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AEROMECHANICS OF LONG JUMPS IN SPIDER CRICKETS: INSIGHTS FROM EXPERIMENTS AND MODELING

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ABSTRACT

Flapping, gliding, running, crawling, and swimming in animals have all been studied extensively in the past and have served as sources of inspiration for engineering designs. In this paper, we describe the aeromechanics of a mode of locomotion that straddles ground and air: jumping. The subject of our study is the spider cricket of the family *Rhaphidophoridae*, an animal that is among the most proficient of long-jumpers in nature. The focus of the study is to understand the aeromechanics of the aerial portion of the jump of this animal. The research employs high-speed videogrammetry to track the crickets' posture and appendage orientation throughout their jumps. Experiments demonstrate that these insects employ carefully controlled and coordinated positioning of their limbs during their jumps so as to increase jump distance and stabilize body posture. Simple phenomenological models based on drag laws indicate that the conformation of the limbs during the latter portion of the jump is stable to pitch and enables these animals to land in a controllable manner. Insights from this study could be useful in the design of micro-robots that exploit jumping as a means of locomotion.

INTRODUCTION

Small jumping robots and vehicles have the potential to combine the benefits of unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs); jumping vehicles would have the stability and ground access of UGVs and the speed and agility of UAVs. Such vehicles would provide effective means for exploring complex urban and natural terrains for tasks such as search and rescue as well as environmental monitoring. A number of animals such as spiders and crickets, among others, employ jumping as their primary mode of locomotion [1-5,8]. Analysis of such animals could lead to bioinspired designs for micro robots and vehicles that can move efficiently over complex terrains.

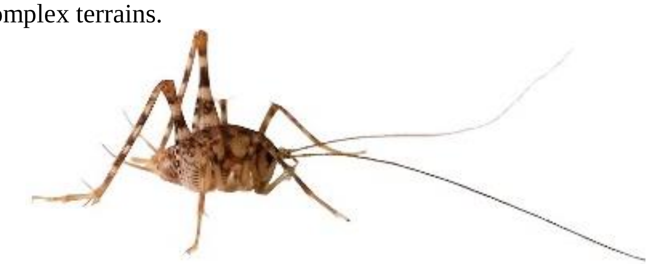

Figure 1. *Rhaphidophoridae, or what is commonly referred to as a 'spider cricket'.*

For our study we have chosen an animal that is among the most proficient of long-jumpers in nature: *Rhaphidophoridae* (Fig. 1), an animal that is also sometimes referred to as a 'spider cricket,' 'cave cricket,' or 'camel cricket'. These wingless animals can be found in damp and dark environments such as basements in the Northeast part of United States. Our preliminary work with these animals indicated that they were capable of jumping more than 60 times their body length. Furthermore, despite jumping this immense distance, it was observed that these wingless crickets usually managed to land on their feet, indicating an ability to control and stabilize their posture during 'flight'. Jumps are primarily employed by these animals as a mechanism for escaping from predators. The advantage of controlling posture during the jump and landing on

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the feet is that the animal can then rapidly initiate subsequent jumps to increase its distance from the predator. Our hypothesis was that spider crickets coordinate the mechanics of jumping as well as the movement of their limbs during the aerial portion of their jump so as to control and even stabilize their posture. The mechanism for posture stabilization during the aerial portion of the jump is the primary subject of the current research.

The research is based primarily on high-speed videogrammetry that is used to track the crickets' posture and appendage orientation throughout their jumps. In order to understand the effect of body posture on stabilization, aerodynamic models are also developed to predict the aerodynamic forces and moments on the crickets during the aerial portion of their jump. These mathematical models employ drag coefficient data for cylinders to model the aerodynamic force and torque generated by the limbs of the crickets and incorporate body posture and velocity information from the videos. The models are used to examine the effect of body posture and appendage orientation on pitch stabilization. The principles distilled from this study could serve as an inspiration for small jumping robots that can traverse complex terrain.

