The 2017 World Congress on
Advances in Nano, Bio, Robotics and Energy (ANBRE17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Analysis of reaction force and locomotor behavior on geckos in time- and frequency-domain during climbing on vertical substrates

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ABSTRACT

Locomotion is an essential character of animals, and excellent moving ability results from delicate sensing the reaction forces acting on body and modulating the locomotor behavior to adapt to the motion requirement. To reveal the fundamental mechanism of climbing locomotion and also to develop the performance of climbing robots, we have measured the reaction forces acting on each individual foot of moving geckos on vertical substrates and have recorded the locomotor behaviors by using high-speed camera associated with the reaction force. The coordinates of reference points, which were used to describe locomotor behaviors, were regressed by curve fitting to analyze kinematic feature factors, meanwhile, the data of reaction forces were further processed by fast Fourier Transform to calculate power spectrum density, and by discrete wavelet transform to obtain wavelet signals. A good agreement was found between the reaction forces and the inertia forces generated by locomotor behaviors in frequency domain. The results showed that the locomotor frequency of trunk in fore-aft direction was twice that in lateral direction, and the locomotor frequencies and phases of limbs in all directions had no obvious difference. This mechanism may be beneficial for the enhancement of energy conversion efficiency and maintain lower energy consumption. Above research will help to understand better the locomotion mechanism of climbing animals, and further inspire the design of gecko-like robot with variable stiffness.

Keywords: reaction force; time-frequency domain analysis; locomotor behaviour; gecko; power spectrum density

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[#] This work was supported by the National Natural Science Foundation of China (Grant No. 51435008 to Z.D. and 31601870 to Z.W.) and Natural Science Foundation of Jiangsu Province, China (Grant No. SBK2016040649 to Z.W.). We thank Li Wei, Han Longbao and Xu Hui for assistance with data collection and manuscript writing. Shao Minqiang and Wei Yanan provided insightful comments on the manuscript.

1. Introduction

Evolutionary pressure for efficient, rapid and adjustable locomotion, which is a great project of nature, often pushes the envelope of organism design (Dickinson 2000). The change of animals' locomotor behavior is directly caused by the interaction between the animals and environment, i.e. reaction force, the investigation of which thus is an important approach to the research of the animals' locomotion. The reaction forces acting on animals' limbs by external environment have been precisely collected and clearly displayed by many kinds of force sensors (Dickinson 2000; Ren and Hutchinson 2008; Chateau 2009; Wang 2015). However, the reaction force and locomotor behavior (RF-LB) of animals contain tremendous information such as control strategy and synergy mechanism, which could not be totally revealed by time-domain analysis. Ahlborn et al. found that different control strategies were used to produce the necessary propulsive impulse (force·time) when human moved under certain constant speed, that is to say, the choice of stride frequency was enormous (Nilsson and Thorstensson 1987). Animals usually match their stride frequency with the frequency of repetitive motion of propulsive structures (arms, legs, fins, wings). As a result, the energy consumption is a minimum (Ahlborn 2006). Nevertheless, this match mechanism is still unknown and further research need to be carried out on time- and frequency- domain analysis of RF-LB. Common integrated methods of time- and frequency- domain analysis include fast Fourier transform (FFT). FFT is used to determine the sinusoidal frequency content of the signal. The magnitude squared of the fast Fourier transform coefficients yields the power spectral of the signal, while the spectral is used to estimate how the total power is distributed over frequency form a finite record of a stationary data sequence (Stoica and Moses 1997). Spectral analysis finds applications in many diverse fields, such as vibration monitoring (Crandall and Mark 2014), biomedicine (Pagani 1986), economics, meteorology, astronomy and several other fields (Bloomfield 2004).

Based on the integrated time- and frequency-domain analysis of RF-LB on the land animals' locomotion on level surfaces, inverted pendulum model of walking animals and spring-mass model of running ones are built to reveal the mechanism of horizontal movement (Farley and Ko 1997; Dickinson 2000; Reilly and Biknevicius 2003) and successfully inspire the development of quadrupled robot, such as BigDog (Raibert 2008; Wooden 2010) and Cheetah (Lewis 2011). However, no general dynamic model of legged climbing on vertical substrate exists (Autumn 2006; Goldman 2006) and existing climbing robots' performances need to be improved, which could be attributed to a lack of integrated time- and frequency-domain analysis of RF-LB. As extraordinary climbers in nature, geckos have been extensively studied on their morphological structure (Arzt 2003), adhesion mechanism (Autumn 2000; Autumn and Peattie 2002; Bhushan and Sayer 2007) and kinematic characteristics (Li 2009). Time-domain characteristic of geckos' RF-LB during locomotion on various inclines has been well revealed (Wang 2015). In order to reveal the general model inside various kinds of climbing animals, the three-dimensional reaction forces and the locomotor behavior of geckos during locomotion on vertical substrates were measured, and were further analyzed in time- and frequency-domain.

