Biomimetics on gecko locomotion

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Abstract

The systematical report presents our studies on the gecko that integrated biological fundaments for biomimetics – morphology, locomotive mechanics, neural signal decoding and adhesive mechanism that developed a gecko-inspired robot and gecko-robot. A 3 dimensional locomotion gait for a gecko moving on the floor, wall and ceiling was obtained by using one high speed camera recording and image processing. The effect of electric potential on the adhesion was studied. The gecko's foot-toe, a 22 degree-of-freedom motion system, was modulated by stimulating the three neurons on the limb. A stereotaxis method was proposed and the instrument was developed. The brain atlas for the gecko was primarily set up. Based on biological understanding, a bio-inspired gecko-like robot was developed and the characteristics of the mechanics were investigated. The robot's gait and motion coordination was introduced from the three dimensional gait results. Locomotion of the gecko was modulated by implanting electrodes into the gecko's middle brain and stimulating by a wireless controlling system.
Keywords: gecko, locomotion, biomimetics, gait planning, stereotaxis methods, gecko-like robot, wall-climbing robot.

1 Introduction

Locomotion is the fundament of animals' behaviours – preying, escaping and procreating. Through the evolution and competition over the past thousand million years, a lot of animals have developed optimized geometric structures for

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motion mechanism, delicate material topologies for load-carrying or driving, simple and effective control modes for motion and multi-functional surface textures for contacting, cleaning, protecting, et al. These structures, materials, surfaces and neuro-modulation make animals' locomotion much more stable, flexible, robust, efficient and suitable to surroundings than any artificial system [1]. Wall climbing robots, that is, moving on 3-dimensional complex terrain, are highly in demand for cleaning wall and ceiling surface, searching disaster area, exploring unmanned area et al.

The gecko's (*gekko, gecko*) originally habitat is in the southwest part of China, weighing up to 150 g, length 310 mm, speed up to 1.5 m/s, with a load-carrying ability up to 4–5 times of its body weight. It is the biggest sticky animal, which can move on various surfaces, such as floors, walls and ceilings, on rough or smooth surfaces. During the past years, a lot of research on systematical development, protection, taxonomy, morphology and anatomy [2,3], adhesive mechanism [4,5] has been carried out. The research has enriched our understanding of geckos greatly, but systematical report integrated morphology, locomotive mechanics, neural signal decoding and adhesive mechanism together was few. No study was carried out on both biological gecko robots and bio-inspired robots. We reported our research on biological fundaments of gecko locomotion, bio-inspired robot and gecko's locomotion modulation which were performed during the past 5 years in our group.

2 Biological fundaments on gecko's locomotion

2.1 Gait analysis and locomotion

Gait analysis studies animal's locomotion, which involves the measurement of body movement in space (kinematics) and the forces involved in producing these movements (kinetics), which measures parameters of gaits draws various conclusions about the animal (health, age, size, weight, speed, etc.) from its gait. Sequence image photography can reveal the details of human and animal locomotion that are not noticeable with the naked-eye. Since the 1970s and significantly in the 1980s, with the availability of high speed video camera systems, gait analysis has achieved great advances. Many leading orthopaedic hospitals have gait labs which are routinely used in large numbers of cases, both to design treatment plans, and for follow-up monitoring for orthopaedic surgery, cerebral palsy, Parkinson's disease, and neuromuscular disorders for human. The gait analysis is also heavily used in the assessment of sports and investigations into the movement of a large variety of other animals, such as the rat, cat, dog, monkey et al. Gait parameters are grouped to spatial-temporal (step length, step width, walking speed, cycle time) and kinematic (joint rotation of the hip, knee and ankle, mean joint angles of the hip/knee/ankle, and thigh/trunk/foot angles) classes. Gait was influenced by the contact status [6], Tai Chi [7]. The gecko, as typical animals with three-dimensional obstacle free (TDOF) locomotion abilities, its gait and locomotion behavior has been studied [8–11]. This research paid attention to the biological aspect of locomotion and did not make connection with the gecko-like robot. Here we reported our studies on three dimensional locomotion gait of geckos on floor, wall and ceiling surfaces, which aims to understand what gait has been selected by the gecko when it moves on different surfaces and at the same time to provide a more natural gait for the robot's gait design.

