A robotics leg inspired from an insect leg

P.Thanh Tran-Ngoc, Jia Hui Gan, T.Thang Vo-Doan, Hirotaka Sato

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
Institute of Biology I, University of Freiburg, Germany

To whom correspondence should be addressed. E-mail: hirosato@ntu.edu.sg

Abstract
Legged robots can operate in complex terrains that are unreachable for most wheeled robots. While insect legs contact the ground with the tarsal segments and pretarsus, most insect-inspired robots come with a simple tarsus such as a hemispherical foot tip. Insects, like the M. Torquata beetle, use the claws as their attachment devices on rough surfaces. Their sharp claws can smoothly attach and detach on plant surfaces by actuating one muscle. Thus, legged robots can mimic tarsal structures to improve their locomotion on inclined and rough surfaces. We conducted two types of experiments to test the hypothesis that the tarsal flexibility and rigidity play a role in the beetle's smooth walking. By cutting the membrane between the tarsomeres, we disabled the tarsus' rigid ability, so the claws cannot securely hook onto the walking surface. Conversely, after eliminating the tarsal flexibility, the beetle struggled to draw the claws out of the substrate. The results confirm the significance of the tarsus' properties on beetle walking. Then, we designed a cable-driven 3D printed tarsus structure to validate the function of the tarsus via a robotic leg. The tarsal configuration allows the prototype to hook onto and detach smoothly from the walking surface.

Keywords: Locomotion, bio-inspired robotics, beetle, tarsus

1. Introduction
Although traditional robots frequently employ wheels for movement due to their energy efficiency and simple control strategy, this type of locomotion is ineffective when traversing rugged and uneven terrains [1]. According to address this issue, walking machines or legged robots were designed to move on terrains that are inaccessible to wheeled robots. The capacity of walking machines to change their posture to overcome terrain discontinuities is their most notable attribute [2]. However, their mechanism is more complex as well as it requires a more complex control scheme than wheeled robots [3]. During millions of years of evolution, optimal legged systems for movement have evolved. Researchers in mobile robotics have recognized the advantages of incorporating biological principles in the construction of walking robots during the previous few decades. Many researchers have developed a series of four-legged (quadruped), six-legged (hexapods), eight-legged robots inspired by insects and animals [4-6]. As the number of legs increases, the robot becomes more stable, but the control system becomes more complex to construct [7].

Insects have long been a source of inspiration for legged robot designers due to their high maneuverability and ability to adapt to uneven terrain quickly. For example, HECTOR [8] and LAURON [9] are inspired by stick insects, AMOS [10] is based on cockroaches, and BILL-ANT [11] is inspired by an ant. These robots replicated the insect leg structure [12], including the coxa, trochanter, and tibia parts to reinforce their equilibrium while moving. However, the tarsi were replaced by a simplified hemispherical foot tip for locomotion. Feet with different shapes have been designed for some walking robots to improve their locomotive ability in complex terrains [13-16]. Walking robots do not typically include the tarsal structure as well as the attachment device in their designs because they add complexity and may not be necessary for the terrain if it is undulating.
Over millions of years of evolution, insects have developed amazing locomotion devices that help them to walk smoothly on a wide range of surfaces. Most insects can attach to a wide variety of terrains using different attachment systems, which can be broadly classified into smooth adhesive pads, hairy pads, and claws [17-21]. Smooth adhesive pads are generally soft and deformable and can be further subcategorized (e.g., arolia, pulvilli, and euplantulae) depending on their positions on the tarsus [17, 22]. They can adhere well onto smooth surfaces via adhesive forces generated through capillary interactions [23, 24]. On rough surfaces, insects use their hairy pads via attachment forces generated by van der Waals forces [25, 26] and capillary forces [27-29]. Moreover, to ensure the most robust possible grip, both smooth and hairy pads maximize the contact area between the pad and the surface [30]. In cases where this is unfeasible, such as on surfaces with protrusions with mean radii larger than the diameter of the claw tips, insects rely on the claws as means of attachment, as the surface is rough enough that the claws can reliably attach via frictional self-lock [31, 32, 33]. Due to the knowledge from insect attachment systems, the robot system RATNIC [34] is able to move on vertical pipes thanks to the adhesive

