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Musculoskeletal systems that generate extremely fast movements in the trap-jaw ants

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1 Introduction

Quick movement is one of the most important traits for animals to survive in a changing environment. Virtually most animals have evolved strategies to escape from a potential threat.

Understanding the mechanisms underlying adaptive fast movement must be a common issue between biologists and robotics engineers. Biologists have investigated how animals evolved the design principle for generating quick movements. On the other side, robotics engineers must have been interested in the design and control law for their robots to behave like animals.

We here focus on the defensive behavior of the ant genus Odontomachus. The ants have powerful and long mandibles called a “trap-jaw”. The roles of the mandible in ants are generally to hold something to bring back to a nest after hunting, dig the ground to maintain the nest, nurse, and so on. One of the interesting traits of the trap-jaw ants can be seen in their hunting behavior and escape behavior.

The trap-jaw ants capture prey using the mandible with moving at an ultra-high speed [1, 2]. The mandible is also used to generate a defensive jump to escape from a potential threat. Mandible muscles are used to generate mandible-powered jumps as biological actuators. However, the jump speed is much faster than the contraction speed of the adductor muscle. We here performed micro-volume X-ray imaging to understand how the trap-jaw ant generates ultra-fast movement.

2 Materials and Methods

2.1 Animals

Workers of the trap-jaw ants *Odontomachus kuroiwae*, *Anochetus shohki* and *Strumigenys lewisi* were used in this study. The colonies of the ants were obtained from Okinawa, Japan. They were kept in plastic boxes (100×150×50 mm) in the laboratory at Kobe University before use. They were daily fed small infant crickets.

2.2 Behavior analysis

The behavior of the ant was observed and recorded using a high-speed camera (HAS-D71, DITECT). The movement of the mandibles was analyzed using the free motion tracking software Kinovea.

2.3 X-ray imaging

X-ray imaging is powerful equipment to observe the 3D anatomical structure of the exoskeletal muscular system of animals. We here performed an X-ray micro-volume imaging.

To get fine images, we used fixed and dried samples for micro-CT scanning. The ants were anesthetized on ice and fixed with alcoholic Bouin’s fixative solution, stained using 1% iodine diluted in ethanol, and quickly dried. The head of the ants was scanned on the X-ray micro-CT system whose X-ray source was operated at 40kV and 100μA. We obtained the images reconstructed with a voxel size of 5-10μm. The images were saved as a multi-TIF file. The scanned images were then reconstructed to 3 dimensionally using by VGStudio MAX (Volume Graphics, Heidelberg, Germany).

3 Results and Discussion

3.1 Movement of the mandibles

Workers of the trap-jaw ants capture prey with the long and powerful mandible so-called trap-jaw (Fig. 1). The mandible has long sensory hairs that function as tactile mechanosensory receptor organs to detect prey [1] [2]. The sensory neurons that have trunk (giant) axons innervate into the suboesophageal ganglion of the ants. The sensory neurons directly synapse with the closer motor neurons of the mandible. This monosynaptic connection between sensory neurons and motor neurons enables ants to respond quickly to the prey by closing the mandibles.

To observe the movement of the mandible, the ant was mounted on a platform to stimulate the sensory hair on the mandible and initiate the mandible strike. An interesting point is that the speed of closing the mandible is much faster than the speed of muscle contraction. The mandible of the ant

Odontomachus closed within 0.4 msec. The main function of the mandible is holding prey and/ or something to bring into and/or from the nest, and chewing foods. This indicates the adductor muscle is a slow muscle. This suggests that a power amplification system is employed when performing the ultra-fast movement of the mandible.

The ants show bouncer defensive jump to avoid a potential threat. All workers do not respond to a threat by jumping, but only aggressive ones [3]. From the video analysis, the closing speed of the mandible was about 140×10^4 degree/s and the jump speed was about 1 m/s. The spring mechanism of the exoskeleton system must one of the candidates. We then focus on the role of the musculoskeletal system of the head of the ant.

Figure 1: The trap-jaw ants, *Odontomachus kuroiwae* (A), *Anochetus shohki* (B), and *Strumigenys lewisi* (C)

3.2 Exoskeletal muscular system of the mandible

To investigate how the ants generate such an ultra-fast movement, we performed X-ray microvolume imaging using an X-ray micro-CT. We then observed and identified the exoskeletal muscular system. Many of studies observed and drew the anatomy of the mandibular muscles [4] [5]. However, anatomical observation after the dissection of animals made us difficult to understand the functional mechanisms underlying the structure of the body. X-ray microvolume imaging provides us with 3D structure images of the exoskeletal muscular system of the ants. Micro CT images revealed the anatomical structure of the mandible adductor muscles (Fig. 2). Contraction of the adductor muscles pulling the tendon attached to the joint closes the mandible. This anatomical design allows the trap-jaw ants to keep holding prey tightly, even if the muscle fibers of the adductor muscle are thin and the contraction length of each fiber is short.

