Compound Foot for Increased Millirobot Jumping Ability

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Bio-inspired compound feet with spines and foot pads were made to improve the take off performance of the Flea, a jumping robot that can jump 30 times its body length. A no-slip model of the flea was used to compare the performance of the flea with and without spines and foot pads on styrofoam, sandpaper 60Cw, and Teflon. On styrofoam, the flea with spines increased its kinetic energy by 65%, bringing the kinetic energy closer to the no-slip model (6.6mJ). On sandpaper the spines did not alter the Flea's performance significantly, and on Teflon the flea could not jump at all. Combining a foot pad with spines increased kinetic energy on Teflon from 0 to 7.8mJ. Therefore the compound foot increases the variety of surfaces that yield good jumping performance for the robot Flea.

Keywords: jumping robot, foot design, takeoff foot interaction, foot spines

1. Introduction

The adaptive evolutionary traits of animals have inspired contemporary robotic designs.[1] Small insect-like robots have many applications, such as search and rescue missions, because they are easily transported, can access smaller spaces, and can navigate rough terrain by jumping.[2] One strategy to significantly improve the performance of bio-inspired robots is to add passive mechanical systems, such as spines. Spines can be used for climbing, where metal micro-hooks are used to catch asperities in the surface.[3–5] Spines have also been used for horizontal traction and challenging terrain.[6,7]

In this paper we focus on a foot enhancement design inspired by com-

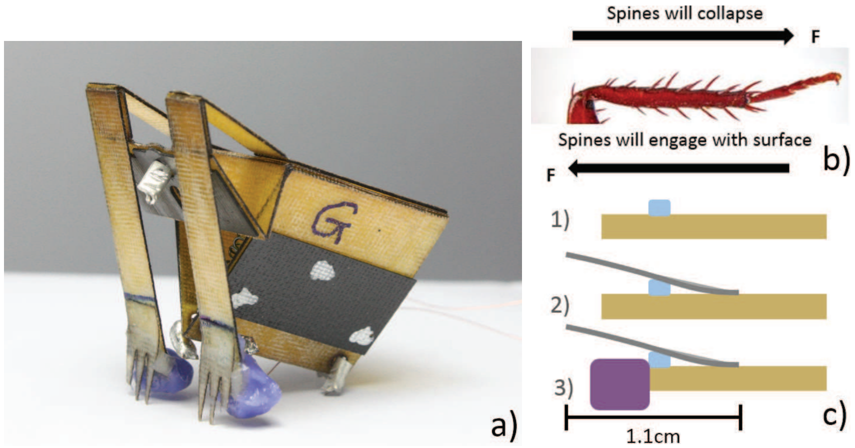

Fig. 1. a) Flea robot with compound feet that include spines and foot pads. b) Anisotropic properties of cockroach leg spines. c) The manufacturing process for attaching the spine and foot pad.

pound feet found on insects. Compliant leg spines provide distributed mechanical feedback, while sticky foot pads allow insects to traverse vertical and inverted smooth surfaces.[8] Unlike past examples, the designs presented in this work are the first studies on the novel application of spine traction to millirobot jumping.

2. Design

2.1. *Robot Platform and Modeling*

The robot used in this work, the Flea (Fig. 1a), has mass 2g and is 2cm long, and can jump 30 times its body size.[9] This robot utilizes a four-bar mechanism to simulate a flea's leg kinematics and is constructed using the Smart Composite Microstructures Process (SCM).[10] Shape memory alloy (SMA) spring actuators were used for a bio-inspired catapult system that quickly releases energy by torque reversal triggering.

This Flea robot was specifically chosen to use spines because of its leg mechanics, reaction force pattern, and size. Unlike many other jumping robots, the legs rotate outward and push off the ground in the horizontal direction, which the spines need for engagement. This was confirmed with the model used in the original flea experiments.[9] This Matlab model was used to find the best case by deliberately simulating no-slip conditions. (For the kinematics and equations governing the dynamics of the Flea during