Fig. 1. (A1) Flower beetle stand on the mesh substrate: (A) The claw of the forelegs. (B & C) Cross-section image of the tarsus. The 3D printed tarsus: (D) the 3D model of tarsus and claw parts. (E) Based on the natural shape of the tarsus, a 3D printed tarsus was designed and manufactured, and this structure was connected to four actuators to replicate the movement of the foreleg.
pads with enhanced frictional properties that mimic the material of smooth pads. However, this robot only climbed on smooth surfaces. For rough or mesh surfaces, DIGbot [16] includes a foot that mimics insects’ claws. The springed tarsus joints allow the claw to change its angle when it contacts the ground and return it to the original position when its grip is released. This passive mechanism helps the robot climb on a screen mesh with a gap of 2cm. However, when the leg angle changes are substantial during turning, spine slippage is more common. Compared to these limitations of artificial robots, insects can walk smoothly on rough surfaces including mesh substrates even when they have claws of different shapes and stiffness [31, 35, 36]. For example, beetles with sharp claws put on a piece of wool cloth can walk smoothly without any signs of difficulty. The tarsus’ flexibility, the result of a chain of ball and socket structure that links the tarsal segments, suggests that it will bend during walking, allowing the claw to be passively angled into a position where it can detach when the leg swings forward. Moreover, the tarsus is actuated only via a single muscle, the claw retractor muscle, within the tibia and the tarsal promotor muscle located at the end of the basitarsus [12, 37]. Thus, we hypothesized that the tarsus’ ball and socket structure is responsible for smooth walking on different terrain among insects. To test the hypothesis, we used the Mecynorhina torquata beetle as a model animal for investigating the role of the tarsus when walking with claws because this insect has only claws to grip onto a walking surface and no adhesive pads (Figure. 1A) [38, 39]. Inspired by the role and the structure of the beetle’s tarsus, we built a 3D printed tarsus which is able to replicate the function of a real tarsus when attached to a robotic leg (Figure. 1E).

2. Materials and Methods

2.1 Animals

We used adult flower beetles M. Torquata (order Coleoptera), purchased from the Kingdom of Beetle Taiwan Co. The beetles were kept in separate cages (15 cm × 15 cm × 20 cm) in a rearing system (NexGen IVC system) and fed with sugar jelly twice per week. The system was maintained at 25°C and relative humidity of approximately 60%. Only male beetles (5–7 cm) were used for all experiments.

2.2 Tracking the trajectories of legs and body

We used a hexagonal mesh made from polyester with a gap of 2 mm across and a Styrofoam plate as the surface for beetle walking. A three-dimensional (3D) motion capture system (6x T40s VICON cameras) was used to record the trajectories of the front leg and body at 100 fps when the beetle walked on the mesh surface (Figure. 2A). To calculate the angular displacement between the tibia and tarsus segments, three retroreflective markers (L1 and R1, 2-mm cylinder markers; L2, L3, R2, R3, 3-mm spherical markers) were attached on each front leg to denote the tibia and tarsus segments (Figure. 2B and C). To identify the stepping patterns when the beetle is walking, an L-shaped frame with three markers (B1, B2, B3, 3-mm spherical markers) was also attached on the beetle’s body to measure the distance between the claws and the reference plane made by the L-shaped frame (Figure. 2B and D).

2.3 Physical constraints in the rigidity and flexibility of tarsus

To eliminate the flexibility of the tarsus when the beetle walked on the mesh surface, we used heat-shrink tubing. In preparation for the tubing process, the beetle was restrained on a frame using nylon cable ties wrapped around the body and legs. Using a cylindrical tube with a diameter of 2 mm, we covered the tarsus and a portion of the tibia (Figure. 3B). Because this tube has a shrink temperature of approximately 90°C, a soldering iron of approximately 150°C was used as a heat source. The heated metal tip was moved along the tubing within 20 s to shrink and wrap it tightly around the tarsomeres, as well as the joint between the tarsus and tibia. After the
experiment, these tubes were removed by a pair of scissors, and the beetles were returned to the rearing system. After being allowed to rest for one day, the beetles were allowed to walk on the mesh substrate. The stepping patterns were measured to determine whether the heat source from the soldering iron impacted the tarsal performance.

