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Design of a Milli-Scale, Biomimetic Platform for Climbing on a Rough Surface

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***Abstract*—Small multi-legged animals that can climb vertical walls with a rough surface have inspired research on climbing locomotion. Most robots that can climb a rough vertical wall are large and heavy due to the large number of actuators required to produce the complex locomotion. This paper proposes a novel design for a small and lightweight climbing robot that uses a single actuator. To guarantee reliable wall climbing, the contact phase of two tripods should overlap. A quick return leg is designed to enable phase overlap without requiring an extra actuator. Alternating tripods are also designed, and small spines with compliance are modeled based on the pseudo-rigid-body model. Layer-based fabrication is used to reduce weight. The resulting biomimetic platform is 10cm long and 10.8g in weight and can climb up a near-vertical brick wall at a rate of 5.57mm/sec.**

I. Introduction

Small mobile robots are capable of scouting areas that are dangerous and difficult to access, such as narrow spaces within a collapsed building. Therefore, small mobile robots could be used in reconnaissance or search and rescue missions [1]. However, miniaturized robots have difficulty overcoming obstacles, and their small size can impede their mobility. Therefore, there is a need for small robots that can climb on inclined obstacles that are bigger than their body.

Many climbing robots have been proposed using suction cups [2-3], magnets [4-6], dry adhesive [7], and spines [8-11]. Among these methods, the spine-based approach can be applied to a variety of surfaces, including dusty and rough surfaces.

Previous studies on large-scale climbing robots that use spines are shown in Table I. These robots employ many actuators to create phase overlap of contacts for stable climbing on rough surfaces. When the Spinybot II alternates its tripods with a phase difference of 180 degrees, the previously used tripod is kept in contact with the surface until fully engagement of the next tripod [8]. The RiSE robot lifts a single leg and makes it engage the next asperities while its other five legs exert force in the fore-aft direction to provide attachment to a rough wall [9]. LEMUR IIB is a quadruped robot that always maintains a grip on surfaces using at least three legs [10]. These robots have shown great success in climbing vertical walls, but scaling them down could be an issue due to the complexity of their mechanisms, actuators, and control schemes.

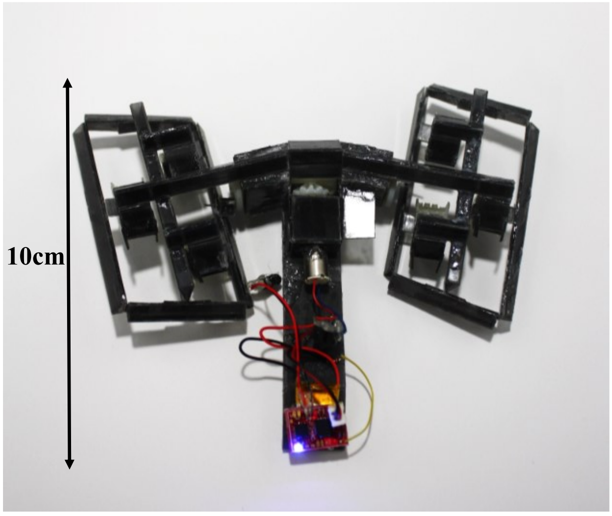

Fig. 1. Small and lightweight climbing platform.

This paper presents a milli-scale climbing robot (Fig. 1) that can climb on a rough surface using a single DC motor. The robot is inspired by how cockroaches climb. Cockroaches are known to be some of the best climbers among small-scale insects. A cockroach can rapidly climb up rough terrain [12] as fast as it can crawl on horizontal ground, based on the following four characteristics: alternating tripods for stability, sprawl angle for inducing lateral force, compliant spines for reliably engaging asperities, and phase overlap for secure alternation of tripods.

