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ScienceDirect
Journal of Bionic Engineering 14 (2017) 191–201

Effects of Pendular Waist on Gecko's Climbing: Dynamic Gait, Analytical Model and Bio-inspired Robot

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Abstract

Most quadruped reptiles, such as lizards, salamanders and crocodiles, swing their waists while climbing on horizontal or vertical surfaces. Accompanied by body movement, the centroid trajectory also becomes more of a zigzag path rather than a straight line. Inspired by gecko's gait and posture on a vertical surface, a gecko inspired model with one pendular waist and four active axil legs, which is called GPL model, is proposed. Relationship between the waist position, dynamic gait, and driving forces on supporting feet is analyzed. As for waist trajectory planning, a singular line between the supporting feet is found and its effects on driving forces are discussed. Based on the GPL model, it is found that a sinusoidal waist trajectory, rather than a straight line, makes the driving forces on the supporting legs smaller. Also, a waist close to the pygal can reduce the driving forces compared to the one near middle vertebration, which is in accord with gecko's body bending in the process of climbing. The principles of configuration design and gait planning are proposed based on theoretical analyses. Finally, a bio-inspired robot DracoBot is developed and both of the driving force measurements and climbing experiments reinforce theoretical analysis and the rationality of gecko's dynamic gait.

Keywords: multi-legged robot, wall-climbing robot, dynamic gait, pendular waist, GPL model

doi: 10.1016/S1672-6529(16)60390-6

1 Introduction

As a type of mobile robots, wall-climbing robots can apply to the vertical walls to perform multifarious tasks, including anti-terrorism, post-disaster rescue and military reconnaissance. According to previous studies[1–4], it can be seen that mesoscale legged robots adopting trot gait have high maneuverability on different surfaces[5,6]. Up to now, many mesoscale climbing robots with pivot joints like the RiSE[7,8], the Stintov and the StickyBot[9,10,11]have been developed and applied in different environment medium, including trees, glasses or concrete wall. However, their work is restricted to relatively low velocities because of the quasi-static gait[12]. Unlike the previous climbing robots, the gecko-inspired robot CLASH[1] adopting a dynamic gait can obtain a speed of 10 cm·s^{-1}, or 1 BL·s^{-1} (body lengths per second). Clark and Provancher applied linear joint or a pending body to the climbing robots. The DynoClimber containing two axial arms can obtain upward velocity of 66 cm·s^{-1}, 1.5 BL·s^{-1}[13–19]. Taking full advantage of the impetus from the swinging tail, ROCR can achieve a maximum climbing speed of 15.7 cm·s^{-1}, 0.34 BL·s^{-1}[20]. In spite of the highly efficient climbing, DynoClimber and ROCR face severe challenge of stability during swing. The lack of supporting feet leads both of them to tend to rotate around the normal directions of climbing surfaces[21].

Since the 1980s, the dynamic gait has been put forward[22,23]. Based on a simple spring-mass model, Blickhan expounded the principle of animals running in terms of speed[24]. Inspired by the cockroach's research, Schmitt proposed the Lateral Leg-Spring (LLS) model to describe the horizontal movement mechanism of insects, in which the lateral pendulum is considered[25–27]. To imitate the pendular feature of geckos in climbing process, Full and Goldman built the F-G climbing model with two axial limbs. F-G model shows the excellent performance by the simulation and test of the developed prototype on vertical surface[17,28,29].

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Benefiting from the dynamic climbing gait, gecko can climb at a vertical speed up to 72 $cm \cdot s^{-1}$, 5.3 $BL \cdot s^{-1}$[30,42]. According to Zaaf's study, the features of the gecko's gait were analyzed[31]. In Dai's work, the motion law of pendular waist is explored and the dynamic forces at the supporting feet are captured, which shows a high energy efficiency[32–35]. Referring to Dai's research work, the waist is regarded as the centroid of the gecko and the sinusoidal path is employed in our research, which is extracted from the waist track. According to the bio-inspired model with a waist, Woochul conducted the kinematics and simulation[36]. Dai and Cabelguen investigated the function of the lateral bending during the vertebrate's climbing movement[33,37]. The conclusion from Cabelguen's work indicates that the bending waist plays both roles in gecko's climbing process: (i) Resist torsional forces translated to the trunk by the limbs and (ii) Generate an upward burst. For bionic robot research, different stride lengths, climbing speeds and other parameters could be chosen and set to make the theoretical analysis and gait planning, thus the forces are more suitable for consideration. Meanwhile, the locomotion stability of geckos is enhanced because of the decrease in lateral force on the trunk.

