

Biomechanics and Simulation of Cricket for Microrobot Design

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Abstract

This paper describes the kinematic analysis of two different cricket locomotion modalities, and the use of these data in a dynamic simulation to combine and simplify the insect's complex three-dimensional movements. The results of this simulation will then become the input to the design and control of a microrobot capable of mimicking the walking and jumping behaviors of the cricket.

1 Introduction

Roboticians have used insect behavior as a source of design considerations for some time now¹⁻³. Insects are extremely agile and successful in maneuvering over a wide variety of surfaces. Researchers at Case Western Reserve University have already developed three hexapod robots based on insects. Robots R-I and R-II were based upon stick insects, with all six legs of the same construction. R-I had two degrees of freedom (DOF) in each leg, and R-II had three. Controllers were developed to enable insect-like gait movement, and R-II was able to perform complex movements such as turning and yawing in place, and also walking over slatted surfaces⁴.

A more recent hexapod robot, R-III, was closely modeled after the cockroach *Blaberus discoidalis*. It had distinctly different leg construction for each of the three pairs of legs³. Hind legs were large and specialized for power (3 DOF), middle legs were smaller with an additional DOF (4) to enable turning, and front legs were smaller still, with yet another DOF (5) for enhanced dexterity. This robot demonstrated an extremely complex postural controller able to respond to perturbations and lift a payload equal to its own 30 pound weight⁵.

Robots I – III were much larger than their animal models, 18 inches to 30 inches in length. They also required tethering for their power and control sources. More recent initiatives have identified the need for much smaller and autonomous robots. These could be used as multiple “scouts” to survey and analyze dangerous areas. By nature of their small size and relatively low production expense, such robots could prove highly valuable in reconnaissance.

In order to produce such a robot, we need to identify an insect model that is capable of locomotion in a number of very different situations. Kinematic observation and

analysis of the insect can then serve as the raw data for simulation to determine a method of implementing these behaviors into a micro-sized (2 inches) autonomous robot.

2 Biological Observations

2.1 Insect Morphology

A key feature of insect leg construction is its multi-segmented nature. Segment joints can have a single or multiple degrees of freedom (DOF). The result is movement capability that enables successful walking, climbing and jumping in a wide variety of terrains.

As with all insects, the cricket has six legs, matched in pairs across the thorax. In contrast to the cockroach, another insect that has been extensively studied with regards to walking locomotion⁶⁻⁹, the legs of the cricket are positioned in a more vertical plane. Additionally, the rear legs are extremely large in size relative to the middle and front legs, enabling them to propel the cricket in both walking and jumping. In this regard, the cricket is much more like other orthopteran insects such as the locust, which has been studied extensively by neurobiologists¹⁰⁻¹².

Each of the three pairs of legs, though very different in size and function, has five distinct segments (Fig. 1A). Starting from the body attachment point, they are: coxa, trochanter, femur, tibia and tarsus (which is actually a number of small segments with a claw at the end). The coxa segment is very small in all legs of the cricket. In contrast, the coxae of the cockroach are much larger. The significant feature of the coxa is the existence of a soft tissue, 3 DOF joint that connects it to the body of the animal¹³, enabling complex positioning of the entire leg. The trochanter is an even smaller segment, connecting the coxa and femur through two 1 DOF joints. Most of the movement between the coxa and the remainder of the leg occurs at the 1 DOF joint between the coxa and trochanter that effectively moves the femur. This is the coxa-trochanter-femur (CTF) joint. The joint between the trochanter and femur has very little movement, as is the case with most insects.

Due to the small size of the coxa and trochanter, and the extreme difficulty in accurately visualizing them, the movements of the body-coxa (BC) and CTF joints were approximated as a single 3 DOF body-femur (BF) joint. As will be discussed later, this was consistent with the

desire to combine and minimize joints and DOF to enable a robot design with realizable production characteristics.

The femur is the largest segment of any cricket leg, in both mass and length. Again, this situation is in stark contrast to the cockroach, where the coxa makes up the largest mass of the leg. In the hind leg, the huge muscle mass enables jumping and kicking behaviors through the rapid leveraging movement of the tibia. The tibia segment makes the vertical drop connection to the tarsus, or foot, which actually contacts the ground. The femur-tibia (FT) and tibia-tarsus (TT) joints are also 1 DOF. With the exception of the mostly immobile trochanter-femur joint, all of the 1 DOF joints (CTF, FT and TT) act in the same plane.