By applying these principles, a small and lightweight platform that can climb near-vertical rough surfaces was

TABLE I
COMPARISON OF MULTI-LEGGED CLIMBING ROBOTS WITH SPINES

	Spinybot II [8]	RiSE v2 [9]	LEMUR IIB [10]
Mass	0.4 kg	3.8 kg	10 kg
Actuators	7	9	13
Tested media	Brick, stucco	Brick, stucco	Rock
Phase overlap	O	O	O

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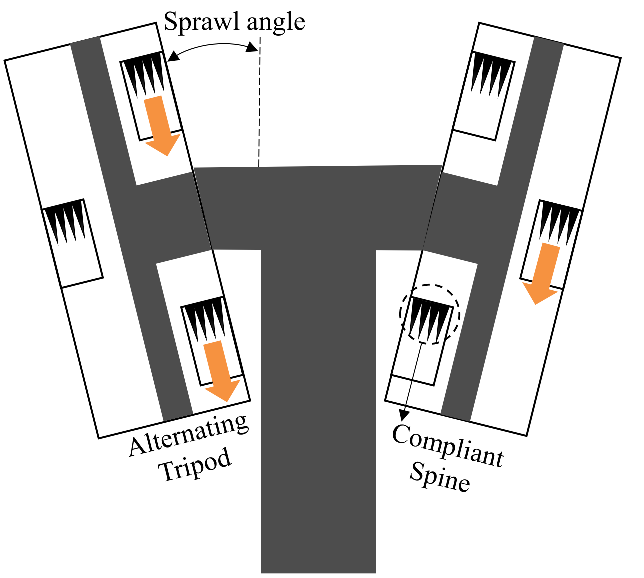

Fig. 2. Concept design integrated with biological inspiration.

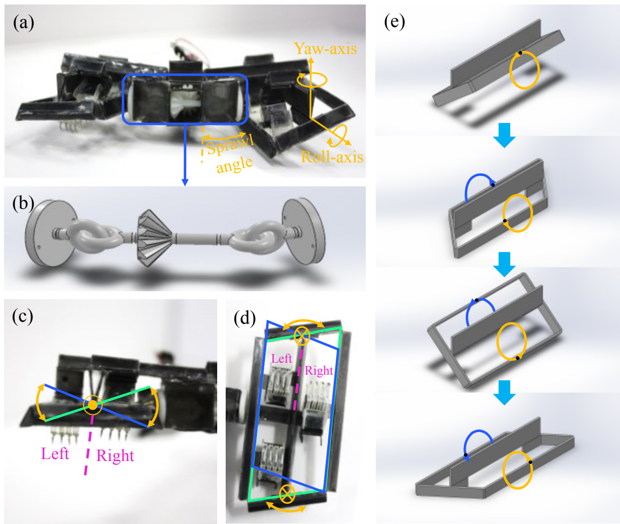

Fig. 3. (a) Components of the transmission system. (b) Shaft with ring-shaped universal joints. (c, d) Rotation about (c) the roll-axis and (d) the yaw-axis. (e) The four different positions of the four-bar linkage, which is composed of eight hinges for an alternating tripod.

designed. Basically the robot employs a tripod gait for stability. The robot's key design principle is a quick-return mechanism for overlapping the contact phase of the alternating tripods. These quick-return legs enable the robot to maintain contact with a surface as the tripods are alternated. In addition, compliant structures are used to make an adaptive foot for better engagement, and a sprawl angle is achieved using ring-shaped universal joints.

In the following sections, the conceptual design, modeling of spine compliance, phase overlap based on kinematics, measurement of engaging force, and climbing experiments are described. Also, the compliance of the foot is modeled based on a pseudo-rigid-body model (PRBM). Phase overlap of the quick-return leg was designed based on kinematics. To validate the robot design, the engaging force was measured using a six-axis load cell.

II. Design

A. Biological Inspiration

Four design principles for a small climbing robot can be extracted from the locomotion characteristics of cockroaches. The first principle is that alternating tripods allow mechanical stabilization against perturbation. Mechanical systems that enable animals to make at least three points of contact with a surface for support make neural control simpler [13]. Therefore, mechanical stability can be improved by applying alternating tripods. The second principle is that a sprawl angle allows a climber to generate a lateral force. The effective sprawl angle that enables cockroaches and gecko lizards to climb quickly is around 10 degrees. When a climber has a sprawl angle of that size, the maximum lateral force and the minimum angular velocity appear [14]. The lateral force generated through the sprawl angle can interlock claws and spines during climbing [12], allowing for better adhesion on a rough surface. The third principle is a compliant spine to engage hard and dusty surfaces without falling. Unlike smooth surfaces such as glass, it is difficult to use either a hairy pad or an adhesive pad repeatedly on a rough substrate because of the presence of dust and debris. In fact, hornets attach to a fine surface with an arolium and to a rough surface with claw- and spine-based friction [15]. Therefore, the compliant spine mechanism is required to work well on a real vertical wall. The fourth principle is the phase overlap of contacts. Cockroaches use phase overlap for secure engagement during alternation of tripods. During the phase overlap period, the fore-aft force becomes minimal and the peak negative force pulls the animal back toward the wall, while the legs are alternated [12]. Therefore, phase overlap allows stable engagement of the opposite tripod. The concept design integrating these characteristics can be seen in Fig. 2.