2. Materials and methods

2.1 Animal

This study was carried out in accordance with the Guidelines for Laboratory Animal Management in China. The experimental procedures were approved by the Jiangsu Association for Laboratory Animal Science (Jiangsu, China). All efforts were made to minimize the suffering of the animals. *Gekko geckos* (mass, 63.4±2.6g mean ± s.d.; snout-vent length, 137.8±5.5mm; N = 6) were purchased from a supplier in Guangxi province (China). They were kept under natural light cycle, temperature at 25±2°C and humidity at 60%-70%.

2.2 Experimental equipment

Details of the force measurements and behavior record have been described in previous work (Dai 2011) (Fig.1A). Briefly, the forces acting on each foot were measured by the FMA, which consisted of separate force sensors having a smooth glass square on top (30×30 mm with 1 mm clearance gap). The three-dimensional reaction forces acting on each foot were measured: the lateral force (F_L), the fore-aft force (F_F), and the normal force (F_N) (Fig.1A).

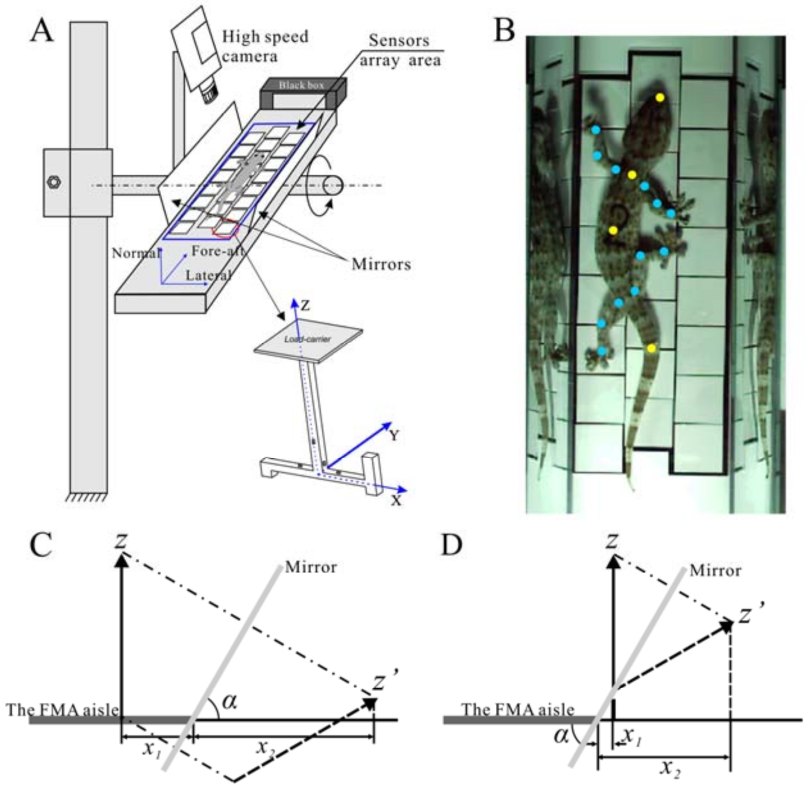

Fig.1 (A) Experimental equipment. (B) Geckos climb up vertical FMA freely. (C) Optical path of reference points projected orthographically onto array area. (D) Optical path of reference points projected orthographically onto mirrors area. (α= 55°).

The positive fore-aft force drives locomotion, while the negative lateral force acting on the left foot, pulling away from the gecko trunk, and the negative normal force indicates the presence of adhesive force acting on the gecko's foot. Synchronously to the force measurement (500Hz), a high-speed camera (iSpeed-3, Olympus, 1280×1024 pixels) recorded each trial at 500 Hz. The start of the video recording was triggered by sending a TTL-pulse to the camera and the data acquisition board synchronously using a manual switch. Because the camera was rotated along with the FMA, and was consistently perpendicular to the plane of the array, we obtained standardized dorsal views of the animal movements. The two mirrors were placed on both sides of the array channel at 55°, enabling us to see the lateral of the gecko from a side-on view.

2.3 Analysis of locomotor behavior

Before the trial, the reference points were marked on each gecko's back with nail polish (Fig.1B). We marked 4 reference points on the trunk (including P_{SN}-tip of the snout, P_{SH}-midpoint of two shoulder joints, P_{TR}-midpoint of the trunk, P_{TA}-the second pattern point on the tail) and 3 reference points on each limb (each joint, i.e. shoulder/hip, elbow/knee and wrist/ankle with one reference point marked on it, and altogether 12 reference points marked on 4 limbs) to describe the trunk's and limbs' kinematic characteristics, respectively. The coordinates of all reference points in lateral and fore-aft direction during gecko motion were chosen from experimental photos using i-SPEED Viewer software (i-SPEED 3, Olympus, Inc., Japan)(Fig.2).