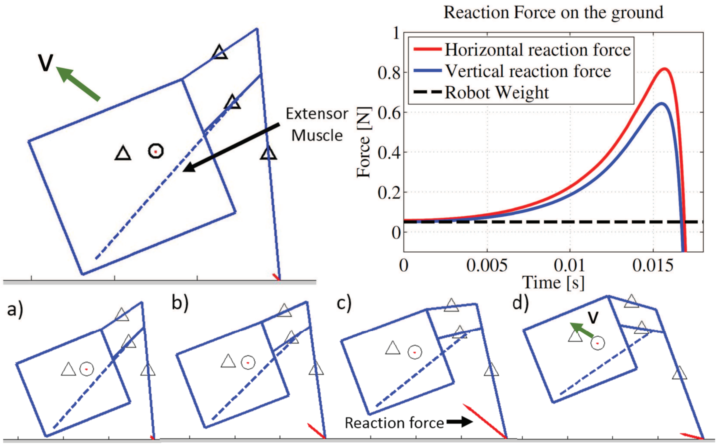

Fig. 2. (Top Left) The no-slip model of the Flea robot in Matlab with a spring as the extensor muscle. The model represents the flea just after triggering, where the extensor muscle has lowered past the bottom leg joint. (Top Right) Plot of the horizontal and vertical reaction forces as the Flea in the Matlab model jumps with no-slip conditions. (Bottom) Sequential pictures of the Matlab model of the Flea jumping with no-slip condition. Frame d is just before take off.

flight, please refer to Noh et al., 2012.) The geometric dimensions, spring stiffness of the extensor muscle, and mass in the model were changed to match the current flea with spines attached. The model showed that angling the body forward created a larger and earlier horizontal force approximately proportional to the vertical force (Fig. 2). Fig. 2a-d shows the progression of the jump, where the leg first engages the surface, engages without slipping, and then propels the flea forward to the left, backward to the right.

2.2. *Insect Inspired Spines and Foot Pad*

The spines on the robot feet shown in Fig. 1a are inspired by the passive leg spines on cockroaches tibia-tarsus joint (Fig. 1b). These spines provide such significant traction that they can compensate for the absence of feet on steep inclines.[11] These spines are similar to ones used in salticid spiders during jumping.[12] To mimic this passive surface engagement mechanism, the spine attachment is fabricated from a 6mm x 11mm piece of 6 ply, 0.12 mm thick fiberglass with 3 points cut out. These spines increase the weight of the robot by 2.5%. To attach the spines, a 2mm thick piece of super soft silicone (Ecoflex 30 by Smooth-On) is placed on the leg (shown in part one

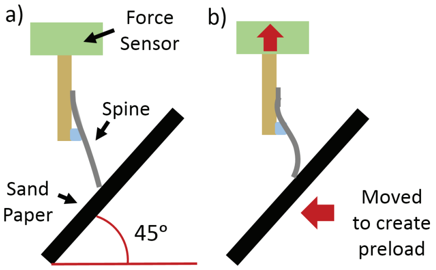

Fig. 3. Leg with spine during a stiffness test using a 1 axis force sensor and sandpaper as the engagement surface.

in Fig. 1c). The spine is glued onto the leg over the silicone, causing it to stick out of the leg at 20° to more directly engage surface asperities.

The foot pad, shown in Fig. 1a, is based off of insect foot pads that prevent slip on vertical and inverted surfaces.[8] The leg under the spine is dipped in a mix of resin and hardener several times until the desired foot pad height is achieved, such that if the spine slips and the leg rotates, the foot pad will engage the surface. Here the foot pads are 4mm tall and add 0.14g of weight, increasing the robot mass by 6%.

3. Results

3.1. *Performance of Leg Spines*

Vertical compression tests were performed on a single robot leg using a force sensor and Sandpaper to prevent slipping (Fig. 3). The surface first moved into the spine to create a preload and bend the spines inward to mimic a normal jump (Fig. 5.2b). This buckling gives the spine higher friction than if the spines were bent in the other direction, and can be further explained by a pseudo-rigid body model of an initially curved, end-force loaded cantilever beam.[13] Using the spine compression and force measured from these tests, the spine stiffness was determined to be 2.4±0.1 kN/m.