This paper presents a GPL (Gecko inspired mechanism with one Pendular waist and four Linear legs) model to investigate the effectiveness of gecko's pendular waist that can optimize the driving forces on the legs. Taking the relevant morphological and kinesiological parameters as reference, this paper shows the description and dynamics of the GPL model, plans the waist trajectory, and calculates the forces on the bidiagonal supporting legs. Comparisons of different waist positions and trajectories are made to cognize the climbing competence. By extending beyond this space, it is speculated that the pendular waist plays the same role on other quadruped reptile species. So, a robot prototype is developed based on the GPL model to test if it can meet analytical expectations.

The remainder of this paper is organized as follows. The gecko's morphology and kinesiology in vertical climbing are discussed section **2**. In section **3**, an analytical model extracted from the bio-researches on gecko is proposed. Then, comparison is made between the calculated driving forces on supporting legs and the gecko's experimental data. Also, climbing simulation is made on a 3D model. In section **4**, a bio-inspired robot named DracoBot is developed, and the driving forces are measured to compare with our theoretical analyses. Finally, the paper concludes our studies and describes the future work.

2 The morphology and kinesiology of gecko

It has been observed that lizards swing their waists when climbing on horizontal or vertical surfaces[38–40], as shown in Fig. 1. Accordingly, the mass centroid wags as a result of body's bending. According to Dai's study[32], with regard to an adult gecko (14 cm in body length and 65 g in weight), the lateral amplitude of the waist pendulum is about 20 mm, as shown in Fig. 2. The

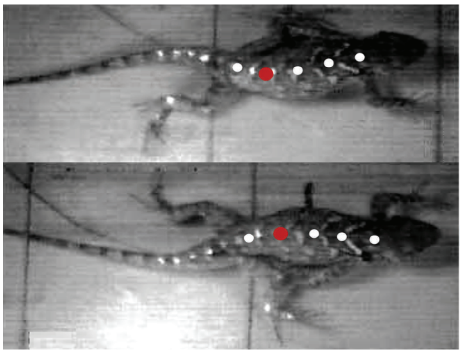

Fig. 1 Morphology of a lizard during rapid climbing on horizontal surface[39].

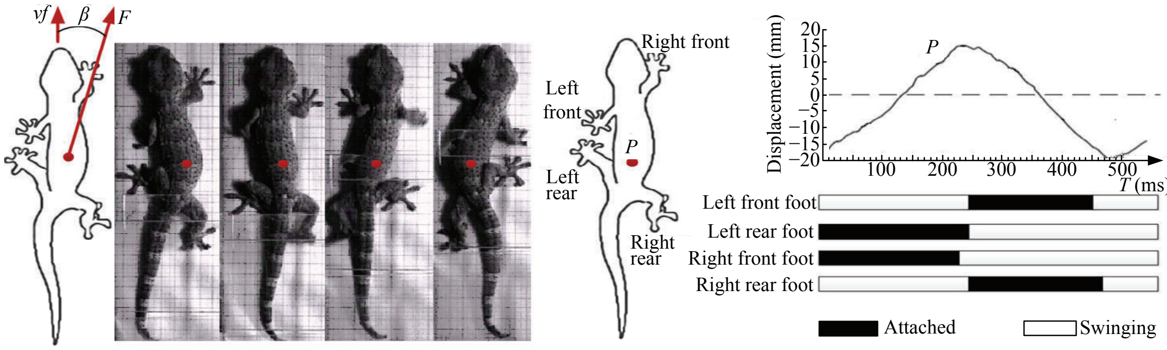

Fig. 2 Driving angle and morphology during geckos climbing on vertical surface[33].