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Hard to be killed: Load-bearing capacity of the leech *Hirudo nipponia*

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ABSTRACT

With the evolution for several millions of years, leeches have developed a perfect capability to resist mechanical loads, which provides many inspirations to engineer new materials and new devices. To uncover the mechanism of its strong survival ability, several mechanical approaches, such as compression, tension, adhesion, impact and blood suction experiments were tried. Our experimental results show that a leech (*Hirudo nipponia*) can surprisingly withstand a compressive force of nearly 10^6 times its body weight. In tension, this animal demonstrates large deformation and its strain can reach a value bigger than 3. To avoid being removed from the host skin, it produces an adhesion force superior to 118 times its body weight, and it can endure an impact force at least 1500 times its weight. Also the leech skin can bear an internal fluid pressure of around 6 times the atmospheric pressure. These data show that the leech cannot be killed easily through normal mechanical loading approaches. All these amazing performances lie in hierarchical structures and ductility of the skin with highly developed and compact annuluses, and this feature is beneficial to leech's survival.

1. Introduction

With the evolution for millions of years, living creatures have formed very robust capabilities to adapt to the environment and survived to date. The typical examples include the water walking of striders (Hu et al., 2003; Hu and Bush, 2010; Koh et al., 2015) and mosquitos (Wu et al., 2007), wall climbing of geckos (Autumn et al., 2000; Gao et al., 2005), strong adhesion to solids of tree frogs (Federle et al., 2006), etc. These magic behaviors have spurred the admirations to explore their secrets, thus a cutting-edge disciplinary, i.e. bionics is quickly emerging, and many novel materials and devices have been invented, such as superhydrophobic fabrics (Zhou et al., 2012), wet-tolerant adhesive patches (Baik et al., 2017), super-tough fibers (Dalton et al., 2003), and strong shear binding-on materials (Qu et al., 2008).

Another special creature which should not be forgotten is leech. Most people feel that the leech is a terrifying animal, as some species of them feed on blood of hosts, such as *Hirudo nipponia*. However, medical leech's blood-taking function is helpful to eliminate blood stasis of human bodies, which was first reported by the Greek poets, Nicader of Colophain, in his medical poems in 200 BCE (Wells et al., 1993). Later, an interesting legend was recorded in the book *Lun Heng* that, the King Hui of Chu (?-B.C. 432) swallowed a leech and then his abdominal pain was cured (Wang, 1974). Blood-sucking leeches can actively take animal's blood, but they are not always attackers–they are also potentially harmed by their hosts. Notably, leeches appeared on the earth at least 50 million years ago (Bomfleur et al., 2015), indicating that they must have evolved to possess strong abilities to survive.

Many challenges await the blood-sucking leech for obtaining the blood of hosts. The first one is that they might be trampled by big animals, such as human beings, cattle, horses and goats (Keim, 1993). Secondly, when the leech is attached on an animal's skin, the animal would feel pain and starts to shake, run and jump. To avoid being removed, the leech must produce a very strong adhesion force on the skin. Moreover, animals with a long tail, such as cattle, often use the tail as a defensive weapon to whip the leech. If all these threats do not harm the leech, it then succeeds in tasting blood at will. This disgusting parasite is very greedy, as it absorbs too much more blood than we could expect at first; but its body never explodes due to internal pressure, indicating its high elasticity. Therefore, the question is how and why the leech has the excellent capability of resisting external loads, and how to kill it easily. Accordingly, several mechanical approaches, such as compression, tension, adhesion, impact and blood suction experiments were tried to pursue this goal, directed towards a comprehensive exploration on the limit loads that a leech can withstand.

The outline of this article is as follows. In Section 2, material and methods are formulated in detail. Next, all kinds of experiments, such as compression, tension, adhesion and pulling off, impact and fluid filling are carried out to test the limit loading capacity of the leech. Then the microstructures of the skin are observed by the optic devices. Also, theoretical models are given to predict the related behaviors,

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which are compared with the experimental results. Finally conclusion follows up.

2. Material and methods

2.1. Material

In the experiment, one common leech named *Hirudo nipponia* was selected for this study, which has better performances than some other species of leeches. Throughout this investigation, three groups of leeches with the average mass $M = 0.1$, 0.18 and 0.26 g were sorted, which were named as Group I, II and III, respectively. Leeches (*Hirudo nipponia*) were bought from the company titled *Chongqing Zhiwei biotechnology Co Ltd*, and then kept in a vessel in our lab in the room temperature. The earthworms (*Pheretima guillelmi*) used for comparison were bought from the Lou Jun earthworm breeding farm in Rugao of Jiangsu Province, and then kept in a vessel in our lab in the room temperature. They are used for medical purposes, belonging to consumables.