METHODS AND PROCEDURES

The insect chosen for the study is the spider cricket of the family *Rhaphidophoridae*, shown in Fig. 1. Insects were collected from a number of residential basements in Virginia and Maryland. Collected animals were kept in an enclosure through the duration of the study. The animals were fed fish-food and the humidity of the enclosure was maintained via regular spraying of water.

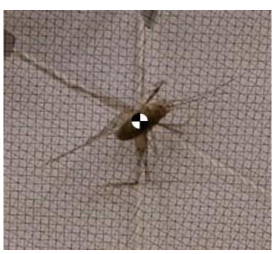

Figure 2. *Center-of-mass (CoM) of cricket determined using plumb-line method. CoM determined from this method is indicated on the body.*

Center-of Mass Determination: The location of the center-of-mass (CoM) of the cricket is a crucial factor in posture stabilization. In the current study, the CoM of the cricket was determined using the plumb-line method (Fig. 2). The cricket was hung by a limb such that is it was free to rotate and a plumb-bob is held from the same point by a string. First, the cricket was hung by a hind limb and then from a mid-limb. Both configurations were recorded by camera. Then, the images were overlaid in Adobe Photoshop. The intersection of the two strings is the center of mass of the cricket. Figure 2 shows the location of the CoM. It is important to note that the CoM is located between the hind limbs rather than at the midpoint of the cricket. This is not surprising given that the hind limbs account for over 15% of the total weight of the animal. The masses of the crickets were typically 0.134g±0.001g and the crickets' bodies were typically 11.15mm±0.03mm in length.

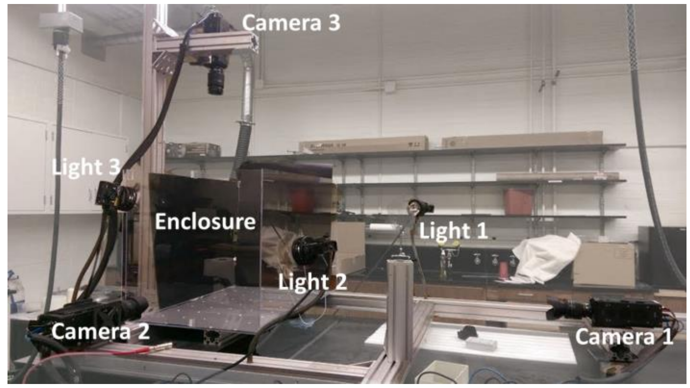

Figure 3. *Picture showing the key elements of the videogrammetry setup.*

High-Speed Videogrammetry: High-speed videogrammetry was employed to gain insights into the kinematics of the jumps. Five healthy animals of various sizes with intact limbs were selected for the experiments. The videogrammetry setup is shown in Fig. 3 where an acrylic enclosure of size 3x2x2 ft. was used. The floor of the enclosure was covered with high-grit sand paper so as to provide a consistent and high degree of traction for the animals. Three synchronized Redlake Y4L high-speed cameras paired with Nikon AF Nikkor 24-85mm f/2.8 – 4D IF close focusing lenses were used to record cricket jumps over periods of 10 seconds, over which the cricket was made to jump through repeated stimuli. To this effect, an experimenter prodded the cricket in the rear with a thin plastic tube. To accurately capture the jumps without blur, recording frame rates of 400-600 frames per second and exposures of 200-800 μs were used. Given the shutter speed and the need for a small aperture to provide adequate depth-of-field, the enclosure was illuminated using multiple high-intensity halogen lamps. Figure 4 shows composite frames from a video showing the various stages in a jump.

