform on (ii) is held with tweezers to show wing opening of the moth. The X-Ray image of the dotted part (A) shows the probes inserted into the dorsoventral and dorsolongitudinal flight muscles. CT images (B) show components of high absorbance indicating tissue growth around the probe.

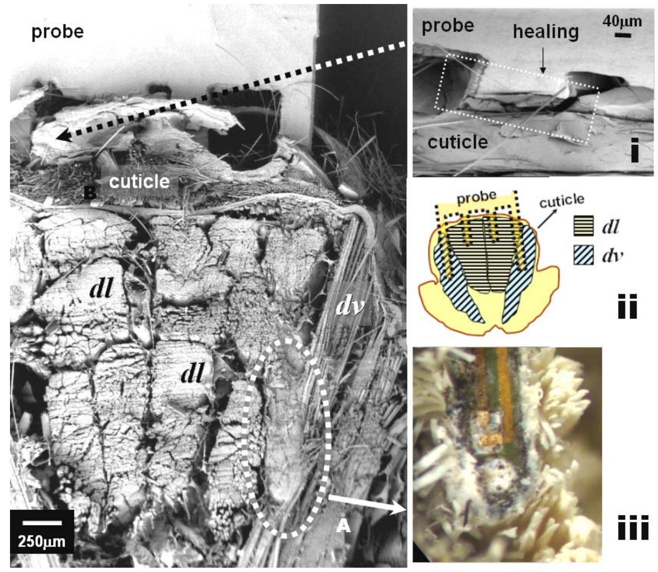


Figure 7: The crossection of thorax near the probe with explanatory schematic (ii) of thoracic flight muscles. Cuticle sealing (i) and muscle growth (iii) around the probe indicates integration by the body. (dl: dorsolongitudinal flight muscle, dv: dorsoventral flight muscle, see Figure 2)

methods: (a) recording the muscle potentials during wing flapping, and (b) measuring I-V curves across the different probes in a tethered flight set-up (Figure 10). Probes that failed in any of these tests were discarded before the wing actuation experiments. The muscle potential recorded from the inserted probe was regarded as an indication of the goodness of the probe operation (Figure 8). The observed inter-spike duration is consistent with the wing flapping rate of moth (20-25Hz).

Rarely, the metal pads of the probe failed due to a currently unknown failure mechanism. Typical I-V curves of good coupling and such a failed probe can be seen in Figure 9. The actuated muscle fibers between the probe pads can be modeled with a simple 3 element RC network (Figure 9). Here R_F denotes the resistance of intra- and extracellular fluids whereas R_L is the leakage resistance of the membrane and C_M is the membrane capacitance. The measured I-V curves (at DC) give the approximate addition of R_L and R_F. The resistivity values obtained from this sum (see Figure 9) for the good probes are in good agreement -

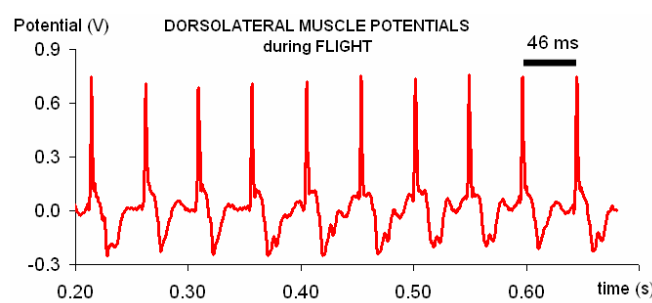


Figure 8: Muscle potential recorded from the dl muscles (see Figure 2 for dl) during wing-flapping. Observed spikes disappeared immediately with the recess of wing flapping.

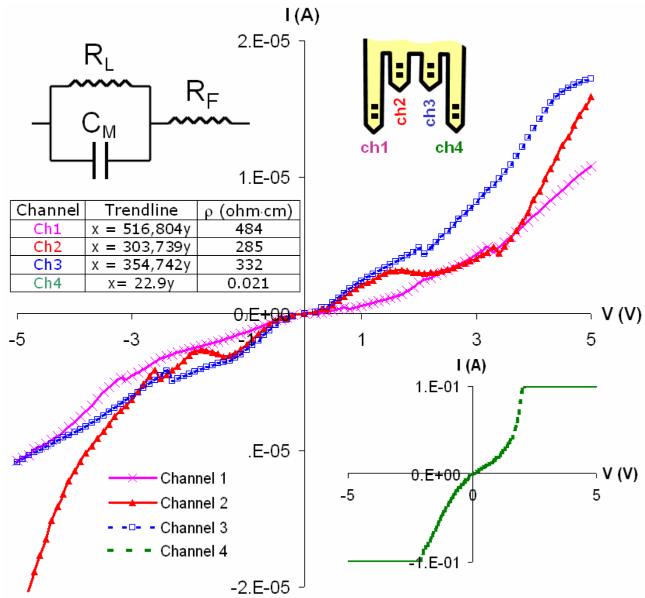


Figure 9: The I-V curves of each electrical pad (measured with Keithley-4200) and the RC network modeling the muscle between the pads. The fitted lines and calculated resistivities are given in the table. Channel 4 (shown separately in 4th quadrant) has poor bio-electrical coupling.

with the range reported for skeletal muscle in the literature (300-500 Ω·cm) [8-10]. The failed probes, however, reads abnormally reduced resisitivity values.

Actuation of Flight Muscles

Phased actuation of probes with biphasic pulses allowed us to control wing motion highly selectively. Upstroke and downstroke actuation on "one" or both wings were demonstrated with power consumption of as low as 10 microWatts. By tethering the moth, we were able to affect the direction of insect flight by controlling the motion of the wing. Figure 10 shows unilateral up- and down-stroke evoked actuation of the wings. The wing actuation and direction of flight can be best seen in movie format [11].

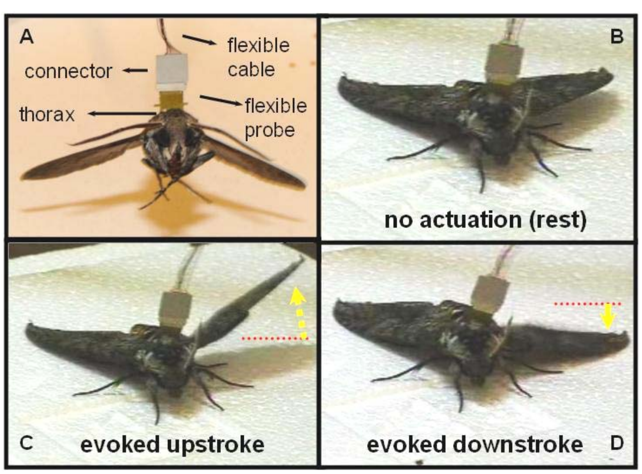


Figure 10: The evoked up- and downstroke of a "single" wing obtained by applying 5V pulses to the indirect flight muscles (snapshots from the recorded movie). Under natural conditions, moths flap both wings together.

3. CONCLUSION

We demonstrated a reliable hybrid tissue-electronics interface in insects that provides flexibility against tissue movement. Inserting the probes at an early pupal stage ensures that the tissue grows around the probes for a highly natural implant. We also showed down- and up-stroke actuation of each wing separately, through which we were able to affect the flight direction of *Manduca sexta.* This work paves the way for future engineering approaches to utilize the bioelectronic interfaces especially for realizing insect cyborgs.

4. ACKNOWLEDGMENT

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