Kinematics and Mechanics analysis of trap-jaw ant Odontomachus monticola

Wenteng Hao, Guang Yao, Xiangyu Zhang and Deyuan Zhang*

School of Mechanical Engineering and Automation, Beihang University, Xueyuan Road No.37, Haidian District, Beijing 100191, P.R. China

*Correspondence: zhangdy@buaa.edu.cn

Abstract. Trap-jaw ants of the genus Odontomachus exhibit spectacularly rapid predatory and fugitive strikes. In order to reveal the extraordinary impact resistance of the apical teeth material, we analyzed the kinematics and mechanics of the closing mandibles. Odontomachus monticola is an Odontomachus species and extensive in China. We video-recorded jaw-strikes to measure the closing velocity and acceleration. The experimental results showed that O. monticola’s mandibles closed at a highest velocity of 35.42 m/s and a highest acceleration of 750,000 m/s² within an average duration of 0.16 ms. In addition, in order to measure the strike force, we developed an extraordinary measuring method with poly (vinylidene fluoride) (PVDF) piezoelectric film. First, the dynamic calibration of the PVDF piezoelectric film was conducted, then the calibrated piezoelectric film was struck by O.monticola. Finally, the mandible strike force was calculated according to the calibration result and the output signal. The measurements results demonstrated that the strike force ranges from 102.2 N to 235.2 N, which is impressive contrast with O.monticola’s body weight.

1. Introduction

Arthropods are celebrated for their morphological variation, and many species have developed extraordinary characteristics for a diversity of functions such as the exceptional jumping ability of fleas [1], the extreme rapid takeoffs of locusts and flies [2], and the crushing strikes of stomatopods [3]. These exceptional speeds and accelerations are always accomplished under the help of specific innovations such as latches, lever arms and spring mechanisms which assist in storing and releasing huge amounts of energy [4]. One surprising example is the extremely fast mandible strikes of trap-jaw ants, which have the rapidest speed in the animal kingdom [5].

The morphological and neurobiological characterization of the mandible strikes of trap-jaw ants were carried out by Gronenberg and his groups in a list of papers [6-10], and the species Odontomachus bauri’s mandible strikes can achieve impressively high speed of more than 60 m·s⁻¹ [5]. In addition to equipping trap-jaw ants with the capability to disable prey, the mandible snaps have been evolutionarily co-opted for ballistic movement. These movements are shown as ‘bouncer defense’ jumps [11], where the ants are impelled horizontally away from a threat, and ‘escape jumps’, where the mandibles are placed against or aimed at the substrate then fired, launching the ants into the air [5]. The mandible was modeled as a thin rod of uniform density, which rotates around a fixed axis, by Patek et al [5], whereas actually the interior of mandibles consists mainly of a large tracheal sac filled with air [12]. The mass of mandibles is very light, however, O.monticola’s escape jumps surprisingly...
yielded heights ranging from 6.1 to 8.3 cm and the mean horizontal distance of defense jumps reached 22.3 cm (5.3–39.6cm) [5], which are both much longer than its mean body length of 1.31 cm. Furthermore, there is always obvious sound when the jaw strikes. Therefore, we presumed that the extremely light mandibles generate significantly instantaneous strike force to propel the ants to jump. In addition, the actual strike force is still unexplored, no researchers have measured trap-jaw ants’ instantaneous mandible strike force.

Therefore, investigations were firstly conducted on visualizing the complete strike process of Odontomachus monticola by using available imaging technology. And then, the mandible strike kinematics was analyzed simultaneously. In addition, the actual strike force was measured by an extraordinary measuring method with poly (vinylidene fluoride) (PVDF) piezoelectric film. The objectives of our work were as follows: (i) to characterize the kinematics of trap-jaw strikes using high-resolution video images; (ii) to measure the strike force using PVDF piezoelectric film and the force sensor.