We developed a three-dimensional gait measuring system (Fig 1 A) (IBSS—TDLS—1) which consists of a high speed CMOS camera (Microtron, MC1311, Microtron, Germany), a lens (35mm, Nikon, Japan), a computer to save the film, a lane with marked line (Fig. 1 B) and two mirrors with 45–47° to the lane. The lane and the mirrors can be set in floor, wall and ceiling positions. Geckos for the experiments were marked in white points about 5 pixels on the joints (Fig. 1 B). The motion of the gecko was recorded at speeds of 100 to 1000 per second. Then we scanned each image using Sigmascan software and read out the pixel's position of each joint from the image in real image and in two-mirror image. Through mathematical calibration, the angles between the tibia and the femur—α, between the femur and the body plane—γ and between the femur and the direction of the vertical line of motion—β can be obtained.

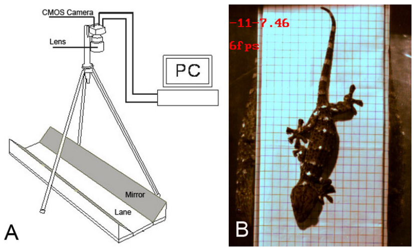

Figure 1: Three-dimensional gait measuring system.

Figure 2 indicates the 3 dimensional gait of a gecko moving on a floor at a speed 340 mm/s. We can find that in most cases, there are body-diagonal two feet on stance phase and the other body-diagonals on the wing phase. The phase change was carried out by a little bit earlier change from wing to stance in forelimb (around 16 ms) and then little later in the hind limb (around 16 ms). The gait transformation is (1) forelimb in left (FL) and hind limb in right (HR) on stance phase, (2) FL, forelimb in right (FR) and HR on the stance phase, (3) FR, HR and hind limb in left (HL) on stance, and (4) FR and HL on stance. The three dimensional gait of the gecko moving on a wall and ceiling were carried out. The results suggested that the stance and wing phase are different from that on the floor. On the ceiling the duty factor is 0.75, much higher than that on the floor 0.55 and on the wall 0.5

We also filmed the locomotion gait of a gecko when it moves on the wall and ceiling, the results suggested that duty factors on ceiling is from 0.73 and 0.82 for the motion speed 273 and 115 mm/s respectively. On the wall, the duty factor is around 0.5 to 0.6 at slow speed 31 mm/s and 0.53 to 0.59 at speed 242 mm/s.

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 60º to 150º, the angle between the femur and the body plane, γ, rotates from -20º to 40º and the angle between the femur and the direction of the vertical line of motion, β, rotates from –80º to 80º.

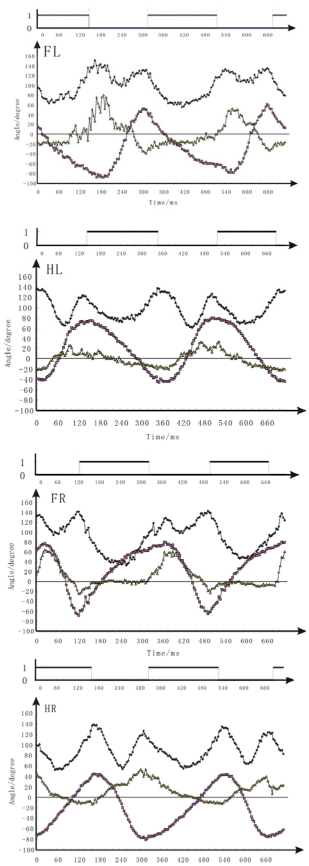

Figure 2: Three-dimensional gait of gecko.

We have been obstructed for several months when we developed a gecko-like robot for the legs in stance phase were intervened and made the sticky contact failure to generate adhesive forces. We set the gecko's gait into the robot's controlling software and solved the problem based on the understanding of the gecko's locomotive behaviors.

2.2 Sticky mechanics and adhesive mechanism

There are three ways for animals to stick on surfaces cataloged from the geometric structures: mechanical locking, soft smooth adhering and hairy setae adhering. Mechanical locking claw seems the basal element belongs to all sticky animals; soft smooth adhering element is concomitant with secretion of viscous liquid and hairy setae adhering happens between two solid bodies. Most animals do have two elements to make sure the sticky attachment, such as bee with claw and smooth pad, gecko with claw and setae pad.

For the hairy pad, adhesive mechanism has been extensively studied during past several years. At first, Van der Waals force was considered as only adhesion mechanism [12], the effects of capillary force was also been experimentally verified [13]. We studied the possible effect of electric potent on the adhesion.

Based on this mechanism, it is predicted that artificial hairy gecko pads with smaller setae diameter would produce higher adhesion. Nano-structures for synthetic gecko foot-hair have been fabricated by nano-molding methods [14] and an artificial gecko hair that could adhere onto a ceiling [15]. How to overcome the inter-adhering and fabricate slenderer setae is the frontier topic for artificial gecko setae research.