2.2. Compression and tension

The experiments on compression and tension of the leech are both conducted on the universal testing machine, and the loads are applied on the leech quasi-statically. The experiments are performed under the room temperature, around 25 °C. The morphology of the leech during loading process is recorded by a camera (Nikon D720). The stress-strain curves can be given by the testing machine. In the compression experiment, two vertically adjustable acrylic slabs are adopted to clamp the leech (inset of Fig. 1a), which are parallel and mounted on the universal testing machine (Autograph AG-X 250 kN). The loading velocity is 0.007 mm/s, whose strain rate is 0.16 min^{-1} (less than 2.5 min^{-1}), which satisfies the requirement of quasi-static loading (Brainerd, 1994; Carrington and Gosline, 2004). Firstly, the range of the limit load is tried, where six specimens of *Hirudo nipponia* with weight being $M = 0.18 \pm 0.02$ g are tested. The compressive forces of $P = 1.0$, 1.4, 1.6, 2.0, 2.5 and 3 kN are respectively applied on the leeches to find if it is dead or not, and the limit load is judged in the vicinity of 1.6 kN. Next, three groups of alive leeches with different body mass $M = 0.10 \pm 0.02$, 0.18 ± 0.02 and 0.26 ± 0.02 g (Group I, II and III) are selected to test, where each group includes 10 leeches for specimens. The compressive load is applied on each one with the loading step being 0.2 kN. For example, for the first one, the load is 0.6 kN; for the second one, the load is 0.8 kN; and for the third one, the load is 1.0 kN, and so on. After compression, all the leeches are placed for one week and observed whether they are alive or not. We have observed that when the leech is dead, its body becomes very soft and smells bad, and its body length becomes bigger. In this case, the leech can never respond to any stimuli, even being needled, and we can judge it has died. And vice versa, an alive leech will quickly respond to a gentle stimulus, and its body does not smell bad. When the leech is compressed to die one week later, the corresponding force is just the tolerant compressive load. For accuracy, each value is confirmed by another three leeches with the additional compressive experiments.

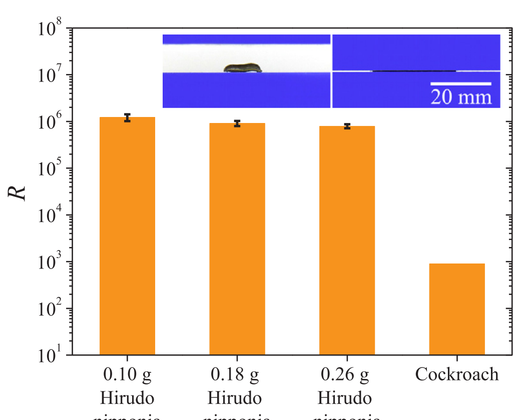

Fig. 1. Compression experiment. The ratio between the limitation compressive force and mass for leeches (Group I, II and III) and cockroaches (Jayaram and Full, 2016), where $R = P/(Mg)$. Inset is the loading process of a leech under compression, where its mass $M = 0.1$ g, initial length 12.95 mm, width 3.7 mm, height 2.66 mm, and the contact area with the substrate being 30.69 mm^2. After compression to the limit, the length is 28.34 mm, width 5.83 mm, height 0.49 mm, and the contact area being 140.94 mm^2.

In the tensile experiment, also three groups of alive leeches with body mass $M = 0.10 \pm 0.02$, 0.18 ± 0.02 and 0.26 ± 0.02 g are tested, where each group includes 3 specimens. The leech is clamped by the fixture in the universal testing machine (UTM–1432). The surface of the jaw is serrated with width being 1.02 mm and depth being 0.78 mm, which can prevent the slipping of the leech. We can measure the force to fix the loading ends from the jaw via the force gauge of UTM–1432 with the precision of 0.1 N, which is around 78.7 ± 7.1 N. The loading velocity is 0.083 mm/s, and the loading process can be viewed as being in a quasi-static state (Brainerd, 1994; Carrington and Gosline, 2004). The skin is taken from the leech by cutting the leech and removing the guts.

2.3. Adhesion and impact

In the adhesion experiment, Leeches belonging to Group I, II and III are tested, where each group includes 5 specimens. When the leech is adhered to the acrylic or glass surface for 2 s, its adhesion force keeps constant. Noticing that there are two suckers for one leech, their adhesion forces are both measured. The adhesion forces are then measured by a force gauge (ZP-100 N, with the precision of 0.01 N) when the leech is pulled off from the surface.

As for impact experiments, leeches belonging to Group I, II and III are tested, where each group includes 21 specimens. The leech is launched by a slingshot, and then it impacts on the iron surface, with the launching velocity being in the range of 18–56 m/s. The impact load on the leech is recorded by a high speed impact force sensor (Suzhou OBTE, with the data collection frequency 30 kHz), and the impact process is recorded by a high speed camera (HotShot cc, 5000 f/s). The definition of the maximum impact force for a living leech is the value when it is at the critical state between death and living. In practice, it is very difficult to judge it is dead or not when it is after impact, as some of them may be in shock and not really die. To observe its living state, we keep these leeches after impact for one week. After one week, we identify whether these leech are alive or dead, and the corresponding impact force value can be determined. Earthworms for comparison are tested in the same condition as that of the leeches.

2.4. Blood suction and internal fluid pressure

Leeches belonging to Group I, II and III are tested, where each group includes 5 specimens. A commercially used frog (which can be bought from the fresh market in Qingdao city) is used as the host, and the leech sucks its blood thus the body begins to expand. An electronic balance (PT-405, with the precision 0.01 mg) is adopted to measure the body weight before and after the leech sucks enough blood. For a hungry leech, it quickly sucks the skin when it attaches the fog within several seconds. When the leech sucks enough blood, it will not attach to the fog skin naturally; and even we put it on a new fog again, it won't suck the fog any more. For an alive creature, we judge that it has sucked enough blood.

To estimate the critical internal pressure caused by fluid that the leech skin can bear, a simulation experiment is conducted, i.e. injected water is used to replace blood, and this way is convenient to realize.