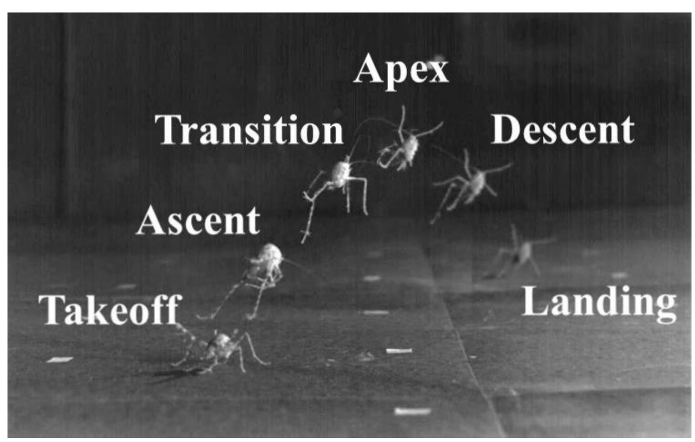

Figure 4. *Labeled image of entire jump of a specimen, showing takeoff, ascent, transition from ascent posture to descent posture, apex, descent, and landing.*

The cameras were calibrated in three dimensions using a direct linear transform (DLT) with a calibration rig which was photographed once per session to account for changes in the experimental setup or camera settings. Testing with items of known dimensions showed an error of less than a millimeter with the calibration rig; the calibration was therefore accurate enough to extract the necessary information about the cricket's body throughout its jump. The DLT toolkit developed by Hedrick [7] was used to track the path of the cricket's CoM, head, and tail throughout the jump. Additionally, for one or more points in each jump, the locations of each joint was tracked. The tracked points are shown in Fig. 5.

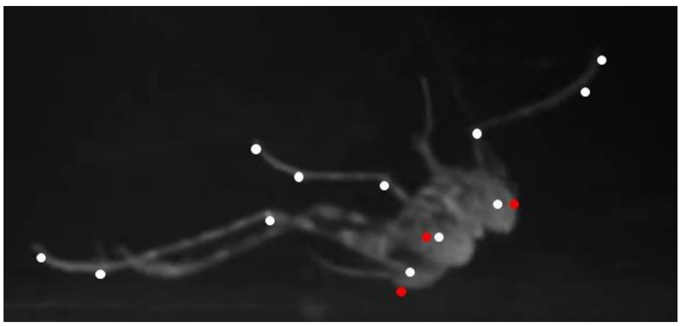

Figure 5. *A still from the video showing the points that are tracked on the body of the cricket during the jump. The red points show the locations of the head, CoM, and abdomen tip and are tracked throughout the entire jump. The white dots represent the limb joints and are determined at one instance during the descent portion of the jump. For simplicity, only the joints on one side of the cricket's body are shown; in actuality, all six limbs would be tracked for a total of 24 joint points.*

Pitching Moment Estimation via Aerodynamic Modeling: The current work focused on a bilaterally symmetric jumping condition wherein the animal jumps forward with no appreciable roll or yaw angle and also no lateral movement. In this situation, the following two conditions need to be satisfied for stable 'flight' through the air: (1) the net aerodynamic pitching moments (M) about the animal's CoM, should be nearly zero. i.e.

$$\bar{M} = (M_P, M_R, M_Y) \approx 0 \quad (1)$$

where *P*, *R*, and *Y* correspond to pitch, roll, and yaw respectively, and (2) particularly for bilaterally symmetric jumps, any small perturbation in the pitch angle of the animal about its equilibrium orientation should generate a restoring pitching moment that would tend to bring the animal back to its equilibrium orientation; i.e.

$$\frac{\partial M_p}{\partial \theta} < 0 \quad (2)$$

where θ is the pitch angle. One objective of the current work is to examine the degree to which the above two conditions are satisfied for the cricket during its jump.

In order accomplish, this we need to estimate the aerodynamic pitching moment on the cricket as it moves through the air. To obtain this estimate, we employ a simple aerodynamic model that assumes that the majority of the aerodynamic moment acting on the insect is due to the aerodynamic drag on the outstretched limbs. This assumption is based on the fact that although the head-thorax-abdomen likely produces a significant portion of the total drag, the small moment-arm for this drag generates little torque. In contrast, the outstretched limbs have a much larger moment-arm about the CoM and likely generate most of the aerodynamic torque. The limbs of the crickets are assumed to be made of three linear segments, each modeled as a circular cylinder with a specific diameter δ and length λ (See Fig. 6).