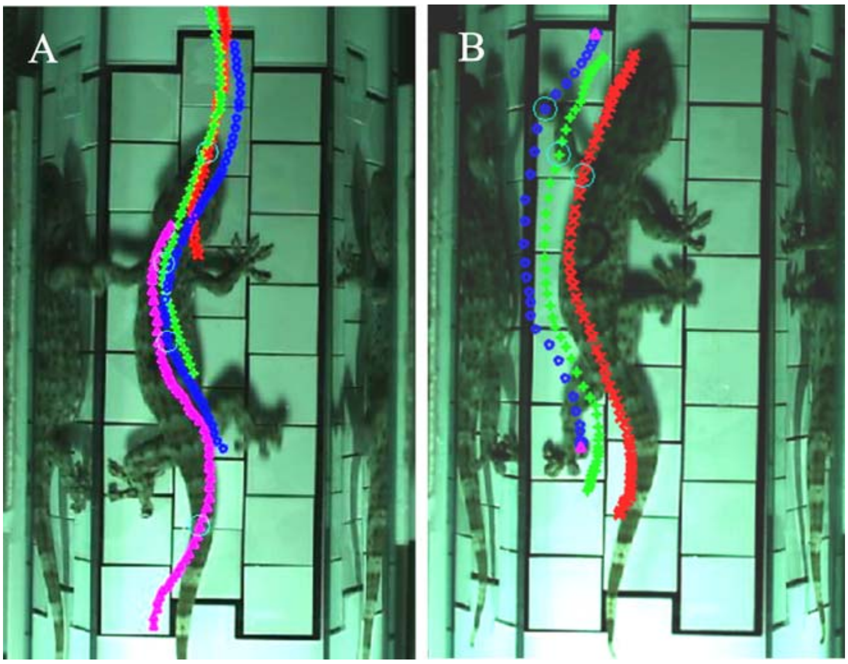

Fig.2 The coordinates of reference points on trunk (A) and limbs (B) in lateral and fore-aft direction during gecko motion for one stride were chosen from experimental photos using i-SPEED Viewer software (i-SPEED 3, Olympus, Inc., Japan).

The forward speed of the trial (v) was calculated by the coordinate in fore-aft direction of the mid-point of the left and right shoulder joints. Only trials in which the gecko moved at a near-steady forward speed were evaluated further. If the increases or decreases in forward speed were more than 15% of the average forward speed in this trial, the trial was discarded. With the help of mirrors, the position of points in normal direction can be obtained during the locomotion on the FMA aisle, using only one high-speed camera. Restricted by the width of array channel, some reference points on gecko's limbs would be projected orthographically onto array area or mirrors area during locomotion, as shown in Figure 1C and 1D, respectively. To formulate normatively and concisely, according to the imaging law of flat mirror and knowledge of plane geometry (Young and Freedman 2008), the coordinates of points in normal direction can be expressed as equation 1(Fig.1C) and equation 2(Fig.1D):

$$z = \frac{x_1}{\tan\alpha} + \frac{x_2 - x_1}{\sin(2\alpha)} \quad (1)$$

$$z = x_1 \cdot \tan\alpha + \frac{x_2 - x_1}{\sin(2\alpha)} \quad (2)$$

Where α is the angle between the mirror and the FMA, x_1 and x_2 are the lateral distance from object and image to the intersection of the mirror and FMA, respectively. In order to obtain the kinematic feature factors (such as amplitude A, circular frequency ω and initial phase φ) of trunk's and limbs' locomotion in all directions, MATLAB (Mathworks Co., Ltd, R2013a) was further used to regress the data of coordinates and corresponding time of each reference point, R-square was presented to evaluate the goodness of fit.

Kinematic characteristics of trunk

All phases of the undulatory motion of the animal midline are well-fit by a posteriorly travelling single-period sinusoidal wave and the R-square (R^2) is no less than 0.9 (Maladen 2009; Maladen 2011), and the mathematical model is also successfully used to present the lateral locomotor behavior of amphibians salamander (Bennett 2001) and terrestrial quadruped lizard (Ritter 1992; Farley and Ko 1997). Thus, sine function was used to describe the relationship of the lateral coordinates with the time of reference points on trunk (Eq.3).

$$x_{\mathrm{T}}(t) = p_{0x} + A_{x\_\mathrm{T}} \cdot \sin\left(\omega_{x\_\mathrm{T}} \cdot t + \varphi_{x\_\mathrm{T}}\right) \quad (3)$$

Where $x_{\mathrm{T}}(t)$ is the lateral displacement of reference points on trunk at time t and p_{0x} is the initial lateral displacement; A_{x_T}, ω_{x_T} and φ_{x_T} are corresponding amplitude, circular frequency and initial phase, respectively. The frequency and maximum acceleration of lateral trunk bending were obtained as $f_{x\_\mathrm{T}} = \omega_{x\_\mathrm{T}} / 2\pi$ and $a_{x\_\mathrm{T}} = A_{x\_\mathrm{T}} \cdot \omega^2_{x\_\mathrm{T}}$, respectively.