2.3 Foot-toe behaviors under electric-modulating on limb motor nerves

High speed video recording and study suggested that the toes of the gecko foot behaviors as abduction first, contacted with surface and then adduction its toes during attachment. The locomotion, from point of mechanical point of view, results from a 22 degree-of-freedom motion by the gecko's foot-toe system. It is almost impossible to be driven and be controlled by traditional mechanical system for such size. This study aims to understand how the locomotion is modulated by the gecko's neuron system.

By using a stereo microscope, we anatomized the gecko's forelimbs and hindlimbs near the spine, carefully separated the three nerves from the subcutaneous tissues and muscles, used two different type of signals – single pulse and continuous pulses, to make the stimulation on each nerve. The signal is unipolar rectangular pulse (0.1–0.3V, 2ms, 25 Hz, number of pulses is 1 or 20) by multi-channel biological signal collecting/processing system (model: RM6240, Chengdu Instrument factory, China). We stimulated three neurons and let the behaviors of abduction, adduction and rotation of the toes and the foot respectively [34].

To observe the relationship between afferent impulses from the gecko's toes and palm and external forces acted on them, a force transducer (JZJ-01, Chengdu Instrument factory, China) was chosen to apply forces to the gecko's toes and palm respectively, simulating the forces on the gecko's foot generated naturally during its movement, and the RM6240 system was used to record discharges of the exposed nerves. Frequency characteristics of discharge were obtained through frequency histogram statistical analysis.

2.4 Stereotaxis method and instrument

The stereotaxis method was first applied in 1908 to study the central neural system by Horsley and Clarke. It has become the essential techniques for the investigation of the brain structure and function. The gecko, unlike the rat，mouse, cat, has an embryonic form of external auditory carnal [12], which cannot be used for locating the head [16]. Based on the study of skull structure, We selected exclusive points two infraorbital margins (Fig.3, point C and C′) as the posterior points for fixation and the topside of the teeth located on the rostral side of the maxillary bone (Fig.3 (a) , point D) as another point for locating. We, first time in literature, introduced a stereotaxis method and developed an apparatus suitable for Gekko gecko (Fig.3). We set up the line passing through the bregma and paralleling to a line connecting bilateral infraorbital margin as x axis. Then, we defined a plane, that is a horizontal plane in stereotaxis instrument, passes through the axis x and the point 4.8 mm higher than the nasale point as XOY plane; the sagittal plane, YOZ plane, is the plan which perpendicular to the axis x and passes through the bregma; the plane, XOZ plane, which pass through the axis x and is perpendicular to the horizontal plane is the coronal plane. We designed a set of head holder which includes three parts: two bilateral infraorbital margin clamps, a gecko adaptor holding the rostral side of the upper jaw. Experiment carried out on this instrument show that the instrument allocate accurate, operate simple, commercialize at low-cost for it is compatible with standard stereotaxis instrument.

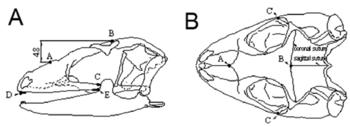

Figure 3: Skull structure of gecko Point B bregma; Point A nasale; Point C, C’ and D for locating.

2.5 Brain atlas

To set up the brain atlas of gecko is another fundamental work for modulating locomotion and understanding the spatial-behavior relationship.

The brains of 10 adult gekkos (*Gekko gecko*, Guangxi, China), BL: 159.5±4.6 mm(from the rostral side to the apertura cloacalis) BW: 79.5±6.2 g, were serially sectioned in transverse and sagittal planes at 10 μm. The bodies of cells were stained with cresyl violet (Nissl method) and the fibers were stained with Luxol blue G according to the techniques of Kliiver and Barrera. The sections from the olfactory bulb to the anterior spinal cord were input a computer. The sections were studied in more detail with the light microscope, and the cytoarchitectonics and fiboar-chitectonics were delineated at a magnification of 40 x, and would be made the reconstructions if necessary. Figure 9 show samples of slice in sagittal (left) and coronal (right) plane.

3 Bio-inspired gecko-like robot

3.1 Mechanics

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) [17]. Our results indicated that the maximum RMWe was 1.094% for Puboischio-tibialis 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.