3.2. *Jumping Performance of Flea with and without Spines*

To evaluate the spine's utility during jumping on a robotic platform, the Flea was tested on three different surfaces: Teflon, styrofoam, and sandpaper 60Cw. Three trials were recorded with a high speed camera for a close up view and a video camera to view the overall jump. The Flea was tested first without spines, then with spines. The Flea in both cases was unable

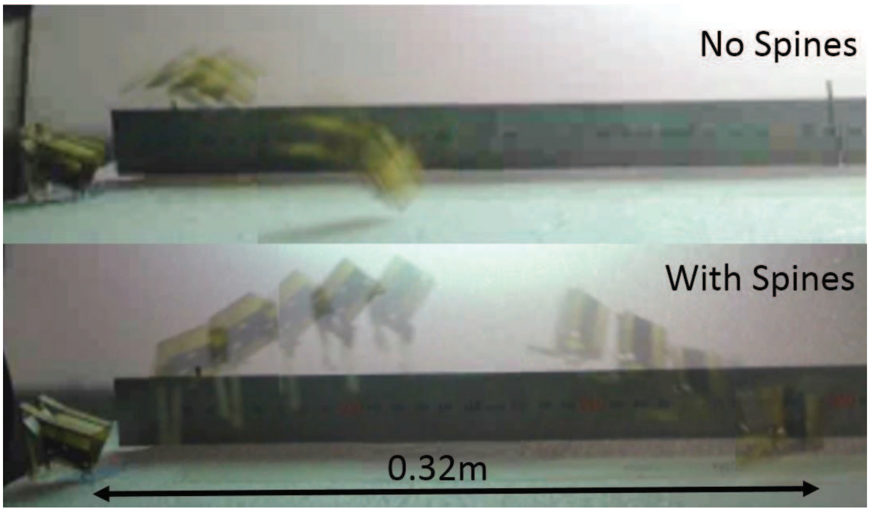

Fig. 4. Sequential pictures of the Flea jumping on styrofoam where the top is without spines and the bottom is with spines.

to jump on Teflon, but could jump on both styrofoam and sandpaper. The jump trajectories of a Flea robot with and without spines can be seen in Fig. 4. The jump of a Flea without spines can be seen in Fig. 5, where one leg slips at moment Fig. 5b. However, with spines the Flea is able to engage the surface and the spines bend at instant shown in Fig. 5d as the leg rotates out.

To compare the flea performance on different surfaces we calculated kinetic energy and take off angle, since they directly affect parameters such as the horizontal distance the flea can travel. Kinetic energy was calculated using take off velocity, and take off angle was tracked from video footage. The take off angles in all trials ranged from 32°- 37° and were statistically insignificant from each other from an ANOVA test. Therefore in this paper we will be focusing on the kinetic energy results shown in Table 1.

Table 1. Kinetic Energy of the Flea (mJ) at Takeoff

Surface Type	No Spines or Foot Pad	Spines	Spines and Foot Pad
Styrofoam	3.6±1.1	6.0±0.5	7.1±0.6
Sandpaper	6.4±0.2	5.8±0.2	8.0±0.2
Teflon	0±0	0±0	7.8±0.3
No-slip Model	N/A	6.6	7.9

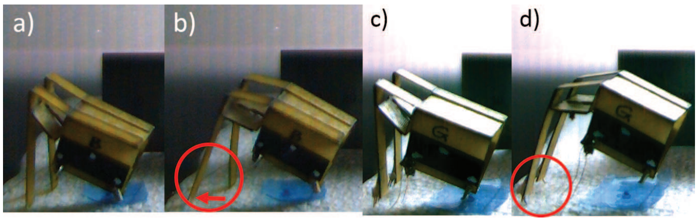

Fig. 5. The Flea without spines (a&b) and with spines (c&d) jumping on styrofoam where a&c is immediately before triggering and b&d is immediately after triggering.

On sandpaper, a surface with reasonable engagement for an unaltered Flea, the kinetic energies for the flea with and without spines are close to the no-slip model's values of 6.6mJ. The spines decreased the rotational velocity by 8% and the kinetic energy in the Flea experiment from 6.4mJ to 5.8mJ (Table 1). Since the kinetic energies are not statistically different from each other, we conclude that there is no change in kinetic energy with the addition of spines on sandpaper.

On styrofoam the Flea without spines slips. The spines increase the kinetic energy from 3.6mJ to 6.0mJ, bringing the Flea closer to the no-slip model (Table 1). Since this is a statistically significant increase, the addition of spines increase the Flea's performance on styrofoam. The rotational velocity also decreased by 58%, making the Flea more stable in flight.