B. Transmission and Sprawl Angle

There is a limit on the number of actuators due to the space limitations of a small platform. Therefore, designing a transmission that uses a limited number of actuators to accomplish the desired motion becomes more important. This study uses a four-bar linkage with two hinges for the roll-axis and the yaw-axis in its middle to enable alternating tripods, as shown in Fig. 3 (e). Movement in the opposite phase to the roll-axis and yaw-axis like a lever can be seen in Fig. 3 (c) and (d). These two kinds of movements allow the right legs and left legs to have a phase difference of 180 degrees on the central axis, as indicated in Fig. 3 (c).

Bevel gears were used to transmit power to both sides with a single DC motor. Gears and shafts were designed and integrated with ring-shaped universal joints to make a sprawl angle. Whole components were assembled in CAD and created with a three-dimensional (3D) printer (Object260 Connex, Stratasys, Co., Ltd.).

C. Compliant Spine Mechanism

In order to climb rough surfaces, the spine mechanism should have compliance. Unlike carpet or loose cloth, a rough surface can cause bouncing due to the overshoot of the wall reaction force. This can make climbers ricochet off a wall and fall because of pitch-back moments induced by reaction force. Adding compliance to a foot not only slows oscillations of the

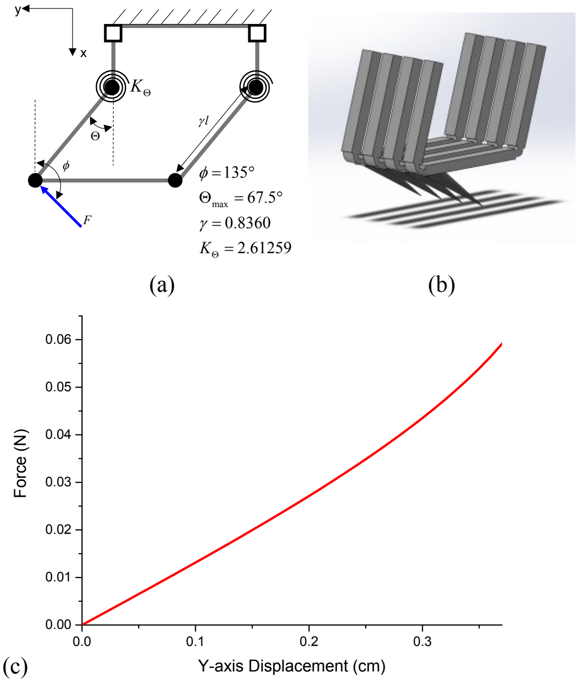

Fig. 4. (a) Spine modeling and numerical data [16]. (b) A compliant foot with four spines. (c) Spine force plotted against deflection.

ground reaction force but also increases the damping ratio to prevent bouncing [17]. Therefore, the attachment can be stabilized. A previous study of the design of a compliant spine proposes the following requirements: Spines should engage on the surface individually, and the load should be distributed evenly. The angle of the spine should be kept constant, and spine should not slip at asperities even when the load increases [18]. Another study suggests that an angle between 45 degrees and 60 degrees is appropriate to make the adequate adhesion [19].

In this study, a PET film has been used to make a small spine with compliance, because a single foot with four spines is 8mm × 5mm × 8mm. Modeling of the compliant spine is performed according to the PRBM [16]. By putting a torsional spring element at a specific position on the beam, a deflection similar to an actual beam can be simulated.

$$K = \gamma K_\Theta \frac{EI}{l} \quad (1)$$

$$\gamma l F = K\Theta \quad (2)$$

$$F = \frac{1}{\gamma l}\gamma K_\Theta \frac{EI}{l}\arcsin(\frac{y}{\gamma l}) = \frac{1}{l^2}K_\Theta EI\arcsin(\frac{y}{\gamma l}) \quad (3)$$

where γ is the characteristic radius factor, K_θ is the stiffness coefficient, Θ is the deflection angle, E is the modulus of elasticity, I is the moment of inertia, and F is the force exerted on the tip of compliant beam.