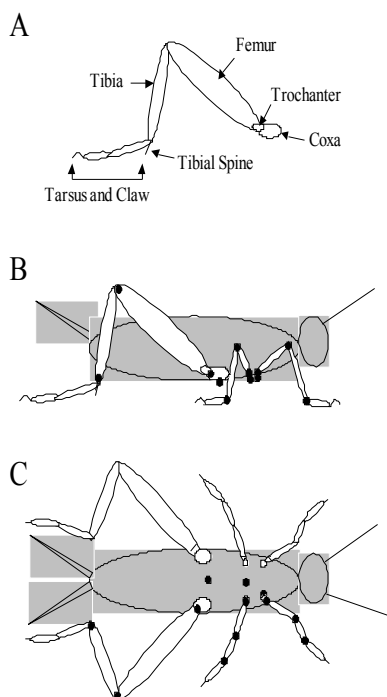


Figure 1. Schematic of cricket. A. Hind leg with segments identified. B. Side view of all legs with digitizing points marked. C. Ventral (bottom) view with digitizing points.

Although the legs and segments are not arranged in complete orthogonal planar fashion, we have determined a relative x-y-z axis orientation to assist in analysis. By definition, the animal's horizontal, longitudinal line (directed tail to head) is the x-axis and rotation about this axis is α . The lateral, horizontal side-to-side line is the y-axis and rotation about it is β . Finally, the vertical line directed upward is the z-axis and rotation about it is γ . Thus, the BF joint can have α , β and γ rotations. The CTF, FT and TT have β rotation only.

2.2 Experimental Setup

The movements of the cricket legs during locomotion involve the complex coordination of these many segmented, multi-jointed legs. In order to observe and measure these movements, it was necessary to employ high-speed video (Redlake Motionscope, 250 frames per second) in three dimensional space. This required that the animal be observed simultaneously in two orthogonal planes.

A treadmill has been developed⁹ with a transparent belt and subsurface mirror at a 45° angle (Fig 2). This enabled a concurrent side and ventral view of the animal. Small dots of paint were applied at joint locating sites on the body and legs (Fig 1B. and C.). Digital video was recorded as the cricket moved on the treadmill surface. The location of each joint was then digitized in the two views in each frame. This provided x (longitudinal), y (lateral), and z (vertical) space locations which were loaded into a spreadsheet based analysis program. Customized software then reconstructed the true three-dimensional angles of the leg joints as they moved through space.

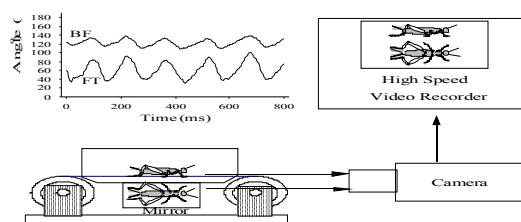


Figure 2. Diagram of treadmill and video acquisition apparatus. Example of digitized joint angle positions at top left.

2.3 Walking

Crickets, as do cockroaches, typically walk utilizing an alternating tripod gait⁶. That is, the front and rear legs on one side, along with the middle leg on the opposite side, will be supporting and propelling the animal while the remaining three legs (the other tripod) swing forward for the next cycle. Because of the structural and attachment differences among the legs, each pair of legs must move its segments in a very different way than the others. This means that the cricket-based robot must have not only construction differences in the legs, but control differences as well.

The rear legs of the cricket move in a near-vertical plane during walking. They provide the main power to push the animal forward. Their orientation, as determined by the connection of the coxa to the body, has the femur directed

up and backwards and the tibia down and backwards. The tarsus extends rearwards from the tibia. Although this orientation is quite different in the x-axis position from the cockroach⁹, the movement patterns of the joints show some similarities. The stance (power) phase consists of a synchronized increase in the CTF and FT joint angles, extending the femur back and the tibia down and rearward. The excursion of the CTF, again approximated by the BF “joint”, is smaller than that of the FT joint (Fig 2), a difference between cricket and cockroach. The tarsus contacts the ground, first with its distal (claw) end, and then increases its contact area toward the TT joint. At the end of the stance phase, the tarsus is lifted off the ground (in some cases the claw is left in ground contact) and the leg is moved forward.