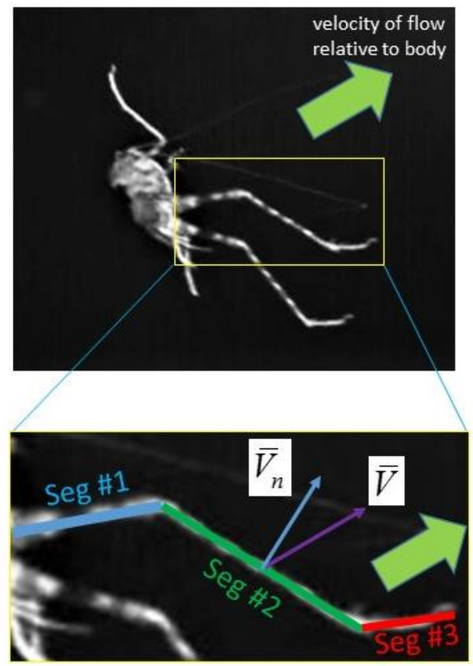

Figure 6. *Figures describing the procedure used to determine the aerodynamic torque on the body of the insect during the jump.*

The drag force on a given limb segment is calculated as

$$\bar{F}_D = \frac{1}{2}\rho\left|\bar{V}_n\right|\bar{V}_n\,\delta\,\lambda\,C_D(\mathrm{Re}) \quad (3)$$

where ρ is the density of the fluid (in this case, air), V_n is velocity of the air relative to the cricket in a direction normal to the leg segment, and $C_D(\mathrm{Re})$ is the drag coefficient based on the local Reynolds number $\mathrm{Re} = \left|\bar{V}_n\right|\delta / \nu$. From the drag force, the net moment is calculated as the sum of the individual moments for all the limb segments:

$$\bar{M} = \sum \bar{r} \times \bar{F}_D \qquad (4)$$

where $\bar{r}$ is the vector of the displacement from the insect's center of mass to the midpoint of a limb segment.

To analyze the collected data, several MATLAB scripts were written. First, the displacement of the CoM over time was used to determine the velocity for the particular frame for which the joints were tracked. For that frame, the component of velocity perpendicular to the each limb segment V_n is calculated. The Reynolds number for each segment was then estimated as described above. In our experiments, the Reynolds number varied from about 25 to 250. For estimating the drag coefficient, the exponential fit provided in the classical work Dennis and Shimshoni [6] was employed. The net torque acting on the cricket's body from its limbs was then calculated and decomposed into pitch, roll, and yaw components.

RESULTS AND DISCUSSION

The cricket's jump can be split into several distinct regimes as shown in Fig. 4; these are: takeoff, ascent, apex, descent, and landing. Each component is crucial to the cricket achieving long, controllable jumps. Before any quantitative analysis is performed, qualitative observations provide valuable information about the jumps. Prior to takeoff, the cricket crouches (Fig. 7(a)). This allows the cricket to maximize the force it exerts against the ground during takeoff. Through most of the ascent, the cricket maintains the posture seen in Fig. 7(b). In this posture the fore-limbs and mid-limbs are tucked tightly backward and underneath the body. The head is also tucked downward to present a rounded surface to the flow. This posture maximizes streamlining and will likely contribute to increasing the length of the jump. The cricket moves in a ballistic trajectory for most of its ascent. Just before the apex, approximately 40% of the way through the jump, the cricket rapidly transitions to a different posture, shown in Fig. 7(c), where all the limps are splayed out. The animal maintains this posture for the rest of the descent. This seemingly stable descent regime is the primary object of this study. Finally, the animal lands with its hind limbs contacting the ground first, followed by the body, and then bounces once or twice before coming to rest.