The equations are arranged in (1) - (3) to match the required force with regard to y-axis deflection induced by an engaging force from a single leg. The engaging force range is from 0.1N to 0.6N, and the force caused by four spines is in this range as shown in Fig. 4 (c). The compliant spines are fabricated to

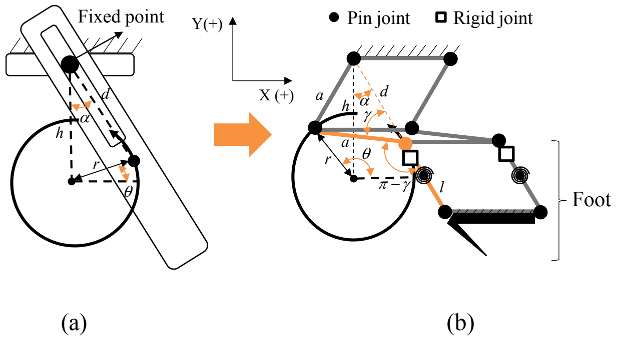

Fig. 5. Design parameters of (a) a conventional quick-return mechanism and (b) a quick-return leg.

meet the aforementioned requirements. Therefore, the spines works on surfaces individually and the angle of a spine is kept constant at 45 degrees as shown in Fig. 4 (b).

D. Quick-Return Leg for Phase Overlap

A conventional quick-return mechanism using a slider was considered for the platform in order to produce the phase overlap (Fig. 5 [a]). During actuation of the quick-return mechanism, the return phase is shorter than the contact phase. When two mechanisms with a phase difference of 180 degrees move, there should be a period when the two mechanisms touch the surface at the same time. Therefore, this mechanism could create a phase overlap period. It is difficult to miniaturize a conventional component such as a slider. It is necessary to convert the slider to a two-dimensional (2D) mechanism, and two four-bar linkages are proposed to replace the linear motion of the slider.

In order to design a quick-return mechanism by the planar fabrication, two conditions should be satisfied. When the yellow dashed line becomes a tangent of the circle (Fig. 6), the intersection of yellow dashed line and the circle should be higher than half of the circle. This intersection becomes a

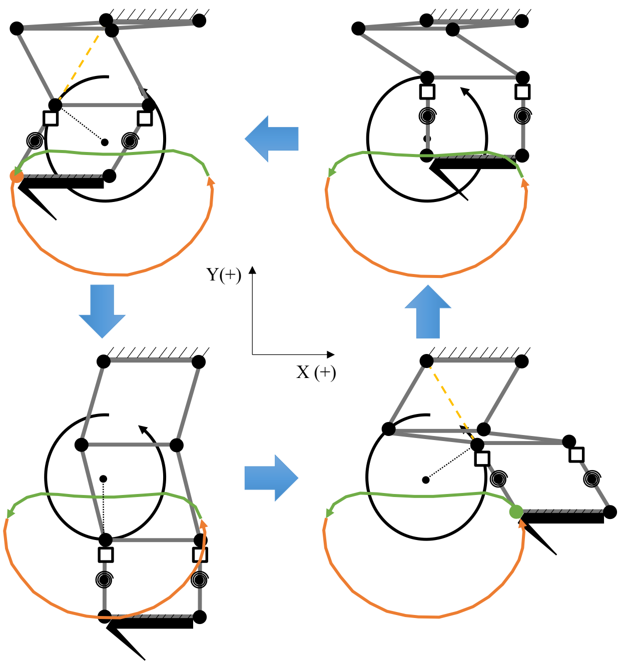

Fig. 6. Schematic diagram of the quick-return leg.