Although the geckos maintained a near-constant speed during climbing on vertical substrate, there were acceleration and deceleration process during every gait cycle (Autumn 2006). Hence, a linear factor $v_{y\_\mathrm{T}} \cdot t$ was added to the sine function (Eq.3) to describe the relationship of the fore-aft coordinates with the time of reference points on trunk (Eq.4).

$$y_{\mathrm{T}}(t) = p_{0y} + v_{y\_\mathrm{T}} \cdot t + A_{y\_\mathrm{T}} \cdot \sin\left(\omega_{y\_\mathrm{T}} \cdot t + \varphi_{y\_\mathrm{T}}\right) \quad (4)$$

Where $y_T(t)$ is the fore-aft displacement of reference points on trunk at time t and p_{0y} is the initial fore-aft displacement; v_{y_T} is the average locomotion speed; A_{y_T}, ω_{y_T} and φ_{y_T} are corresponding amplitude, circular frequency and initial phase, respectively. Similarly, the frequency and maximum acceleration of fore-aft trunk movement were obtained as $f_{y\_T} = \omega_{y\_T} / 2\pi$ and $a_{y\_T} = A_{y\_T} \cdot \omega_{y\_T}^2$, respectively.

Kinetics characteristic of limbs

The data of coordinates of reference points on limbs (joints of shoulder/hip, elbow/knee and wrist/ankle) in all directions and corresponding time were further regressed by curve fitting to obtain the kinematic feature factors. As a transition from the trunk to limb, the joint of shoulder/hip has similar kinematic characteristics as trunk, thus, a same form of function was used to regress the corresponding data to obtain the kinematic feature factors. Nevertheless, the kinematic characteristics of elbow/knee and wrist/ankle were distinguished by swing and stance phase (Fig.2B), and hence was described by a piecewise function. Detailed kinematic feature factors were listed in table.1.

1.4 Data processing of three-dimensional reaction force

While geckos were climbing on a vertical FMA aisle, the reaction forces acting on each foot of geckos in all directions, i.e. lateral, fore-aft and normal forces were collected by FMA. The reaction forces were further processed by fast Fourier transform (FFT) to reveal the frequency-domain characteristics.

Power spectral density (PSD) by FFT

Power spectral density (PSD) of the time-domain reaction force in all directions was computed via FFT to estimate how the total power was distributed over frequency. The Hanning window was introduced to the periodogram computation with the purpose of getting more control over the bias/resolution properties of the estimated PSD. Since the sampling frequency of FMA was f_s=500Hz, and as a result, the Nyquist frequency was f_s/2=250Hz (Oppenheim 1989), we could obtain the PSD of the three-dimensional reaction forces over a frequency range from 0Hz to 250Hz.

3. Results

3.1 Analysis of locomotor behavior

Locomotor behavior of trunk

The kinematic feature factors of four reference points on trunk (i.e. P_{SN}-tip of the snout, P_{SH}-midpoint of two shoulder joints, P_{TR}-midpoint of the trunk, P_{TA}-the second pattern point on the tail) in lateral and fore-aft directions were obtained by regressing the corresponding data (Fig.3). The R-square goodness of fit tests revealed that it performed well with all coefficients of determination lager than 0.90 (Maladen 2009; Maladen 2011) (Fig.3). The linear coefficient v_{y_T} in curve fitting Eq.4 could be regarded as the average speed of geckos during climbing vertically (v_{y_T}=0.78±0.08m/s). Obtained locomotor frequencies of each reference point on trunk showed no obvious difference in fore-aft direction (f_{y_T}=9.73±0.7Hz, n=4), the same was true in lateral direction (f_{x_T}=4.85±0.44Hz, n=4), the former was approximately twice the latte. For each reference point, the amplitude in lateral direction (A_{x_T}) was significantly larger than that in fore-aft direction (A_{y_T}); however, the maximum acceleration in lateral direction (a_{x_T}) was close to that in fore-aft direction (a_{y_T}).