The middle and front legs of the cricket are very similar in size, appearing almost as mirrored elements. Again, their small coxal segments and attachment anatomy impose a more vertical plane orientation, as compared to the cockroach. At rest, the front legs have a slight up and forward positioning of the femur while the middle legs have a slight up and rearward femur orientation. Both tibias project downward. Movements of these two pairs of legs also appear somewhat similar. Both sweep forward and backward, but in opposing cycles. Middle legs begin their stance phase with the femur angled very slightly forward, followed by a rearward horizontal sweep of the femur (γ rotation at BF) to a point lateral to the hind leg attachment. Tibial extension and tarsal placement approach but do not interfere with the hind leg swing anterior extreme position (AEP).

The front legs have the most articulation in their coxa and trochanter segments [9]. This allows these legs to project far forward during their swing phase so that they can provide rearward movement during stance without interfering with the middle legs as the animal moves forward in space. This feature is similar to cockroach front leg structure and its behavior during walking¹⁴. Front leg stance begins with the femur extended forward nearly parallel with the body longitudinal line. The femur is then pulled to the rear at the coxa (β rotation at BF) with a corresponding γ rotation as the segment sweeps rearward. Coincidental tibial extension results in a posterior extreme position (PEP) that appears to contact the middle leg at its AEP. The stance phase of the middle leg appears to begin prior to the transition of the front leg from stance to swing. Repeated observations revealed no negative effects on walking as a result of this close positioning.

2.4 Jumping

Although cockroaches appear to be faster and more agile walkers than crickets, they must climb over obstacles that they encounter. This may entail significant time and energy expenditures, and may limit the animal’s ability to successfully traverse certain terrains. The cricket has additional behaviors – kicking and jumping -- that make it an attractive model for roboticists. The defensive kick

behavior of the rear legs of the cricket has been well-characterized¹⁵. Similar hind leg activity is utilized in the jump. We have measured cricket jumps of a distance up to 20 body lengths with an apex height of up to 7 body lengths. A robot with even a partial replication of this characteristic would have significant locomotion advantages for traversing small bodies of water or steep obstacles, or simply moving quickly and efficiently over uninteresting terrain.

Video analysis showed that cricket jumping was accomplished primarily through the action of the rear legs. While the front and middle legs altered the positional angle of the body and did provide some forward body motion, comparison of takeoff angles (Fig. 3) indicated no correlation between takeoff angle and distance jumped. Indeed, long distance jumps were seen when the takeoff angle was nearly flat.

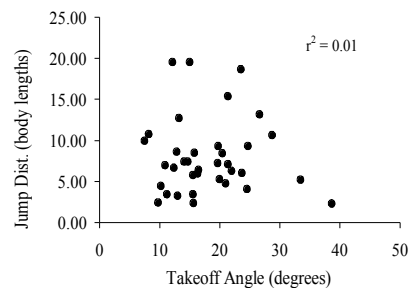


Figure 3. Scatterplot of 37 separate jumps comparing takeoff angle and jump distance. No correlation observed.

The jump behavior of the hind legs involves a characteristic pattern reminiscent of locust kicking that has been studied extensively¹¹. First, the BF (y-axis, β rotation) and FT joint angles begin to decrease. As this is occurring, the BF joint angle increases as an α rotation about the x-axis. The result is abduction of the femur away from the body, with the FT joint moving down toward the ground (Fig. 4A and B). The animal reaches a position with the femurs nearly parallel to the ground at a near perpendicular angle to the body longitudinal line. Concurrently, the FT joints are fully flexed as well with the TT joint and the entire tarsus segment in ground contact at the lateral edge of and parallel to the body longitudinal line. This “cocking” phase of the jump takes approximately 60 ms.

Jumping follows at less than 4 ms latency (the frame rate of the high speed video). It occurs without the additional tensioning pause seen in the locust [7]. The FT joints are rapidly extended, coinciding with TT extension and a BF rotation that has the entire rear leg spread out nearly straight as the cricket lifts off from the ground (Fig 4C). This takeoff stage of the behavior lasts approximately 20 ms until the animal is completely airborne.