2. Materials and Methods

O.monticola workers were collected in Yunnan province in May, 2016. Colonies were maintained in an ecological nest with porous stones and fed a diet of mealworms, every two days. The body mass of O.monticola ranges from 16.6 mg to 22.5 mg (Sartorius BS 224 S Max=220g, d=0.0001g electronic balance). Their mandibles’ lengths range from 1.61mm to 1.89mm (OLYMPUS SZX16 stereomicroscope).

2.1. Kinematics analysis

In order to film of trap-jaw strikes, a high-speed camera (50,000 frames per second, 20 μs shutter speed; Olympus I-Speed 3) was used. Ants were fixed using a drop of dental wax (applied to the top of head) to the end of a thin rod that could rotate to keep the jaws perpendicular to the high-speed camera’s axis. And the ants can strike freely. Then the ants were stimulated to strike by touching their ‘trigger hairs’ with a thin metal probe. The kinematic data was used to calculate velocity, acceleration and the lag time (if any) between the first mandible to close and the second.

2.2. Strike force measurement

The instantaneous mandible strike force is difficult to be obtained with common miniature force sensors because of the micro-scale of the mandible and the mandible’s apical teeth. Therefore, we developed an extraordinary measuring method to acquire the strike force.

PVDF piezoelectric film is a new type of polymer piezoelectric material. Because of its light weight, thin thickness, high sensitivity, extremely fast dynamic response and wide frequency respond range, it has broad application prospect in the force impact measurement field [13]. PVDF piezoelectric film will come to electrical polarization and produce electric charges when exerted by stress. And the charges are proportional to the mechanical stress. When the mechanical stress is removed, the piezoelectric film will return to electrically neutral [13]. We selected SDT1-028K piezoelectric sensor (Made by MEAS Cooperation, USA), which can be used for impact monitoring. This kind of piezoelectric film (28 mm × 13.2 mm) is only 75 μm thick, and the piezoelectric constant is -33 pc/N. The SDT1 piezoelectric sensor consists of a rectangle silvered piezoelectric film and a concentric cable of the length of 18 inches. And the piezoelectric film is doubled back to form a self-shielded area allowing it to work in high-EMI environment.

First, the dynamic calibration is essential to measure the strike force using the PVDF piezoelectric film. Therefore, a particular and effective dynamic calibrating method was adopted to calibrate the piezoelectric film. Through the observation and analysis of the apical teeth’s shape, as shown in figure 1, the apical teeth are made up with three different teeth including two canine teeth (1,2) and one cheek tooth (3). It is obvious that the two canine teeth are on the outside of the mandible, while the cheek tooth is closer to the root of the mandible than the other two teeth.
Figure 1. Scanning electron micrographs of the apical teeth. (a) a dorsal view of left mandible’s apical teeth. (b) a dorsal view of right mandible’s apical teeth.

In order to calibrate the piezoelectric film accurately, a method of free fall was adopted. An impact hammer shown in figure 2 was made by solidifying a small steel ball (Diameter: 8mm) with the cut-off apical teeth by using epoxy glue at the temperature of 60°C for 6 hours. Then a string for holding in hand is glued at the end of the impact hammer. The non-uniform mass distribution in the impact hammer can guarantee the apical teeth pointing to the force sensor during the free fall process.

Figure 2. Strike force measurement experiment setup. (a)The dynamic calibration setup of PVDF piezoelectric film. (b)The mandibles striking experiment setup.

The dynamic calibration setup is shown in figure 2 (a). The PVDF piezoelectric film was glued tightly on the surface of the impact cap of the PCB force sensor (Made by PCB Cooperation, USA) by cyanoacrylate glue. The impact cap was installed at a heavy pedestal and connected with the oscilloscope (Tektronix TDS 2012C). The positive and negative electrode of the PVDF piezoelectric sensor were connected with the charge amplifier (B&K 2692) to amplify the charge signals, which were ultimately delivered to the oscilloscope as well. At first, the force sensor on which the calibrated PVDF piezoelectric film was glued was struck by the free falling apical teeth of the mandible. The heights of free fall range from 5 cm to 21 cm with the increment of 2 cm. Different heights of free falling apical teeth produced different impact forces and different output charges. Then through the linear fitting of the symbols, the calibration result can be obtained.