The cuticle connecting the third tarsomere to the second tarsomere and the membrane underneath it was destroyed using a pair of scissors to decrease the rigidity of tarsus. A pair of micro-dissecting spring scissors (Vannas tweezer, pattern no. 5, tip size 0.05 × 0.01 mm) was used to remove the cuticle around the tarsomere (Figure 3A) until the membrane was exposed. The membrane underneath the cuticle was then cut.

2.3 3D printed tarsus

The artificial tarsus was designed based on the structure of the beetle’s tarsomere, especially the structure of the ball and socket configuration. Firstly, the X-ray image of the foreleg tarsus was captured to show the structure inside in different shades of black and white (Figure. 1B). Then, sandpaper was used to remove the cuticle and create a cross-section view of the tarsomeres. The ball and socket configuration of each tarsomere was exposed, and the shape of the cuticle around it was captured under the microscope (Figure. 1C).

Using the tarsomeres’ cross-section view, we designed a 3D model of the artificial tarsus on a CAD software (SOLIDWORKS) (Figure. 1D) and 3D printed the prototype from polylactic acid material. The shapes of tarsal articulations are arranged in such a way that the tarsal chain bends downwards. In the kinematics of the joint between tarsomeres, the position between condyles and the retractor tendon affects the tarsal movement (Figure. 4A). A string and steel alloy compression spring (outer diameter of 4.5 mm, spring constant of 0.54 N/mm) was used to replicate the function of the tendon and the membrane of the beetle’s tarsus, respectively (Figure. 3C1). By pulling the string, the tarsus was bent, and rigidity increased, thus opening the claw (Figure. 3C2). When the string was released, the tarsus returned to its original position because of the elastic force of the springs (Figure. 3A). The kinematics of the claw is influenced by the structure of the unguitractor apparatus, which links the tendon and the claw together [31, 40]. On the basis of the mechanism of the beetle’s claw (Figure. 4B), we designed a new mechanism for the artificial tarsus that made the claw open and rotate downwards when pulling the string, as well as returning to its original position when released (Figure. 4C).

To replicate the movement of the beetle’s front leg, we used a set of four actuators: three actuators for the rotation of the coxa, femur, and tibia and one actuator for pulling the string to switch the artificial tarsus between rigid and flexible conditions (Figure. 1E). The movement of the entire artificial
leg does not entirely resemble the natural walking of the beetle in this experiment. In a natural walking of the beetle, one cycle involves the leg lifting and lowering once each, whereas, in the artificial leg, one cycle involves the leg lifting and lowering twice each. This deviation is necessitated because, in the stroke that propels the beetle forwards, the leg swings backward. Had the artificial leg swung similarly backward, the mesh would have been deformed horizontally, thereby preventing the height of the mesh from being taken accurately and from concluding the effects of the rigid tarsus. As such, the leg was modified to swing up and down instead of horizontally.

2.4 Demonstration of the 3D printed tarsus

We used a square mesh made from nylon material with a gap of 25 mm across as the surface for the artificial claw to hook into in these experiments. The trajectory of artificial tarsus was tracked by the motion capture system that was used to record the trajectories of the beetle walked on the mesh surface (Figure. 2A). The framerate for each camera was set at 100 fps. Reflective markers were used for tracking by the VICON system. Seven retroreflective markers (3-mm spherical markers) were attached along the artificial tarsus to track its movement (Figure. 3C1). To visualize the mesh's deformation, we also placed four retroreflective markers (3-mm spherical markers) along the perimeter of the area where the claw contacts the mesh, the displacement of the mesh were calculated by the mean displacement of these four markers.

