REVIEW ARTICLES

Research progress in gecko locomotion and biomimetic gecko-robots*

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Abstract Geckos are known for their excellent ability to climb walls and run on ceilings. Previous studies of the gecko's locomotive and adhesive mechanisms, its neuro-sensory and neuro-modulatory systems, its fabrication of artificial setae array, and other related developments, have inspired further research on gecko-based and gecko-like robots. Key research findings in this area are reviewed in the present paper.

Keywords: *gecko*, locomotion, biomimetic, modulation, gecko-like robot.

Locomotion is a fundamental property of both natural and artificial systems. Geckos are known for their excellent locomotive and adhesive abilities upon a variety of surfaces. A large number of research have been carried out on the gecko's locomotive and adhesive mechanism[1,2], but no systematic study that integrates the current understanding of the gecko's morphology, locomotive mechanics and adhesive mechanism has been conducted. Three dimensional-terrain obstacle-free (3DOF) robots, generally called wall-climbing robots, possess the ability to move on various surfaces—smooth or rough, horizontal floors, vertical walls, up-side-down ceilings and so on. 3DOF robots have stringent requirements and wide applications[3—5] and, most recently, have been constructed by mimicking the movement behavior of geckos[6]. Currently, the performance of the 3DOF robot—its degrees of robustness, agility, and reliability and its ability to mimick natural animal's behavior—is far from satisfactory compared to that required by engineers in the laboratory. In order to improve the performance of the 3DOF robot, we must fully understand the locomotive mechanisms, relevant attaching and detaching principles, controlling regulations, neuro-sensory and neuro-modulatory rules, the bottlenecks in design and manufacture of an artificial gecko-based robot's pads and key points for improving energy efficiency[7]. In this paper, we review the progress made in this field and discuss perspectives of future development.

1 Locomotion and driving mechanics

Animal locomotion results from the movement of bones around joints, where bones are the links of a motion mechanism and skeletal muscles are the actuators driving the mechanism. The gecko has 28 vertebrae that rotate relative to each other. The fore- and hind-limbs of two species of geckos have been dissected[8,9]. The first is a ground-dwelling gecko lizard (*Eublepharis macularius*, *EM*) and the second is a highly specialized climbing gecko lizard (*Gecko gecko*). Zaaf et al. measured the muscle mass, mean muscle fiber lengths, cross-sectional areas and moment arms of both gecko species. They concluded that climbers, such as the *G. gecko*, generally possess powerful retractor muscles crossing the shoulder and hip joints. Additionally, the specialized climber is able to exert higher flexion moments across the elbow, which prevents the animal from falling backwards. However, *G. gecko* appears to be constrained in its ankle extension capabilities by the presence of adhesive toe pads. The level-running species, *EM*, on the other hand, shows a relatively strong development of the extensor muscles in the lower limbs, allowing these lizards to run in an erect posture. As expected, both species show large likenesses on a gross

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morphological basis when comparing their phylogenetic similarities. Adaptations to their preferred locomotor substrate become apparent only when considering the functional properties (i.e., joint moments) of the appendicular musculature. Ding[10] and Zhang[11] have dissected the *G. gecko*, and investigated, in considerable detail, the skeletal and muscular features, but not related to locomotive abilities.

We have systematically studied the *G. gecko*'s bone structure, relative muscle weight (muscle weight / body weight × 100%, defined as RMWe) and relative muscle length, width and thickness (muscle length, width and thickness / head-to-body length × 100%, defined as RML, RMWd and RMT respectively)[12]. Our results indicated that the maximum RMWe was 1.094% for *Puboischiotibialis*, and the minimum RMWe was 0.004% for *Extensores digitorum breves*; the maximum RML, RMWd and RMT were 3.678% for *Pectoralis*, 1.322% for *Puboischiotibialis* and 0.423% for *Caudifemoralis*, respectively. These measurements show that the ratio of muscle weight of forelimb to post-appendage is 1:1.4, suggesting that the post-appendage plays a leading role in gecko locomotion.

On the basis of a 3-dimensional video recording and gait analysis, we discovered that during locomotion, the angle between the tibia and the femur (α) increases from 60° to 150°, the angle between the femur and the body plane (γ) rotates from −20° to 40°, and the angle between the femur and the direction of the vertical line of motion (β) rotates from −80° to 80°. Each foot was coming into contact with the target surface and was rotating relative to the tibia. Ventral movement on the target surface resulted in great distances. The rotational angle of the femoral bone in relation to the body decreased from 20° to 40°, in order to pull up the body to enable it to stride on the floor successfully. When a gecko moves on a wall and ceiling, its ventral side nearly surfs upon the target surface. Moving in this manner enables the gecko to reduce the turnover torque generated by its body mass.