Furthermore, a platform (shown in figure 2 (b)) where the calibrated PVDF piezoelectric film was struck by the O.monticola was set up. Likelihood, the ants were fixed using a drop of dental wax (applied to the top of head) to the end of a thin rod that could rotate to keep the jaws perpendicular to the plane of the piezoelectric film. And the ant can strike freely, meanwhile the PVDF piezoelectric film was kept horizontal. The positive and negative electrode of the PVDF piezoelectric film were
connected with the charge amplifier to amplify the charge signal, which was ultimately delivered to the oscilloscope. Then the ants were stimulated to strike by touching their ‘trigger hairs’ with a thin metal probe. The output signals were recorded every time when the ant struck the film. Finally, the strike force was calculated according to the output signals and the calibration result.

3. Results and Discussion

![Figure 3](image)

Figure 3. The high-speed kinematics of trap-jaw strikes. (Scale bars: 1 mm) (a) A side view of an O. monticola worker with mandibles cocked in preparation for a strike. (b) The first mandible to fire attains a lightly higher velocity than the second mandible. (c) The second mandible to fire attains a higher acceleration than the first mandible. (d) High-speed video images present a typical unobstructed strike (20 μs between each frame). The duration time of the strike is 0.18 ms.

The high-speed video results are shown in figure 3. As clear from the results, O. monticola’s mandibles closed at a highest velocity of 35.42 m/s and a highest acceleration of 717,299 m/s² within an average duration of 0.18 ms. From figure 3 (b), before the first mandible scissored past the second one, the first mandible accelerated to 35.42 m/s, and then a mild fluctuation was witnessed; however, the second mandible’s velocity gently increased during the first 70 μs, and then experienced a considerable boost from 4.29 m/s to 30.49 m/s. From the figure 3 (c), before the first mandible scissored past the second one, its acceleration continued to decrease, and even became negative during the first 90 μs, while the second mandible’s acceleration continuously raised and enjoyed the highest acceleration approximately at 90 μs.
With high-resolution video images, asynchronous locomotion of the mandibles was observed. In all strikes, the left and right mandibles closed sequentially, with an obvious average interval of 0.08 ms. Both mandibles braked before reaching the midline, demonstrating that maximal force generates before the mandibles meet.

| Height/cm | Impact force/N | The output voltage of the film/mv | The output charge of the film/pc |
|-----------|----------------|----------------------------------|----------------------------------|
| 5         | 7.12           | 140                              | 70                               |
| 7         | 8.01           | 172                              | 86                               |
| 9         | 8.90           | 184                              | 92                               |
| 11        | 10.68          | 210                              | 105                              |
| 13        | 12.19          | 220                              | 110                              |
| 15        | 13.34          | 256                              | 128                              |
| 17        | 16.81          | 320                              | 160                              |
| 19        | 22.68          | 442                              | 221                              |
| 21        | 31.14          | 618                              | 309                              |

The calibrated data is presented in table 1. The height of the free falling apical teeth was changed to obtain different strike forces. And according to the parameter settings of the charge amplifier, the value of the charge signal is two times of the value of the voltage signal.

![Figure 4](image.png)

**Figure 4.** The calibration results of the PVDF piezoelectric film. (a) The two different output signal of one struck. (b) The calibration line of the PVDF piezoelectric film.