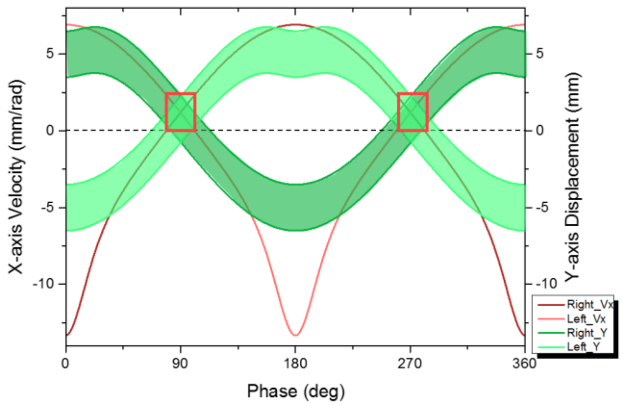

Fig. 7. Overlap phases (the red boxes) in a cycle.

reference point to distinguish the return phase and the work phase. The second thing is to maintain a constant angle $\pi - \gamma$ between the yellow solid lines shown in Fig. 5 (b) to make a symmetrical trajectory. A quick-return leg trajectory that satisfies these kinematics conditions is shown in Fig. 6. The green line and the orange line indicate the return phase and contact phase, respectively, in the schematic diagram.

$$d = \sqrt{r^2 + h^2 - 2rh\cos\theta} = 2a\cos\gamma \tag{4}$$

$$\alpha = \arccos\left(\frac{d^2 + h^2 - r^2}{2dh}\right) \tag{5}$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} (d+l)\sin\alpha \\ r + h - (d+l)\cos\alpha \end{pmatrix} \tag{6}$$

where d is the leg length from the fixed point to the foot, r is the length of the drive link, h is the distance between the center of the circle and the fixed point, θ is the phase of the motor, γ is the angle between a link and an extension of l link (yellow dashed line) and α is the angle between the leg and the vertical center line (black dashed line).

The trajectory of the leg is calculated in (4) – (6) based on kinematics. The trajectories of x-axis velocity and y-axis displacement were plotted to verify the period of phase overlap. In the overlap region, when a tripod with positive x-axis velocity maintains engagement to generate adhesive force, the other tripod also has enough positive x-axis velocity to engage with a surface. The y-displacement should be equal to enable both tripods to contact the surface at the same time. The region in which the legs have an equal y-axis displacement is extended through the compliance of the spine mechanism about the y-axis. Therefore, phase overlap is represented in the red boxes in Fig. 7.

III. Fabrication

The fabrication method is fundamentally based on the Smart Composite Microstructure (SCM) process for a small platform. This 2D-based fabrication process uses laser micromachining and lamination. A composite such as CFRP or GFRP is used to provide rigid link, and a flexure such as polyimide film is used for the revolute joint [20]. Modification

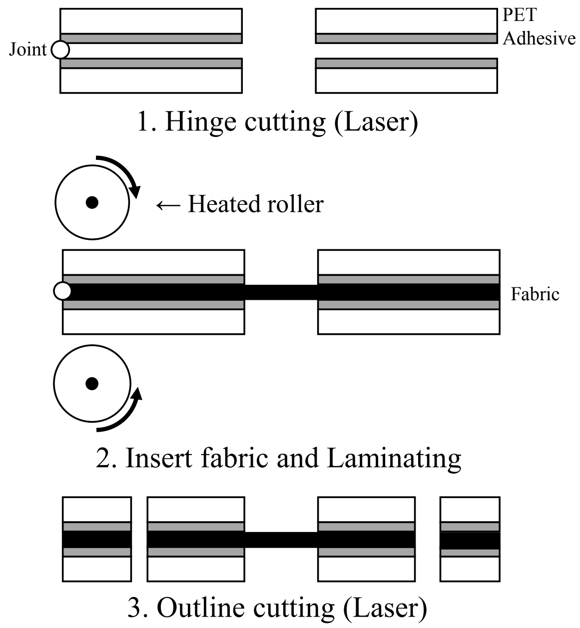

Fig. 8. Facile fabrication using laminating film.

of the process has been proposed using poster-board and polymer films for fast prototyping and manufacture [21]. In this paper, the fabrication process has been simplified and the stiffness of the rigid link has been increased by using laminating film. Because the laminating film contains an adhesive, thin fabric can be inserted between sheets of the film without requiring an additional adhesive sheet. The three step process is shown in Fig. 8: (1) cutting the hinges, (2) laminating, and (3) cutting the outline. The entire process can be completed in 10 minutes on average. After lamination, the compact platform is fabricated through an assembly process. Electronics and material used in fabrication of the platform are shown in Table II.