Our unpublished studies suggest that the mechanism for a gecko-like robot should set one degree of freedom for a cylinder pair for the femur and tibia and two degrees of freedom for the sphere joints between the foot and tibia and between the femur and body. Traditionally, robots are driven by heavy, high-speed motors, making the design of a more flexible and efficient robot nearly impossible. However, recent developments in smart materials, such as artificial muscles, have made possible the emergence of a lighter weight, more efficient and flexible gecko-robot that uses a distributed actuator. Through results provided by anatomical studies and gait analyses of the gecko, robotics engineers may become inspired to adopt the gecko's controlling regulation for locomotion in determining the optimal geometric design fin building gecko-like robots.

2 The adhesive mechanism of the gecko foot

A key point for 3DOF locomotion is that the feet must have the ability to generate adhesive forces. It has been presumed that the adhesion of the gecko foot is generated between its setae, or toe pad, and on the target surface by van der Waals forces[1]. The setae, studied by means of dissection and microstructure observation, exist on the flap of the toe, which molt, on average, once every two months, and their geometric size ranges from 10 to 40 nm in diameter and 100 to 200 μm in length (Fig. 1(a)). Autumn et al.[1] measured the adhesion of a single, excised gecko seta. They detected high adhesion of the seta when it was preloaded and had made contact with a target surface at a certain angle and with small, relative sliding (Fig. 1(b)). Gao et al.[2] and Glassmaker

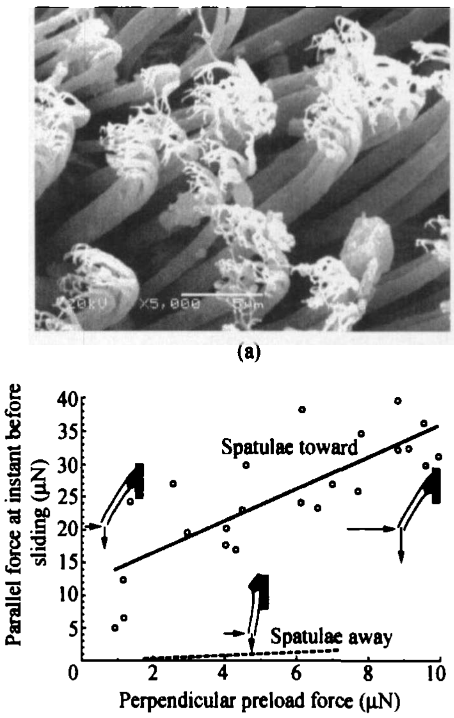


Fig. 1. Micro-structure and the adhesion of gecko setae. (a) SEM image of *gecko setae G. swinhouise*[16]. (b) Measuring results of single seta of *Gecko gecko*[1].

et al.[13] suggested that the adhesion of nano-scale seta predicted by the Johnson-Kendall-Roberts (JKR) model[14] coincides well with that actually observed in the laboratory.

One of the most important details is the sliding that is evident during experimental trials. This observation does not coincide well with the predictions suggested by the theory of van der Waals forces or the JKR model. Neither of these theoretical constructs requires sliding. Our studies[15,16] suggest that the setae on the gecko toe are very likely living cells, in which the surface electronic state and shape can be modulated by neuro-signals. The setae's major biochemical compound, β-keratin[17,18], is similar to human hair, which possesses the capability to conduct an electric charge during relative sliding.

3 Contact mechanics and control of the foot

Using a high-speed video camera (up to 1000 frame per second) we observed the attaching and detaching movements of the gecko toes: toes abducting first; then the center of the foot attaching on the target surface; finally, toes adducting. During the toes adducting process, setae slide against the target surface and generate redundancy and self-balanced friction forces[16,19]. We also observed that when the gecko adhered on the ceiling for a period of time, the foot would repeatedly attach and detach in order to maintain contact adherence. These observations validate the importance of the relative sliding of setae against the surface during adhesion. The measurements, carried out by using a two dimensional force sensor, also showed that the tangent forces were about four times that of normal correspondent forces (Fig. 2)[19]. In order to reveal the inter-feet relationship of the ground reaction forces upon gecko feet, we developed an array with 16 three-dimensional force sensors. Preliminary tests have produced similar results[20]. The complex motion mechanism and ground reaction forces raise several questions.

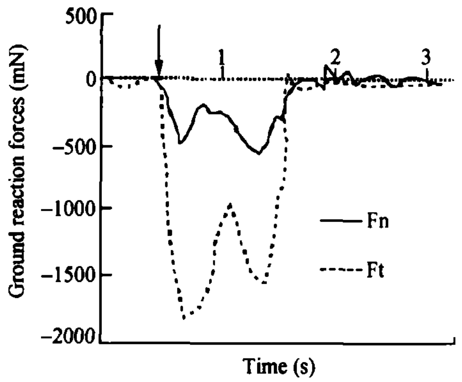


Fig. 2. Contact force between toe and surface.

The first question is how the gecko modulates the movement of the toe with 22 degrees of freedom. To answer this, we dissected the nerves of the posterior limb and studied the out-of-spinal control of movement by the electrophysiological approach, which revealed that three nerves—peroneal nerve, tibial nerve and femoral nerve—on the hind limb modulate the toe's abduction, adduction and rotation, respectively, and we stimulated the function of three nerves separately and reproduced the corresponding motion. This means that 22 degrees of freedom can be controlled by only three groups of neural signals, which will simplify the programming and controlling system design.