After collecting the 3D motion data of the 11 markers, the positions of these markers were displayed. Subsequently, the CSV files generated were exported from the VICON Nexus software to provide the positional data for each frame. Using a custom program written in MATLAB, we analyzed the displacement of the artificial pretarsus and the deformation of the mesh. The movements of the artificial tarsus were tracked, stored, and analyzed.

3. Results and discussions

3.1 The tarsus bent differently on different terrains

The tarsus is made up of individual tarsomeres that resemble hollow cylinders, with two consecutive tarsomeres being connected in a ball and socket configuration. The overall arrangement of the tarsus resembles a chain, giving the tarsus flexibility. In the M. Torquata beetle that we used in this study, the tarsus consists of five tarsomeres. To verify if the tarsus plays a crucial role in smooth walking, we tracked the forelegs of the beetles with motion capture cameras to determine if they bend during walking and if there are any significant differences in the tarsus when walking on surfaces of different roughness. This was performed by allowing the beetle to walk on two different terrains: a solid, continuous surface (Styrofoam board) and a flexible, mesh surface (Figure. S1A and B).

The tarsus bent during walking on both terrains. Because the mesh had deeper depressions or holes, the tarsus bent and deformed to a greater degree than when walking on the solid surface (Figure. 5A and B). Specifically, the ability of the tarsus to bend is described by the angle between the claw and the tibia, as shown in Figure. 6A. The mean changes in this angle for the two groups were 55.7° ± 7.2° and 27.7° ± 7.4° (N = 5 beetles, n = 25 trials), respectively. The cycle time needed for the beetle to release its grip, swing its leg forwards, and touch down on the walking surface again was increased by approximately 10% when the beetle was walking on the mesh as compared to on the continuous ground, with a value of approximately 446.1 ± 59.2 ms and 406.6 ± 76.1 ms, respectively (Figure. 6C).

The observations can be explained as follows: when the claw was on the mesh, the claw hooked deeper into the depressions on the surface. When swinging the front legs forward, the claw was not released from the depression immediately, causing the tarsus to deform before the claw was eventually freed. In contrast, on the solid surface, the shallower depressions mean that the claw can be freed more...
easily when the legs swing forward; hence, the tarsus did not deform as much. The motion of the beetle is less smooth when walking on the mesh, as shown by the increased cycle time (Figure 6C, t-test, Supplementary Table S1); however, the increase was only approximately 10%. If the beetle struggled or otherwise faced any difficulties while walking on the mesh, it was likely that they would need a much longer time to complete a cycle. Overall, all these suggested that tarsal deformation plays a crucial role in helping the beetle release its grip from the walking surface.

3.2 Role of the tarsus’ rigidity

Confirming that the tarsus does bend during walking highlights another question: How is it that the tarsus rotates in a specific direction, that is, inwards instead of a random direction, despite it being flexible? Furthermore, the tarsus is angled such that the claw aims into the walking surface rather than sideways. Hence, there should be something that passively aims the claw so that it points into the walking surface.

The outermost layer of the tarsomere is a hard shell, called the cuticle, and underneath the cuticle is a membrane, which wraps around a tendon (Figure 1B). Within the tarsus, this tendon passes through the hollow path within the tarsomeres. One end of the tendon is connected to the claw retractor muscle within the leg section called the tibia, whereas the other end is connected to the unguitractor plate and the claws. When the claw retractor muscle contracts, tension within the tendon increases, causing the tarsus to rotate inwards and become rigid, and also causing the claw to grip onto a surface [35, 37, 40].

Either the cuticle of the tarsomeres or the membrane of the tarsomeres is responsible for passively aiming the tarsus. To identify which structure is responsible for this passive aiming, we compared the trajectories of the claws and the claw angular displacement to the foreleg’s tibia between the following: when the tarsus was intact (Figure 1A), and when the membrane of the third tarsomere on the right foreleg was removed (Figure 3A).