(a) (b) (c)

Figure 7. *Posture at three different stages in the jump: (a) pre-takeoff crouch; (b) initial ascent posture; and (c) descent posture.*

While many dozens of jumps were recorded, we chose five representative jumps that had high quality video data and in which the animal made a forward facing jump that was nearly bilaterally symmetric. Figure 8 shows the trajectory of the CoM of the cricket for these five jumps. Given the limitations imposed by the finite field-of-view and the depth-of-field, as well as the fact that working with live animals diminishes experimental control and repeatability, only portions of the jumps were captured in any given video. The trajectory shows the nearly parabolic shape that is expected, but there is wide variation between these jumps. Parabolic best-fit curves fit through the recorded trajectories were used to estimate the trajectory of the entire jump. These indicate that the longest recorded jump (Jump 2) was about 50 cm where the animal attained a height of about 11 cm, whereas the shortest among these jumps (Jump 4) was about 26 cm long and attained a maximum height of 5 cm.

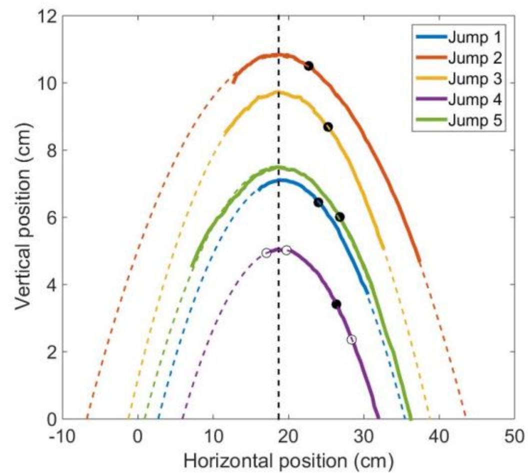

Figure 8. *Trajectory of center-of-mass (CoM) of cricket for five recorded jumps. The solid lines are the recorded trajectories. The curves are shifted so as to align the apex of all the jumps. Parabolic best-fit curves through the trajectory (dashed curves) show the estimate of the entire trajectory. Circles show the time-instances where 3D body posture has been examined.*

For each jump, the body posture and the position of the limbs was tracked. Figure 9 shows the 3D posture of the cricket extracted for Jump 2 at the time-instance indicated in Fig. 8 (filled circles).

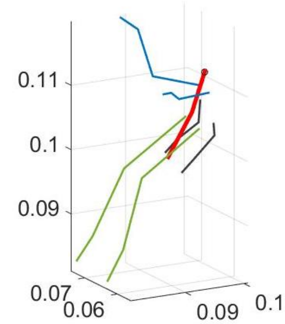

Figure 9. *Recreation of the three-dimensional posture of Jump 2 at the time-instance indicated in Fig. 8. The red line indicates the body posture, and the three segments of each of the six limbs are also shown. Fore, mid, and hind limbs are shown in blue, black, and green color respectively*

To quantitatively assess the degree to which the cricket maintains it posture during these jumps, the pitch angle between the cricket's body and the ground is estimated and shown in Fig. 10. In this figure, the curves are shifted horizontally to align the apex for all the jumps and the horizontal position is normalized to align the jump phases. A number of observations can be made from this plot. First, the angle of body during the initial part of the jump varies over a fairly large range from about 20 to 50 degrees. This indicates that the launch of the animal might be quite different from one case to another. It is also noted that there is a fairly significant increase in the body pitch angle during the first half of the jump for 3 of the 5 jumps (Jumps 2, 4 and 5) indicating that there is generally a pitch-up rotation of the body. As we show later, this might be the result of aerodynamically induced pitch torque.

The general characteristics of the latter half of the trajectory are significantly different. In this portion of the jump, the body angle is maintained to a fairly constant value for the duration of the descent in 4 out of 5 cases (except Jump 2). For Jumps 1, 3 and 5, this angle is roughly in the 50-55 degree range and for Jump 4, the stabilized angle is about 65 degrees. The data therefore provides quantitative support for the notion that during the descent portion of the jump, the body pitch angle is stabilized. We now examine the hypothesis that the posture of the limbs is the driving factor behind this aerodynamic stabilization.