The next question is how the toes and foot are driven. The power from a traditional motor drive would not be suitable, because it would be too heavy for a robot to move. Fortunately, the invention of an artificial muscle, such as the Ion-exchange Polymer-Metal Composite (IPMC), makes it possible to integrate an actuator, a load-carrying structure and a sensor. This would decrease the weight and greatly increase flexibility of motion.

The third question is how the gecko senses its environment and how it senses to the contact status. Experiments have shown that the center of the gecko foot is very sensitive to ground reaction forces, and the toes are able to perceive the value and the direction of the force acting on it. This means that geckos possess a very sensitive feed-back mechanism for detecting its contact status (Fig. 3). This aids us in determining where the sensors should be located and what sensors should be integrated when we design a gecko-like robot.

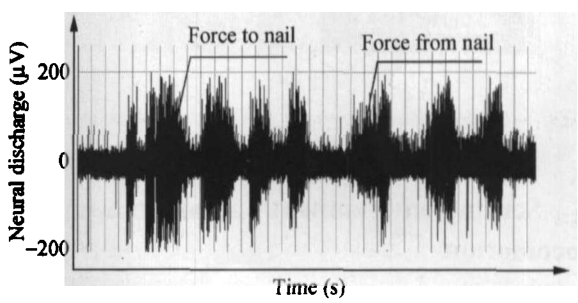
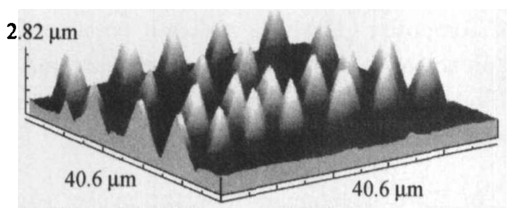


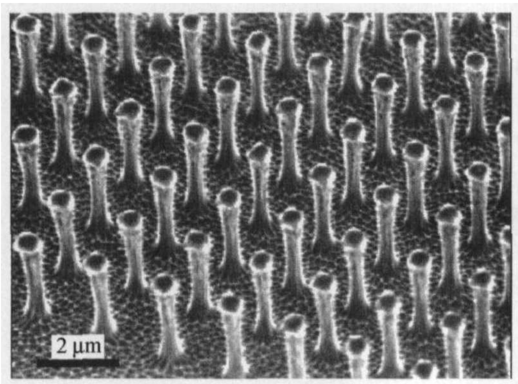
Fig. 3. A force direction on the 4th toe sensed and encoded with different neural encoding.

4 Fabrication of artificial setae

Studies on adhesive mechanisms suggest that artificial gecko pads that have smaller hairy arrays produce higher adhesion. Sitti and Fearing (Fig. 4 (a))[21] have documented two different nano-molding methods to fabricate nano-structures for synthetic gecko foot-hair. The first method uses an atomic force microscope (AFM) probe with an indented flat wax surface, and the second uses a nano-pore membrane as a template. The template is molded with silicone rubber, polyamide and polyester type of polymers under vacuum and then the template is peeled off or etched away. These synthetic nano-hair prototypes have adhesive properties similar to the predicted values for natural specimens (around 100 nN each). By using electron beam etching, Geim et al. (Fig. 4. (b))[22] produced an artificial gecko hair that could adhere a 40 g toy onto a ceiling. Our team has fabricated several gecko-hair attachment devices for a wall-climbing robot, and we have measured their adhesive forces[23—25].



(a)



(b)

Fig. 4. Bionic gecko setae array. (a) Silicon rubber by modeling approach[21]; (b) electron beam[22].

5 Sensing environment and modulating gecko locomotion

During motion, rat perceives the geometric circumstances via their cirri. Talwar et al. electrically stimulated the touch sensation nucleus of the cirrus in rat brain and guided a rat's navigation by remote control[26]. Although many studies were carried out on gecko's vision[27—30], audition[31,32] and olfaction[33], we still do not know which would be the major sensory organ for locomotive behavior. We modulated the gecko's locomotion by simulating outspinal cord nerve. The modulating reliability needs further improvement[34].

6 Further development

Research on gecko locomotion has inspired us to design motion mechanisms, to regulate motion gaits, to develop control programs and to choose the right driving actuator. In order to improve the development of the gecko-based robot and biomimetic gecko-like robot, the following objectives should be addressed:

(a) To directly measure the abundant forces among toes, to build a mechanical model, and to perform dynamic analyses including adhesive forces and abundant forces.

(b) To design a locomotive mechanism that meets the requirement of freedom change when the leg mechanisms transfer from open-linkage to close-linkage.

(c) To study the distributed artificial muscle driving system.

(d) To develop micro-fabrication techniques for the mass production of the artificial hairy adhesive foot.

(e) To explore the nerve web structure in the gecko's brain and from the brain to the muscle.

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