The structure of the joint was carefully observed using micro-CT imaging. Analyzing the images suggested to us that there is a locking structure at the joint. The structure would function as a latch system of the mandible [6]. The latch system of the mandible enables the ants to utilize a buckling mechanism that accumulates energy in the exoskeleton to power the ultra-fast movement.

The ants can move the mandible slowly from the fully opened position. There must be a mechanism to unlock the mandible. From microscopic observation, we found that mouth parts also moved before the ant close the mandible quickly but didn't move when closing the mandible slowly. This suggests that the mechanisms of mouth parts movement are also important. At moment, the detail is still unclear and further investigation is necessary.

Insects evolved buckle systems to generate fast movements using slow muscles. In locusts, it is reported that the exoskeleton structure of the femur-tibia joint change when it jumps and kicks. This bending of the exoskeleton function to accumulate energy to generate the power of jumping [7, 8]. The body size of insects is rather small compared to vertebrate animals. Insects must have evolved unique exoskeletal muscular systems to generate high-speed and powerful movement. Understanding the design principle and control principle of the fast movement of insects must be to help us to develop a novel design and control law for adaptive movement in artificial systems.

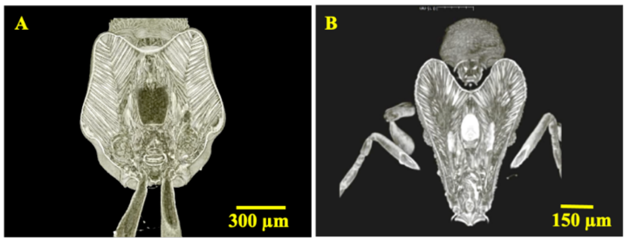

Figure 2: X-ray micro-CT scanning images, *Anochetus shohki* (A) and *Strumigenys lewisi* (C)

4 Conclusion

Fast movement is one of the essential traits for insects to survive a threat. The trap-jaw ants evolved buckling systems in the joints to generate ultra-fast movements. Since the resources available for the ants to generate complex movements are restricted, they evolved buckling mechanisms to generate ultra-fast movement using slow muscles. They accumulate energy in the exoskeleton and release it instantaneously. Understanding the mechanisms that insects evolved to generate fast movements thus provide us with novel design principle and control law of artificial systems.

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5 References

[1] W. Gronenberg, J. Tautz, and B. Hölldobler, "Fast trap jaws and giant neurons in the ant *Odontomachus*," *Science,* vol. 262, no. 5133, pp. 561-563, 1993.
[2] W. Gronenberg, "The trap-jaw mechanism in the dacetine ants Daceton armigerum and Strumigenys sp," *J Exp Biol,* vol. 199, no. Pt 9, pp. 2021-33, 1996.
[3] H. Aonuma, "Serotonergic control in initiating defensive responses to unexpected tactile stimuli in the trap-jaw ant *Odontomachus kuroiwae*," *J Exp Biol,* vol. 233. 2020.
[4] W. Gronenberg, "The fast mandible strike in the trap-jaw ant Odontomachus," *J Comp Physiol A,* vol. 176, no. 3, pp. 399-408, 1995.
[5] W. Gronenberg, J. Paul, S. Just, and B. Holldobler, "Mandible muscle fibers in ants: fast or powerful?," (in eng), *Cell Tissue Res.,* vol. 289, no. 2, pp. 347-61, Aug 1997.
[6] H. Aonuma, K. Naniwa, Y. Sugimoto, K. Ohkawara, and K. Kagaya, "Embodied Latch Mechanism of the Mandible to Power at an Ultrahigh Speed in the Trap-jaw Ants *Odontomachus kuroiwae*," *bioRxiv,* p. 2022.12. 05.519247, 2022.
[7] D. Cofer, G. Cymbalyuk, W. Heitler, and D. Edwards, "Neuromechanical simulation of the locust jump," *J Exp Biol,* vol. 213, no. 7, pp. 1060-1068, 2010.
[8] M. Burrows and G. P. Sutton, "Locusts use a composite of resilin and hard cuticle as an energy store for jumping and kicking," *J Exp Biol,* vol. 215, no. 19, pp. 3501-3512, 2012.