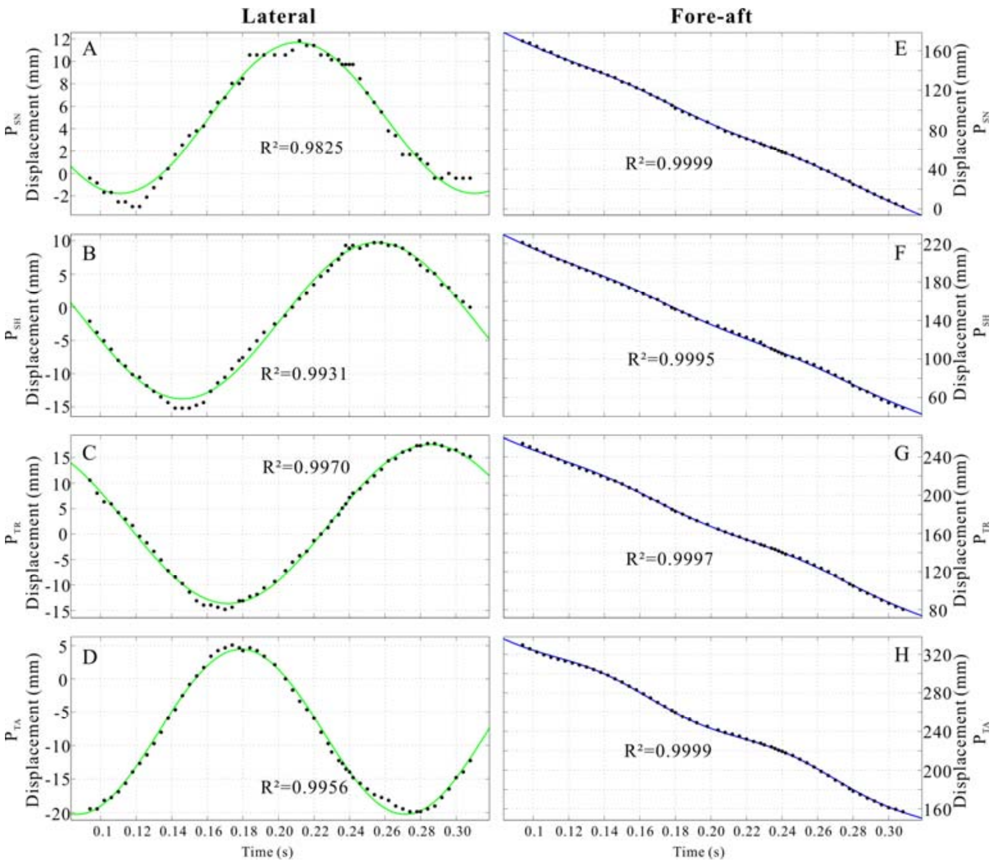

Fig.3 The relation of lateral and fore-aft displacement with time of four reference points on trunk were obtained by regressing the corresponding data.. (n=58)

Locomotor behavior of limbs

The data of coordinates of reference points on left fore-limb in all directions and corresponding time were regressed by curve fitting (Fig.4), corresponding detailed kinematic feature factors were listed in table.1. The swing and stance phase were handled without being distinguished in describing shoulder joint's movement (Figs. 4A, 4D and 4G), while with being distinguished in describing elbow (Figs. 4B, 4E and 4H) and wrist (Figs. 4C, 4D and 4G) joint's movement. The R-square goodness of fit also revealed that it performed well. The results showed that the locomotor frequencies of shoulder joint in lateral (Fig.4A), fore-aft (Fig.4D) and normal (Fig.4G) direction were very close to each other (4.5Hz, 3.9Hz and 3.7Hz, respectively), and the locomotor behaviors were marked with obvious sinusoidal periodicity. However, the locomotor behaviors of elbow and wrist joint showed clear non-sinusoidal periodicity. The locomotor frequencies of elbow joint during stance phase were consistent with that during swing phase in lateral (Fig.4B, 7.7Hz and 7.7Hz, respectively) and normal directions (Fig.4E, 3.8Hz and 4.7Hz, respectively); however, the result was obviously different in fore-aft direction (Fig.4G, 3.4Hz and 9.1Hz, respectively) (Table.1). The locomotor frequencies of wrist joint in lateral (Fig.4C), fore-aft (Fig.4F) and normal (Fig.4I) direction during swing phase were also very close to each other (7.4 Hz, 9.6Hz and 8.2Hz, respectively), while during stance phase, the frequency should all be equal to 0Hz as with no displacement (Table.1). The linear coefficient v_{2y_S} in eq.(A-4), v_{2y_E} in eq.(A-5) and v_{2y_W} in eq.(A-6) could be regarded as the average velocity of shoulder, elbow and wrist joint during swing phase (0.74 m/s, 1.16 m/s and 1.46 m/s, respectively) (Table.1). The maximum accelerations in lateral direction (9.8m/s², 26.9 m/s² and 34.1 m/s²) during swing phase were close to that in fore-aft direction (9.4 m/s², 26.0 m/s² and 47.3 m/s²), but they were obviously larger than that in normal direction (2.9 m/s², 6.9 m/s²and 24.0 m/s²) for each joint (shoulder, elbow and wrist joint, respectively).