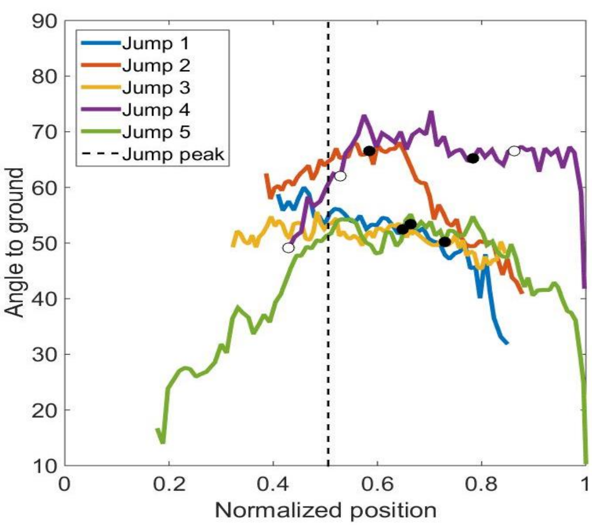

Figure 10. *Pitch angle between body and ground measured from videogrammetry analysis. The horizontal axis is the horizontal distance traveled by the cricket normalized by the total jump distance.*

Figure 11 shows plots of the aerodynamic pitch, roll, and yaw torque for the five jumps based on the posture extracted at instances during the descent that are marked in Fig. 6. Furthermore, to examine the aerodynamic stability of the animal, the aerodynamic torque was not only determined for the actual orientation of the animal but also for a full 360 degree variation of the body orientation. This could be accomplished easily in our mathematical model by rotating the velocity vector relative to the body orientation.

Comparison of the three aerodynamic torques shows that the pitch torque has the largest overall magnitude and the roll torque has the smallest magnitude. This is suggestive of the importance of pitch stabilization. It is also noted that the due to the smaller magnitudes, the roll and yaw torques are likely more affected by experimental uncertainties in our study. The vertical lines in Fig. 11 correspond to the observed angle between the body and velocity during descent. Table 1 shows the maximum pitch torque as well as the estimated pitch torque at the given angle. While the estimated pitch torque is not close to zero for all cases, it is quite small relative to the maximum torque for Jumps 1 and 3 and ranges from 42% to 55% for the other three jumps. Thus, keeping in view the uncertainty inherent in these measurements, the analysis suggests that the posture adopted by the cricket during the descent generates a relatively small pitch torque on the body. The primary measurement uncertainty originates from the measurement of the location of the limb segments from the videos and error propagation analysis indicates that this may generate overall errors in aerodynamic torque that range from 10%-20%.