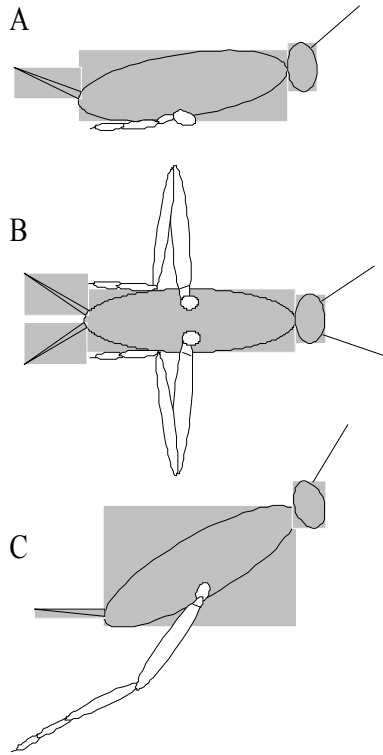


Figure 4. Cricket jump. A. and B. Side and ventral view of rear legs at maximum flex (cocking) position. C. Side view of rear leg full extension at liftoff. Front and middle legs not drawn.

Four separate "good" jumps (distance >6 body lengths) and two "poor" jumps (distance <5 body lengths) were examined in a time sequence study. Measurement of the hind leg cocking phase indicated that time spent in femur promotion (β rotation forward along the Y-axis), accomplished by BC joint movement, was non-existent in the two poor jumps, but present in three of the four good jumps for a period of 20 - 25 ms (avg. = 22 ms). Femur abduction and FT flexion were observed in both good and poor jumps, but the durations were longer in good jumps. Average "good" femur abduction = 29ms, average "poor" femur abduction = 12ms. Average "good" FT flexion = 34ms, average "poor" FT flexion = 19ms.

Durations of BF and FT extensions during the jumps were similar in both good and poor jumps. The preliminary indication is that more time is spent and more movements are performed in the cocking phase of a long jump than a short one. Extensions seem to be the same.

One element of the cricket's anatomy that is critical for successful jump performance was uncovered during high-speed video analysis. At the distal end of the tibia are 3–4 stiff, rear facing spines (Fig. 1A). These spines appear to dig in to the substrate as the animal transfers between the cocking and takeoff phases of the jump, providing traction so that the force developed by the extension can be translated into lifting motion. Intact crickets occasionally "slipped" as they were jumping, with the result being a

rearward kick of the hind leg rather than an upward extension. The animal would perform a short distance somersault or spin sideways, depending upon whether both or one rear leg did not have traction. Surgical removal of the rear facing tibial spines resulted in a consistent and complete failure of the animal to perform a jump. Success in jumping could be returned by placing a block behind the cricket's rear tarsi to replace the traction lost from removing the spines. Similar, although smaller, spines at the distal end of the tarsus were found to not be critical for favorable jumping behavior.

2.5 Biological Summary

Kinematic analysis of cricket walking and jumping provided critical 3-dimensional space point data for simulation modeling of these behaviors. Additionally, insights into mechanical construction were also obtained. Notably, the apparent contact of front and middle legs during each walking step and the requirement for traction spines on the rear tibiae are issues that must be addressed in design.²¹

3 Dynamic model of Cricket

The dynamic model of the cricket is a modified version of our previous dynamic model of the *Blaberus* cockroach^{16, 17}. This simulation was used to incorporate the biological data into the design of the cricket robot. There are a total of 36 DOFs in the model; six DOFs for the body (three translations and three rotations) and five for each of the six legs. Each leg has 3 DOF at the body-coxa (BC) joint, 1 DOF at the coxa-trochanter-femur joint (CTF), and 1 DOF at the femur-tibia (FT) joint. As discussed earlier in the Biology section, the actual cricket leg has a very small and largely immobile trochanter segment connecting the coxa and femur. In the dynamic simulation the trochanter is consolidated into the femur segment. This also served to simplify the calculations, thus reducing computation time. Additionally, the tarsus is not a part of the dynamic model. The simulated leg ends at the distal point of the tibia. Computational efficiency and mechanical simplification of the robot were factors in this decision.

3.1 Filtering

Since there was noise in the raw data, we required a way to refine it such that no important information was lost. Several methods were considered, for example, a low pass filter or a Butterworth approximation¹⁸. The ultimate goal of filtering is an output that best represents the raw data without the noise.