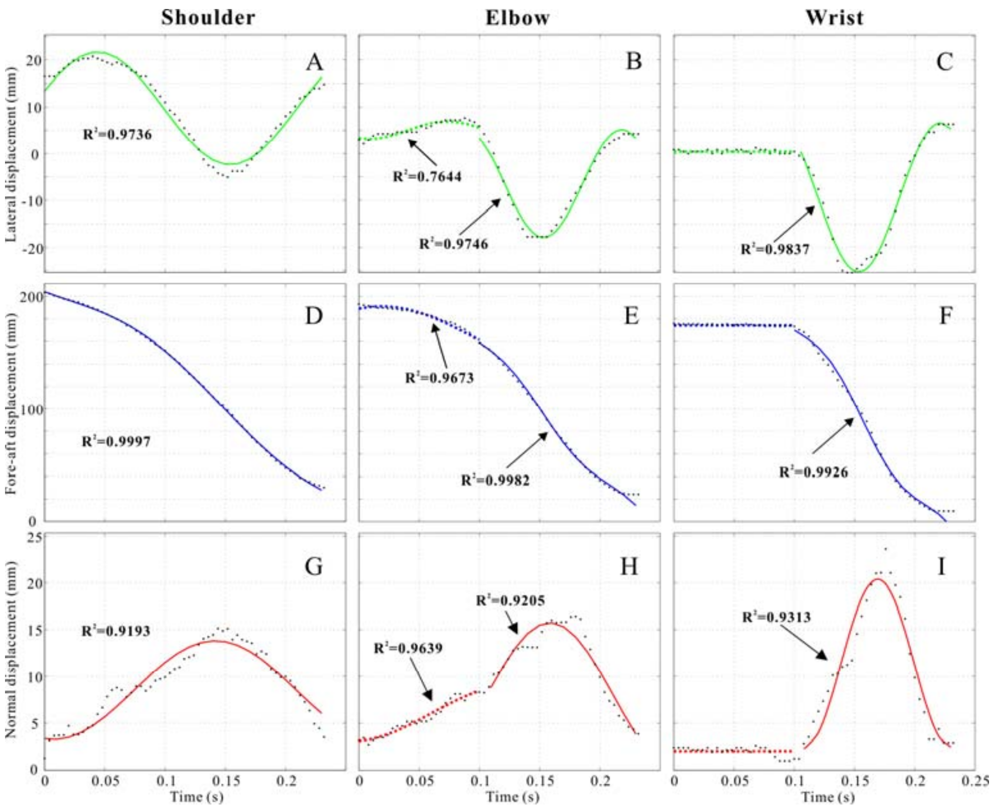

Fig.4 The relation of lateral, fore-aft and normal displacement with time of three reference points on left fore-limb1 were obtained by regressing the corresponding data. 1 (*n*=58)

Tab.1 The kinematic feature factors of three reference points on left fore-limb in all directions were obtained by regressing the corresponding data.

Fitting coefficients		Limb		
		Shoulder	Elbow	Wrist
Lateral	p_{0x} (mm)		5.0	0.4
	v_{1x} (mm/s)		×	×
	A_{1x} (mm)		1.9	×
	ω_{1x} (rad/s)/f_{1x} (Hz)		48.4/7.7	×
	φ_{1x} (°)		-114.4	×
	q_{0x} (mm)	9.6	-6.4	-9.3
	v_{2x} (mm/s)	×	×	×
	A_{2x} (mm)	12.0	11.5	15.9
	ω_{2x} (rad/s) /f_{2x} (Hz)	28.5/4.5	48.4/7.7	46.3/7.4
	φ_{2x} (°)	18.2	-155.4	-137.3
	a_x (swing phase) (m/s^2)	9.8	26.9	34.1
Fore-aft	p_{0y} (mm)		165.9	174.3
	v_{1y} (mm/s)		×	×
	A_{1y} (mm)		25.3	×
	ω_{1y} (rad/s) /f_{1y} (Hz)		21.5/3.4	×
	φ_{1y} (°)		66.6	×
	q_{0y} (mm)	211.5	274.0	319.0
	v_{2y} (mm/s)	-740.0	-1162.7	-1459.4
	A_{2y} (mm)	15.3	8.0	13.1
	ω_{2y} (rad/s)/ /f_{2y} (Hz)	24.8/3.9	56.9/9.1	60.1/9.6
	φ_{2y} (°)	-28.6	43.6	1.9
	a_y (swing phase) (m/s^2)	9.4	26.0	47.3
Normal	p_0 (mm)		6.0	2.0
	v_{1z} (mm/s)		×	×
	A_{1z} (mm)		3.0	×
	ω_{1z} (rad/s) /f_{1z} (Hz)		23.6/3.8	×
	φ_{1z} (°)		-81.3	×
	q_{0z} (mm)	8.5	7.9	11.4
	v_{2z} (mm/s)	×	×	×
	A_{2z} (mm)	5.3	7.8	9.0
	ω_{2z} (rad/s) /f_{2z} (Hz)	23.4/3.7	29.7/4.7	51.8/8.2
	φ_{2z} (°)	-100.0	-180	-52.2
	a_z (swing phase) (m/s^2)	2.9	6.9	24.0