The calibration results are shown in figure 4. The output signals of PVDF piezoelectric film and the force sensor of one struck are illustrated in figure 4 (a). From the graph, the output signals of these two were generated simultaneously. The amplitude of the voltage of the force sensor reached 176 mV, while the amplitude of the voltage of the PVDF piezoelectric film was 68 mV. And it can be seen that response time of the force sensor was much shorter than that of the PVDF piezoelectric film, only taking 3.2 ms. Figure 4 (b) presents the calibration line of the PVDF piezoelectric film. Through the linear fitting of the symbols, the fitted equation was obtained:

$$Q(\text{pc}) = 9.78F(N) + 0.09$$

where $Q$ is the output charge and $F$ is the strike force.
Figure 5. The output charge when an O.monticola worker struck the PVDF piezoelectric film.

The output signal of one struck is indicated in figure 5. The duration of strike was 6 ms (the blue symbols) and after that the PVDF piezoelectric film gradually returned to electrically neutral (the magenta symbols). As clear from the graph, the maximum of the output charge is 2300 pc. All the output charge signals ranged from 1,000 to 2,300 pc during the repetitive impact experiments of 30 times.

Finally, the strike force ranging from 102.2 N to 235.2 N was calculated according to the output charge signals and the calibrated result.

4. Conclusions
The strike process of O.monticola’s mandibles was characterized. The highest closing speed of the mandibles surprisingly exceeding 35 m/s occurred on the first mandible, while the highest acceleration was occupied by the second mandible. And the asynchronous movements of the mandibles were demonstrated with an average interval of 0.08 ms. In addition, a new method was provided to obtain the accurate micro-scale strike force, which can effectively overcome the drawback of qualitative measurement by the piezoelectric films in traditional measuring methods. The result ranges from 102.2 N to 235.2 N which is astonishingly impressive contrast with O.monticola’s body weight. The extreme instantaneous strike force may imply the extraordinary impact resistance of the apical teeth material.

Acknowledgments
The authors would like to thank the financial support from the National Natural Science Foundation of China (No.51475029).

References
[1] Bennet-Clark H C and Lucey E C 1967 The jump of the flea: a study of the energetics and a model of the mechanism J. Exp. Biol 47 59-67
[2] Bennet-Clark H C 1976 The Insect Integument, ed Hepburn H R (Amsterdam: Elsevier) pp 421-43
[3] Patek S N, Korff W L and Caldwell R L 2004 Biomechanics: deadly strike mechanism of a mantis shrimp-this shrimp packs a punch powerful enough to smash its prey’s shell underwater Nature 428 819-20
[4] Gronenberg W 1996 Fast actions in small animals: springs and click mechanisms J. Comp. Physiol. A 178 727-34
[5] Patek S N, Baio J E, Fisher B L and Suarez A V 2006 Multifunctionality and mechanical origins: ballistic jaw propulsion in trap-jaw ants PNAS 10312787-92
[6] Gronenberg W 1995 The fast mandible strike in the trap-jaw ant Odontomachus.1.Temporal properties and morphological characteristics J. Comp. Physiol. A 176 391-8
[7] Gronenberg W 1995 The fast mandible strike in the trap-jaw ant Odontomachus.2. Motor control 
J. Comp. Physiol. A 176 399-408
[8] Gronenberg W 1996 The trap-jaw mechanism in the dacetine ants Daceton armigerum and 
Strumigenys sp J. Exp. Biol 199 2021-33
[9] Gronenberg W and Tautz J 1994 The sensory basis for the trap-jaw mechanism in the ant 
Odontomachus bauri J. Comp. Physiol. A 174 49-60
[10] Just S and Gronenberg W 1999 The control of mandible movements in the ant Odontomachus J. 
Insect Physiol 45 231-40
[11] Carlin N F and Gladstein D S 1989 The ‘bouncer’ defense of Odontomachus ruginodis and 
other odontomachine ants (Hymenoptera: Formicidae) Psyche 96 1-19
[12] Gronenberg W, Tautz J and Hoildobler B 1993 Fast trap jaws and giant neurons 
in the ant odontomachus Science 262 561-3
[13] Khan A, Abas Z, Kim H S and Oh I K 2016 Piezoelectric thin film: an integrated review of 
transducers and energy harvesting Smart Materials and Structures 25