When the membrane of the tarsomere was removed, there was a noticeable change in the trajectory of the claw. In particular, the Z-axis displacement of the claw with the cut membrane was significantly smaller than the claw with the intact tarsus (Figure 5A and C). Also, after the membrane of the tarsomere was cut, the angular displacement of the claw for the foreleg’s tibia was significantly decreased. The mean angle of the intact tarsus was 55.9° ± 8.4°, whereas it was only 25.5° ± 3.9° following the removal of the membrane in the front tarsus (N = 3, n = 15) (Figure 6B). Also, this angular value of the intact leg was similar to the value when an intact beetle walked on the mesh (55.7° ± 7.2°). This shows that the intact leg was not affected by the removal of the membrane on the opposite leg, and it can operate normally during the experiment.

The observations can be explained as follows. For an intact tarsus, the claw was firmly anchored to the mesh. When the beetle starts to swing its foreleg forwards, the claw retractor muscle relaxes to remove the tension within the tendon and increase the flexibility of tarsus. The tarsus was bent because the claw was still securely attached to the surface, causing the angular displacement of the claw to the foreleg’s tibia to increase. When a sufficient pulling force freed the claw, the foreleg finishes its swing, and the claw comes into contact with the mesh again, thereby reducing the claw’s angular displacement. On the other hand, the membrane plays a role in passively aiming the claw so that it points into the walking surface [37, 40]. Hence, when the membrane was cut, the trajectory of the claw changed so that it only leaned on, rather than inserted into the mesh as the beetle stood still. When the beetle moved forward, the claw only flipped and leaned on the mesh as the foreleg finishes the cycle. The angular displacement of the claw became smaller because the claw was no longer attached securely as compared to when the membrane was intact (Figure S1C). As such, the tarsal membrane is the source of the rigidity of the tarsus, which, in turn, is necessary for insects to aim their claws into the surface passively.

![Fig. 6. The angular displacement of the claw when: (A) the beetle is walking on the mesh and Styrofoam plate, (B) the beetle is with intact tarsi and cut membrane walking on the mesh. The cycle time of the beetle foreleg when (C) the beetle is walking on the mesh and Styrofoam plate, (D) the beetle is with intact tarsi and tubed tarsi. Error bar is standard deviation.](image-url)
3.3 Role of the tarsus’ flexibility

We compared the trajectories of the claw and the distance between the claw and the reference plane attached to the thorax between the following cases: when the tarsus was intact (Figure 1A) and when the tarsus was housed within a small tube to inhibit its flexibility (Figure. 3B).

In the case of the intact tarsus, the beetle had no difficulties moving on the mesh surface, as shown in its trajectory (Figure. 5A). In contrast, when the tarsus was constrained, and the flexibility of the tarsus was lost, the beetle had significant difficulties in removing its claws from the mesh (Figure. 5D). Also, the regular cycle between each leg stroke was no longer present. Specifically, the mean cycle time of the beetle front leg in this experiment is much larger than that of an intact leg, with 1594.4 ± 271.3 ms compared with 446.1 ± 59.2 ms, respectively (N = 5, n = 25) (Figure. 6D). To investigate whether the heat source used in the tubing experiment had affected the beetle, one day after removing the tubing, the beetles allowed to walk on the mesh again. The mean cycle time for this case was similar to those of intact tarsus, with a value of approximately 443.4 ± 61.6 ms and 446.1 ± 59.2 ms, respectively (N = 5, n = 25) (Figure. 4C and D, t-test, Supplementary Table S2). This implies that the tarsal performance was not impacted by the heat that was applied to the tube.

The reason for this difference can be explained as follows. When the claw retractor muscle relaxes, tension within the tendon was removed, and the membrane helps to return the
tarsus into its original shape. However, when the tarsus was tubed, the membrane’s elasticity was unable to overcome the tubing, thus effectively removing the tarsus’ flexibility. Hence, when the beetle tried to remove its claws from the mesh, the tarsomeres were unable to bend or rotate into an angle that allows the claw to detach from the mesh, and the front legs must repeatedly swing until the claw was successfully detached via brute force. This process causes the vibration movement in between each leg swing, as captured in Figure S1D. As such, the flexibility of the tarsus due to its ball and socket configuration is necessary for insects to detach from surfaces.