IV. Experimental Results

To verify phase overlap of two tripods, forces with regard to time were measured. In addition, the climbing platform was actuated on an inclined brick to check its performance.

A. Engaging Force Measurement

To measure the force profile and verify the phase overlap period, a load cell (Mini40, ATI Technologies, Inc.) was mounted on a box covered with sandpaper (see Fig. 9). The climbing platform was attached to a linear guide so that it moved along a rail. The experiment was performed to measure the force using a single leg and two alternating legs.

TABLE II
ELECTRONICS AND STRUCTURAL MATERIAL

	Mass	Charateristics
Actuator	1.4 g	3V DC motor (D&J WITH Co., Ltd.)
Battery	0.5 g	10mAh (HHS Co., Ltd.)
RF Receiver	0.6 g	Four channels (drcmall.com)
Rigid Link	0.038 g / cm^2	0.35mm thickness fabric laminated with PET film

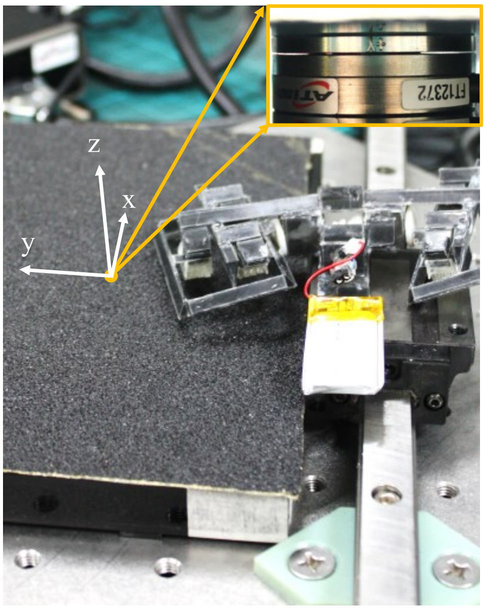

Fig. 9. Experimental setup and the six-axis force/torque sensor.

As shown in Fig. 10 (a), the fore-aft force is kept positive longer than half of a cycle when the force of a single leg is measured. In other words, phase overlap occurs during the middle of the gait. So, fore-aft force with two alternating legs at the intersecting point is kept positive (Fig. 10 [b])

The profile of the normal force should be considered significant. When the fore-aft force is positive in Fig. 10 (a), the area of the positive normal force is larger than the area of the negative normal force. This means that pulling force resulting from shear force cannot compensate for pushing force resulting from the stroke of the opposite legs. Represented in Fig. 10 (b), negative normal force does not appear at all due to a large positive normal force. Thus it can be predicted that engagement on asperities does not occur rapidly and that the shear force is insufficient.

B. Climbing Performance on a Rough Surface

A climbing test was conducted on a brick with an incline from 0 degree to 90 degree. But it can climb up 75-degree brick at most. This platform fails to scale a slope that is greater than 75 degrees because of insufficient pulling force. 2D tracking was conducted with via videotaping, and the climbing speed was determined to be 5.57mm/sec. Y-axis displacement oscillated from 9mm to 18mm. One possible reason for this oscillation is that the contact phase of the quick-return trajectory is not even, causing displacement that creates pitch-back moment, which makes the platform unstable and overturns its body.

V. Discussion

Phase overlap was found, but the appropriate negative normal force was not generated. It may thus be assumed that engagement of the spine mechanism on rough surfaces is not 100 percent guaranteed, and the stroke of the legs is quite short, which makes it difficult to engage properly. As the platform becomes smaller, the stroke of the legs diminishes and the spines are barely engaged on the asperities.

Therefore, a compliant spine mechanism capable of rapid engagement and disengagement is required for the small climbing platform. In addition, the area of negative normal force becomes larger than that of positive normal force when the spines engage on asperities at the phase overlap. This could make it possible for the platform attach to surfaces most of the time. At the same time, the contact phase of the quick-return trajectory should be even, and the oscillation of y-axis displacement need to be kept low to prevent the platform from overturning by pitch-back moment.