We proposed a legged mechanism for gecko-like robot based on the anatomical studies of the gecko [17], which is a multi-joint serial chain [18]. There are two phases for each leg chain: swing phase and stance phase. The mechanism is an open kinematics chain in swing phase and it is a closed kinematics chain in stance phase. When leg changes from swing phase to stance phase, the degree of freedom reduced, the leg chain is over-driven and the impact force generated during contact. Based these characteristics, we defined the mechanism as discontinuous-constraint metamorphic linkage mechanism (MLM), the name was followed the study by Dai et al [19–21]. The contact on target surface with both friction force and adhesive force, existing between the sole and the target surface, is cataloged into three statuses: non-contact, contact with sliding and stable contact, represented by F_s:

$$\begin{array}{lll} F_s = 0 & Open-chain & \\ F_s = C & Close-loop-chain & Slide \\ F_s = \infty & Close-loop-chain & Stable \end{array} \tag{1}$$

The gecko-like robot has a multi-joints mechanism; the moving coordination among the leg mechanism is not only dependent on the geometric scale of each link in the mechanism, but also depends on the surface statuses, because they will permit different initial conditions.

3.2 Gait design and motion coordination

Motion ability of robot depended not only the mechanics and driving system, but also the control and gait design. On the structured surface, the geometric relationship between each leg in stance phase can be predicted and there are two ways to improve the motion coordination among legs – to schedule the gait based on the data from the 3 dimensional gait investigation (section 1.1), or to calculate the step serious by geometric difference. The two means improved the adhesive abilities greatly for wall-climbing robot.

When the gecko-robot moves in an un-structured circumstance, the gait design above should not work properly. We have to study in more detail the gecko's sensing rule and motion modulating technique. More sensors are needed to improve the moving abilities.

4 Modulation on the gecko's locomotion

A lot of research revealed that the mesencephalic locomotor region (MLR) of the midbrain in mammals initiate the locomotion behaviors. Fighting behavior has been recorded from midbrain central gray neuropil in the cat [22], in the rat [23,24], in the lamprey [25]. Two related books were published [26,27] and aggressive behaviors stimulated in the midbrain has been reviewed very recently [28]. On the other hand, most research on the lizard's brain was focused on the neuroanatomy functions in the forebrain in green iguanas [29,30], neural connections in anterior dorsal ventricular ridge in geckos [31], elicited vocalization [32,33], locomotion related stimulation was performed in my group [34]. Here we, first time in literature, applied the electrical stimulation technique to locate the nerve corpuscle in the gecko's middle brain, which response for gecko's locomotion.

40 geckos, with weight from 70 to 100 g and length from 230 to 260 mm, were used in the study. Both acute and awake experiments were performed. In the acute experiment, we anesthetized geckoes with Nembutal, hold their heads firmly by the head holder (see detail in section 1.4) , then opened the skull, cut off the dura, removed off the arachnoid, carried out the craniotomy, implanted the micro-electric electrode and exposed the selected brain area for electrical stimulation, at the same time recording the behaviors.

In the awake experiment, we drilled holes (ϕ0.35 mm) on the gecko's skull by using a micro-dental motor hand-piece, penetrated the dura and the arachnoid of the geckoes' brain by a needle, implanted a number of microelectrodes (stainless with Teflon coating) while the gecko was being fixed on the stereotaxis. We stimulated the gecko to see if the behavior correspondent to the required one until the electrodes were lowered to the selected point, then the gecko's skull were covered by dental cement and the electrode were linked to a connector. The gecko was free and sent to a clean room for recuperating the health for two weeks with normal light, food and water.

In the chronic experiment, the geckos were tested in an open field after recovery from surgery three days later. The stimuli consisted of pulses no more than 300 μA. Response reproducibility was tested at three times just as was allowed between two tests. We tested these stimulation points once a day from 18 to 20 in each evening for the time zone gecko is active. The gecko was successfully modulated for turning right, turning left, moving side et al

5 Conclusions

The research results in the following conclusions：

1) Interdisciplinary studies, especially exploring the biological fundaments from the requirement of engineering point of view may reveal new

research topics. And the biological studies have supported the bio-inspired engineering greatly.

2) A three-dimensional locomotion gait for geckos moving on floors, walls and ceilings was obtained and the results are very helpful in robot's gait design, especially in solving the problem of motion coordination.
3) Very simple but effective modulation of nerves to a 22 degree-of-freedom motion by gecko's foot-toe system suggested that new driving technology has to be developed to meet the further development of the robot.
4) A stereotaxis method was proposed and the instrument was developed, which allocates accurate, operates simple, commercializes at low-cost for it is compatible with standard stereotaxis instrument.
5) Based on biological understanding, a bio-inspired gecko-like robot was developed and the characteristics of the mechanics were investigated.
6) Locomotion of the gecko was modulated by implanting electrode into gecko's middle brain and stimulating by wireless controlling system.

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