3.4 Demonstration with artificial tarsus

In previous sections, we studied the function of the tarsus’ articulation configuration, along with the cuticle and the flexible membrane between two adjacent tarsomeres. In this section, an artificial prototype, with both flexible and rigid tarsi, was designed and manufactured using the structure of the beetle tarsus and kinematic model of the joint between tarsomeres as a reference to confirm our hypothesis (Figure. 3C1).

When the motor simulating the claw retractor muscle “contracts” and pulls the string simulating the tendon, the artificial tarsus was bent, and the claw was opened (Figure. 7A2). The structure was restored to the original state after releasing the string (Figure. 7A1). During the simulation process, the 3D printed tarsus was bent and switched to the rigid condition. The angular displacements between each segment and the basement were measured to show the bending ability of the structure. All segments of the structure were rotated down, the bending angle was increased from first segment 1 to the fifth segment, with 6.2°± 2°, 9.4°± 1.9°, 16.2°± 2.4°, 24.6°± 3.6°, and 27.2°± 5°, respectively (Figure. 7B).

This 3D-printed tarsus was assembled with the actuator sets to mimic the movement of the beetle foreleg. When the motor “contracts” (denoted by state 1), the prototype tarsus bent and hooked onto the mesh surface securely. In this state, when the artificial tibia swung upwards, the height of the mesh markers followed that of the claws closely, indicating that the claw was hooked securely. When the motor “relaxes” (denoted by state 2), elastic components within the prototype tarsus cause it to return to its original position, and no difficulties were observed when the artificial tibia swung upwards. Similarly, this can be seen by how the height of the mesh markers returned to their original position while the claws continued to increase, indicating that the claw was free from the mesh (Figure. 7C1).

In contrast, when the prototype was switched to one with a rigid tarsus (Figure. 3C2), the prototype was able to hook onto the mesh when the artificial tibia swung downwards but was unable to detach when the artificial tibia swung upwards. This was shown by the claw’s marker remaining near the mesh markers during each swing of the tibia (Figure. 7C2). The results suggest that a flexible tarsus is necessary for the claw to detach from a surface and that a rigid tarsus is needed for the claw to hook securely, which also holds true even in the case of artificial robots. Overall, the effects of the flexibility and rigidity of the tarsus are further verified through the artificial tarsus demonstration.

4. Conclusion

In this study, we hypothesized and confirmed the role of the tarsal ball and socket configuration and the necessity of the tarsus’ ability to bend and become rigid in insect walking. In summary, when the tendon is pulled, the ball and socket configuration cause the tarsus to bend at a certain orientation. This position increases the rigidity of the tarsus. Besides that, the claws rotate inwards and open. These conditions help insect claws to hook securely into the walking surface. When this ability for the tarsus to turn rigid was removed via cutting of the membrane, the claw was unable to aim and hook onto the mesh walking surface securely. Conversely, when the tendon is released, the elasticity of the membrane connecting the tarsomeres causes the tarsus to return to its original position, thereby causing the tarsus to become flexible. In addition, the claws rotate outwards and close. These conditions help the beetle to pull their claws out of the walking surface. When this flexibility was removed via the tubing of the tarsus, the claws have significant difficulties in leaving the walking surface.

Finally, we proposed a robotic-inspired biological approach by using a 3D printed flex-rigid tarsus to further verify the role of real tarsus. Using the beetle tarsus as a reference, we constructed a prototype to replicate the movement of the foreleg. The ball and socket configuration permitted the 3D printed tarsus to switch between rigid and flexible conditions, thereby allowing it to hook into and detach from the mesh surface without significant difficulties. Similarly, when using an identically shaped prototype without the ball and socket configuration, the prototype was able to hook into the mesh surface but subsequently unable to detach smoothly. This suggests that the function of the ball and socket configuration can be replicated using artificial means and incorporated into artificial robots to allow them to have the same capabilities as natural beetles.

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