By solving the problems mentioned above through a kinematics-based design, the platform can not only climb on rough surfaces with minimal actuators but can also run up a wall dynamically. Adopting an additional actuator will allow

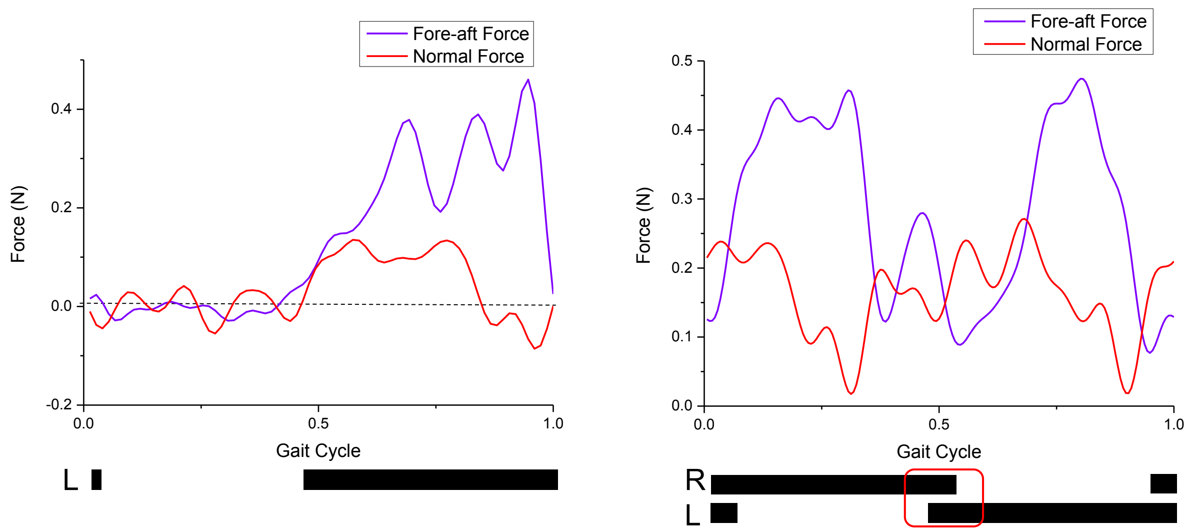

Fig. 10. Force profile for (a) one leg and (b) alternating legs.

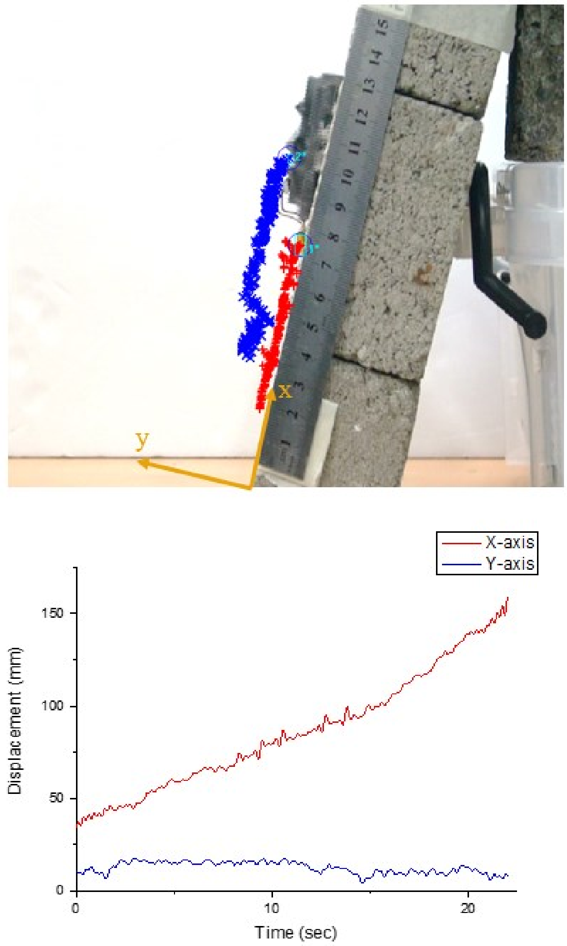

Fig. 11. (a) 2D tracking and (b) displacement of the two axes.

the platform to change its direction. In addition, overall mobility will be improved when a control-based approach is adopted in the future.

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