3.3. *Jumping of the Flea with Spines and Foot Pad*

To evaluate the foot pad's utility, tests were conducted using a Flea with spines and a foot pad on six different surfaces: Teflon, styrofoam, sandpaper 2000Cw, sandpaper 400Cw, sandpaper 220Cw, and sandpaper 60Cw. It should be noted that the particles on the sandpaper are larger as the number Cw gets smaller. From the high speed video, we found spines are effective on rough surfaces, such as sandpaper 60Cw, 220Cw, and 400Cw. The spines engage the surface at the initiation of jump and do not slip (Fig. 6 a-b). However for smooth surfaces (such as Sandpaper 2000Cw, styrofoam, and Teflon) the spines slip far enough to allow the foot pad to engage the surface. This is seen more clearly in Fig.6 c-f, where the leg slips from d to e.

The kinetic energy on Sandpaper 60cw is the highest at 8.0mJ, which is close to the model (7.9mJ) and an increase from the control case (6.4mJ) (Table 1). The kinetic energy on Teflon is the next highest at 7.8mJ, a large increase from 0mJ. The kinetic energy on styrofoam increased from the control case (3.6mJ) and the flea with just spines (6.0mJ) to 7.1mJ.

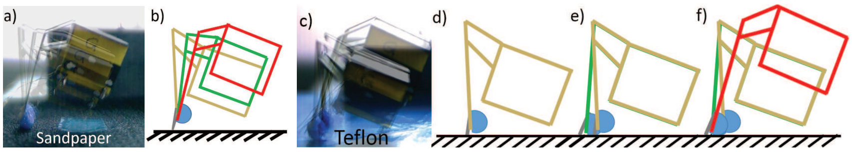

Fig. 6. Launch kinematics of Flea robot with spine and foot pad jumping on sandpaper (Left) and Teflon (Right). a,c) Overlaid frames of the video at different times. b,d-f) Outline of the flea, spine, and foot pad at different frames. Brown is the first frame, green is the second, and red is immediately before takeoff.

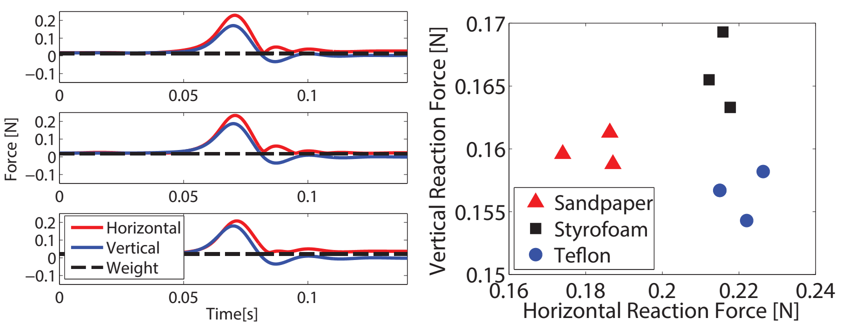

Fig. 7. (Left) Reaction forces obtained from the force sensor for a Flea jumping on Teflon, styrofoam and sandpaper from top to bottom. (Right) Plot of peak vertical reaction forces with respect to horizontal reaction forces for all trials.

To analyze the reaction forces of the modified Flea, the Flea jumped three times each on sandpaper, styrofoam and Teflon attached to a force sensor (Fig.7). In all trials the horizontal force was larger than the vertical force, similar to forces from the model in Fig.2. The largest vertical forces were on styrofoam while the lowest horizontal forces were on sandpaper.

4. Conclusions

The bio-inspired spines and foot pad evaluated in this paper changed the performance of the Flea depending on the surface. On styrofoam, the spines increased kinetic energy by 65%, which is closer to the no-slip model (6.6mJ). However the spines did not alter the Flea's performance on sandpaper significantly, or Teflon where the flea with or without spines could not jump at all. The foot pad was added to allow the flea to jump on Teflon and the kinetic energy increased from 0 to 7.8mJ. The Flea also utilized the foot pad on smooth surfaces such as styrofoam and sandpaper 2000Cw, while continuing to use the spines on surfaces with larger asperities. The addition of the foot pad also increased the kinetic energy of the Flea on styrofoam and sandpaper from the case with just spines. Therefore we have shown that the foot type significantly affects jumping performance, and can be tuned for surface characteristics. By tuning certain foot characteristics such as spines and foot pads, we can have passive systems to increase the performance of robots such as those used for search and rescue.

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