$p_0+v_1t+A_1\sin(\omega_1 t+\varphi_1)$ is the fitting expression during stance phase; $q_0+v_2t+A_2\sin(\omega_2 t+\varphi_2)$ is the fitting expression during swing phase; unused factors are denoted by ×. Detail fitting curve see Fig.4; fitting expressions see Eq.(A-1)-(A-9). (n=58)

3.2 Analysis of reaction force—*PSD of reaction forces*

The time-domain reaction forces in lateral (Fig.5A), fore-aft (Fig.5B) and normal (Fig.5C) direction were further processed to compute the PSD of reaction forces in lateral (Fig.5D), fore-aft (Fig.5E) and normal (Fig.5F) direction, respectively, which were scaled in decibels to obtain the best solution. The PSD clearly showed how the reaction force power was distributed over frequency during gecko climbing on vertical substrates. The main frequencies, i.e. frequencies at which the power/frequency is a minimum, are marked in Fig.5. The main frequency of lateral reaction forces was about 4.15Hz with power/frequency up to 25.62dB/Hz (Fig.5D). As for fore-aft reaction force, the main frequency was about 10.38Hz with power/frequency up to 34.15dB/Hz; there was another peak value of power/frequency at about 0Hz with power/frequency up to 40.46dB/Hz (Fig.5E). However, no obvious main frequency was observed in PSD of normal reaction forces, in which the value of power/frequency was nearly invariable (approximate 20dB/Hz) in the frequency range from 0Hz to 10Hz., and was far less than peak values of power/frequency at 0Hz and 10.38Hz (40.46dB/Hz and 34.15dB/Hz, respectively) in fore-aft direction, and at 4.15Hz (25.62dB/Hz) in lateral direction (Figs. 5D, 5E and 5F).

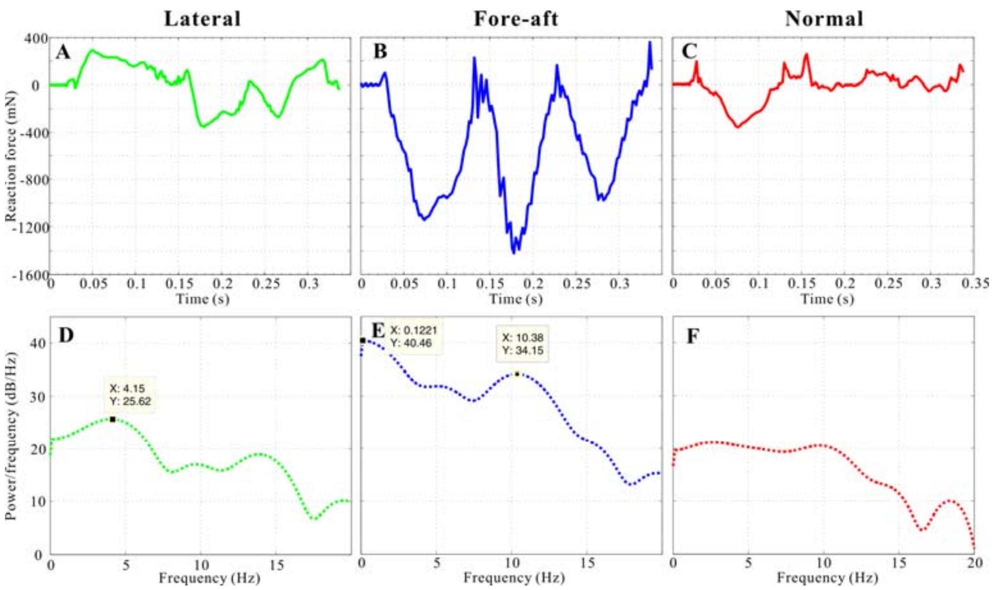

Fig.5 The time-domain reaction forces in lateral (A), fore-aft (B) and normal (C) direction were further processed to compute the PSD of reaction forces in lateral (D), fore-aft (E) and normal (F) direction, which were scaled in decibels to obtain the best solution. (n=170)

4. Discussion and conclusion

4.1 Time- and frequency- domain analysis of RF-LB

In order to understand the relation between the reaction forces and locomotor behaviors, and then, the regression results of measurement on locomotion in all directions were compared with the time- and frequency-domain analysis of three-dimensional reaction force to see the consistence (Figs. 3-6).

Geckos must overcome the pull of gravity during climbing on vertical substrates (Autumn 2006; Wang 2010; Wang 2011). There were two main peak values of power/frequency in PSD of fore-aft reaction forces, one was at 0Hz with power/frequency up to 34.15dB/Hz and the other was at about 10.38Hz with power/frequency up to 40.46dB/Hz (Figs. 5B, 5E). The value and direction of the gravity acting on the geckos did not change when geckos were climbing on vertical substrates, thus the peak value at 0Hz in PSD of fore-aft reaction forces might be caused by the gravity. Obtained frequency of trunk locomotion is f_{y_T}=9.73±0.7Hz, which was quite close to 10.38Hz, thus the peak value at 10.38Hz in PSD of fore-aft reaction forces might be caused by the acceleration and deceleration process during every gait cycle (Autumn 2006).