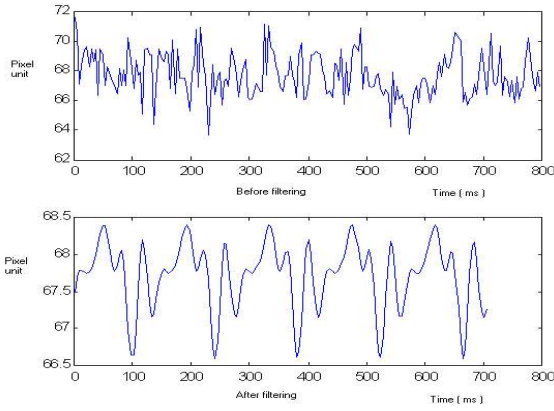


Figure 5. Comparison of a set of data before and after filtering.

We selected five periods corresponding to the five full walking steps that were digitized. The digitized raw data were assumed to be periodic because of the cyclic nature of the cricket walking behavior. Therefore, we used a discrete Fourier transform and neglected frequencies below a selected cutoff. The animal is not capable of smooth motions above this cutoff frequency. The data were then converted back into the time domain. Fig. 5 shows a comparison of some data points pre- and post-filtering. The five periods of stepping can easily be seen in the filtered data.

3.2 Coxa segment approximation

All of the animal's coxa segments are very small, regardless of what leg is examined. However, because the front leg coxa has much more articulation, it was digitized as a separate entity. As discussed previously, the middle and rear legs, were simplified by neglecting the coxa for robot manufacturing purposes. Thus, we initially digitized the BC point at the body centerline for these two legs. However, dynamic simulation utilizing these points resulted in a coxa segment that was inverted to an improper position. To correct this, determination of these joint angles was approximated by applying an optimal line search to locate the true BC point.

We had to estimate the location of the BC joint. For this purpose, we measured the length of the coxa and the body centerline point between the front coxas. We then assumed that the BC joint lies in the plane formed by the femur and tibia. To find the BC joint we located a point in the FT plane that was a coxa length from the CTF joint and a minimum distance from the body centerline point.

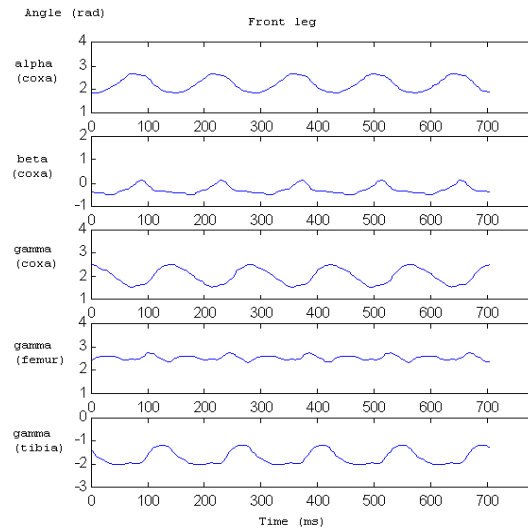


Figure 6. An example of the joint angles input into the simulation for the front leg.

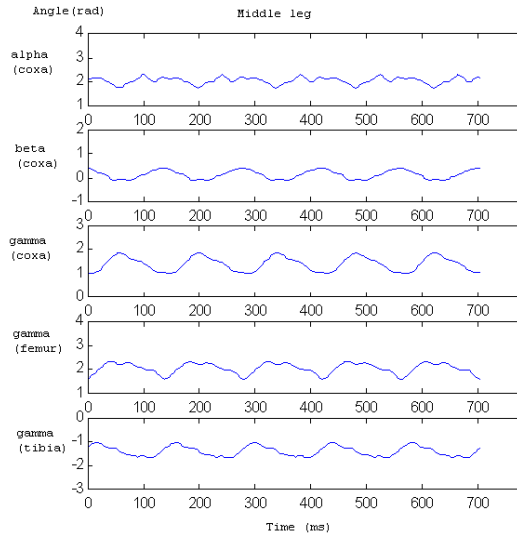


Figure 7. An example of the joint angles input into the simulation for the middle leg.

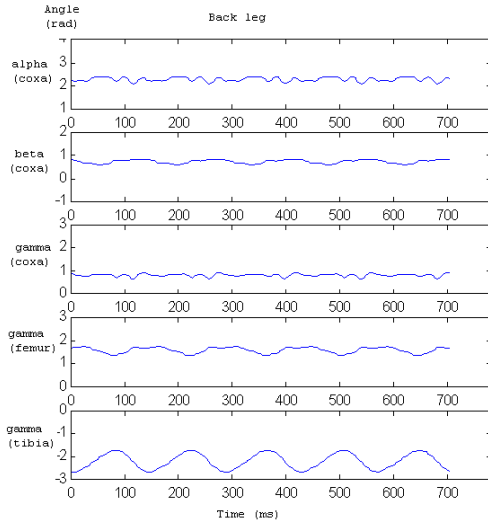


Figure 8. The joint angles input into the simulation for the back leg.

3.3 Walking Simulation

Figures 6, 7, and 8 show the joint angles of the front, middle and rear legs of the cricket during five cycles of a tripod gait. Note that the CTF joint of the front leg is relatively inactive. This suggests its elimination in the robot design. Furthermore, note that the body coxa joint in the rear legs is relatively inactive, suggesting the elimination of these DOF.

Inputs to the dynamic simulation were joint angle trajectories (Figs. 6, 7, 8) and inertia of all leg segments and the body. Joint angle trajectories were obtained from the biological kinematics study of cricket behaviors. The output from the simulation provides the joint torques, body movement, ground reaction forces and the moments in the leg segments. The dynamic simulation used the proportional derivative control law:

Torque for a joint =

$$(\theta_{actual} - \theta_{desired})k + \left(\frac{d\theta_{actual}}{dt} - \frac{d\theta_{desired}}{dt} \right) c \quad (6)$$

Where θ_{actual} is the actual angle, $\theta_{desired}$ is the desired angle, k and c are constants¹⁹.

The joint torques will be useful in selection of the power source for the robot. As joint torques can not be measured in a real cricket, we must predict them from the simulation. The ground reactions will also be beneficial to the design of the robot in that force predictions can aid material selection for leg construction. The ground reactions showed the typical insect walking patterns described by Full for cockroach²⁰ and shown by Nelson and Quinn in simulation¹⁷.

3.4 Testing procedure

A footfall pattern was developed from the kinematic study of cricket walking. Each leg has a different trajectory of stance and swing. A successful cricket robot must approximate these trajectories for coordinated walking. Since the cricket data were taken from an animal moving on a treadmill, they had to be related to a stationary frame. This was done by utilizing fixed coordinates for the body frame and relating each frame's leg coordinates to a fixed body position. The result was a trajectory plotted as if the animal's body was stationary with the leg moving freely. The data shown are from the right side of the cricket body.

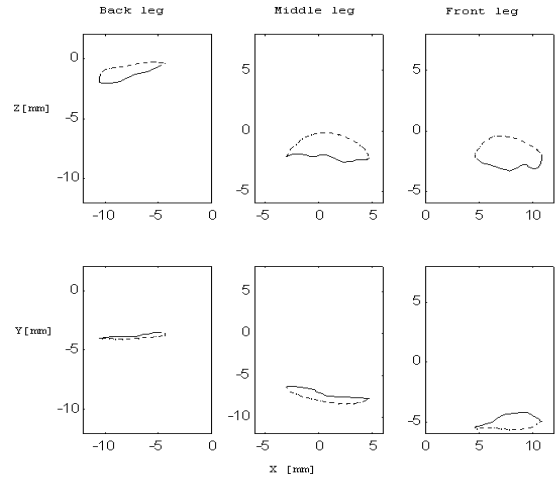


Figure 9. Footfall trajectories utilizing the distal end of the tibia.

The results show the tibia-tarsus trajectories for all three legs in the free walking cricket preparation (Fig. 9). The stance movement (the solid line) may be roughly approximated as a straight line for the back legs. The trajectories represent just one step. However, all cycles demonstrate similar trajectories.

5 Conclusions

Biological kinematic data were obtained from a walking cricket. These data were filtered, and the segmental construction of the insect legs was simplified. Joint torques and ground forces were derived from a simulation, and a series of reproducible footfall trajectories was plotted.

These results show that the ground contact point of the back leg has a very narrow trajectory when compared to the front and the middle legs. Also, the joint angle trajectories show that the BC joint is inactive in the rear leg. Consequently, the cricket microrobot's rear legs have been simplified to include only two single DOF joints. The front and middle legs will require two DOF at the body-coxa, as well as the single DOF at the femur-tibia, to enable more complex joint angle changes required for successful locomotion.

Continuing work will involve the analysis of the cricket jump behavior in the same way, with the ultimate goal of a bi-modal capability in the microrobot.

Acknowledgements

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