The only main frequency of lateral reaction forces was about 4.15Hz (Figs 5A, 5D), which was close to the frequency of lateral trunk bending (4.85±0.44 Hz, Figs.3A-3D). In order to locomote on vertical substrates, geckos must generate an appropriate value of adhesive force in normal direction to maintain stability (Autumn 2006; Wang 2011). No obvious main frequency was observed in PSD of normal reaction forces, in which the value of power/frequency was nearly invariable in the frequency range from 0Hz to 10Hz (Fig.5F).

During climbing up vertical substrates, animals convert biological energy (Cabelguen 2010) into kinetic energy (Autumn 2006), then kinetic energy into gravitational potential energy (Autumn 2006; Goldman 2006). Any transfer of energy from one form to another has a delay, that is, a characteristic transfer time Δt (Ahlborn and Curzon 2004). These delay times are built into all periodic motion sequences, which may be characterized by their periods T or by their frequencies $f=1/T$, in order to utilize the energy effectively (Ahlborn 2006). There was only a single main frequency in PSD of lateral reaction forces; the same was true of fore-aft reaction forces without regard to zero frequency, and the latter was approximately twice the former. By this way, the applied geckos may improve the efficiency of the energy transformation; further enhance maneuverability and stability during climbing up vertical substrates.

4.2 Inspiration to gecko-like robots

Energy efficiency and stability of dynamic walking or climbing robots can be improved by using components inspired by the Reverse-Engineering of biological systems. Many animals are known to actively tune their locomotor frequencies through control of their elastic oscillations to maintain lower energy consumption (Ahlborn 2006). A fish is able to modify its stiffness profile to maintain the tail amplitude with increasing tail beat frequency (McHenry 1995). A model for a robot fish with compliant parts was presented and a coupled fluid-structure model was developed to predict the response and understand the dynamics of the system (El Daou 2014). The energy efficiency and stability of dynamic walking robots can be improved using two biologically inspired components, i.e., passive joint stiffness and active knee control (Migliore 2007). In our research, the experimental results showed that the main frequency in PSD of lateral and fore-aft reaction forces (i.e., locomotor frequency of trunk) took on oneness (zero frequency is excluded); the latter was approximately twice the former. These results could mean that geckos would actively tune their locomotor frequency to lower energy consumption. The frequency of elastic vibrations can be tuned with a non-linear modulus of elasticity or by changing the effective length or cross-sectional area of the elastic members, or by allowing springs in parallel or in series to become active (Ahlborn 2006), which inspires that structures with adjustable stiffness should be deployed in gecko-like robot to lower energy consumption, and then improve the maneuverability significantly. Stiffness matching of locomotion system as well as adhesion system in gecko-like robot also should be taken into consideration. In addition, as a specific climbing robot, it is a great challenge to design its adhesion system, whose stiffness is direct relative to adhesive performance (King 2014). Limited by properties of adhesion materials, there must be a safety threshold for adhesion system of gecko-like robot, thus limitations of adhesion system on locomotor behaviors and forces should be considered in the design of the structure with variable stiffness. By a match between the stiffness of adhesion system and locomotion system, the gecko-like robot can climb up vertical substrates with high maneuverability and stability.

5. Conclusion

For the first time, we have analyzed the data of the three-dimensional reaction forces acting on the geckos' feet through time- and frequency-domain analysis methods; furthermore, we attempted to find the correspondence between reaction forces and locomotor behaviors. The three-dimensional reaction forces acting on the geckos' feet were measured during climbing on vertical FMA; locomotor behaviors were simultaneously recorded by a high-speed video camera (Dai 2011). The locomotor behaviors were regressed by curve fitting, while the three-dimensional reaction forces were processed by FFT to obtain PSD. The characteristic of reaction forces could fully reveal the characteristic of inertia forces generated by locomotor behaviors in frequency-domain. By adjusting the matching relationship of trunk's locomotion frequencies in lateral and fore-aft direction, as well as the limbs locomotion frequencies in all directions, geckos might enhance the energy conversion efficiency and maintaining lower energy consumption.

However, excellent adhesive performance enables geckos not only to climb up vertical substrates, but also to climb on inverse ones (Wang 2015). Previous studies showed that locomotion patterns and behaviors differed largely when geckos were climbing on slopes with different inclines (Wang 2014; Wang 2015), so how do they behave in frequency domain, whether or not the control strategy changes compared to climbing on vertical substrates? In addition, animals have evolved different adhesive mechanism to deal with challenges of inclines (Gorb 2008). Then it is worth to study whether or not animals with different adhesive mechanism have similar characteristics of RF-LB in time- and frequency- domain, and further similar control strategy.

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