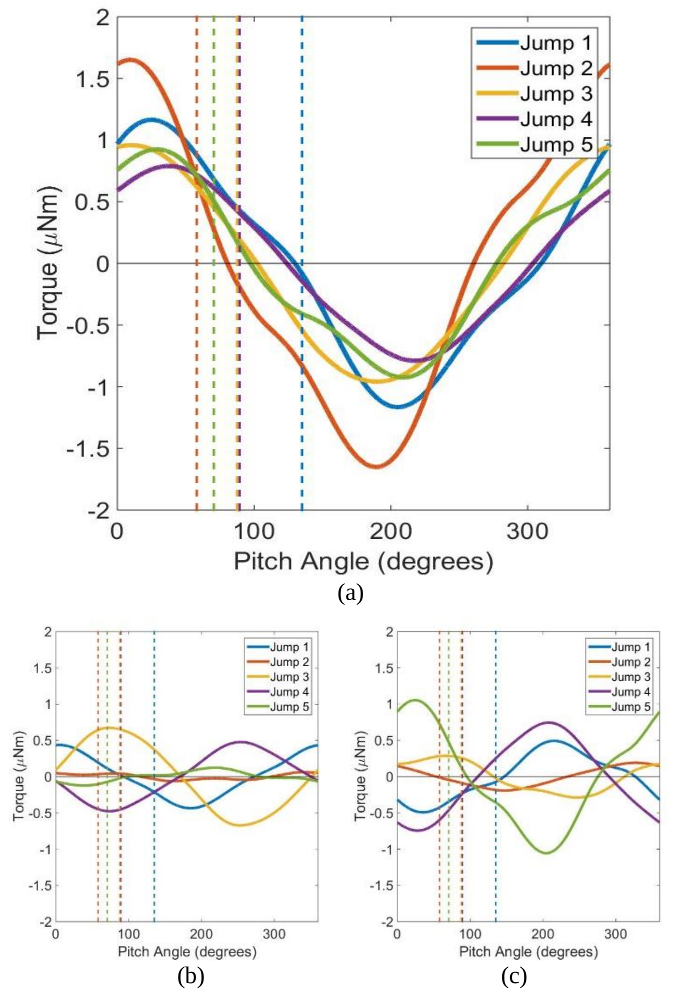

Figure 11. *Torque curves for multiple jumps. (a) Pitch torque. (b) Roll torque. (c) Yaw torque. The vertical lines indicate the actual angle between the body and the velocity*

Jump #	Max. Pitch Torque (μNm)	Estimated Pitch Torque (μNm) (ratio with Max Torque)
1	1.17	-0.08 (-7%)
2	1.65	0.69 (42%)
3	0.96	0.22 (23%)
4	0.79	0.41 (52%)
5	0.92	0.51 (55%)

Table 1. *Pitch torque estimates for the different jumps for a posture adopted during descent.*

As pointed out earlier, the posture is only stable in the pitch if any offset from the equilibrium angle creates a recovery torque, i.e. if the condition in Eq. (2) is satisfied. Figure 11(a) indeed shows that for all the five cases, the slope of pitch torque versus the pitch angle curve is negative at the selected instances. This provides further support for the observation that the posture adopted by the cricket during descent enhances the pitch stability of the animal. The roll and yaw torques do not indicate a similarly consistent behavior in the slopes but this is likely due to the higher experimental uncertainty in these values. Furthermore, cross coupling between pitch and the other two degrees of freedom is also expected to more complex and difficult to predict.

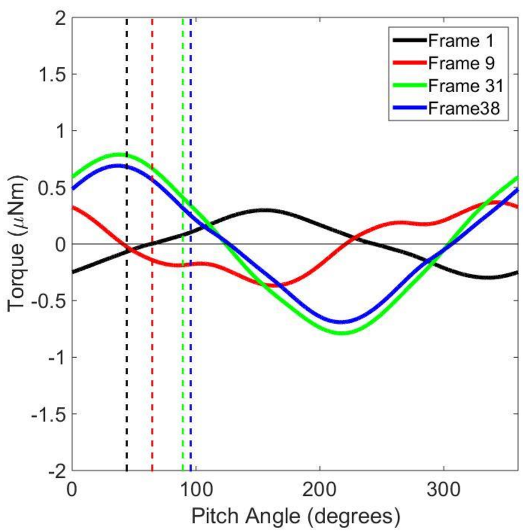

Figure 12. *Aerodynamic pitch torque curves for 4 postures during the jump of Jump 4. The vertical lines indicate the actual angle between the body and the velocity. The frame is indicated in Fig. 8 with white dots.*

Finally, we examine and compare the stability of other postures adopted by the animal during the jump. In particular, for Jump 4, we examine the pitch torque as a function of the relative velocity angle for 4 instances as indicated in Fig. 8. Figure 12 shows a plot of pitch torque for the 4 instances as a function of the pitch angle. Frame 1 is a frame during the ascent. The ascent posture is bullet-like and designed to maximize jumping distance. As such, it is unsurprising that the pitch torque does not exhibit the same characteristic curve seen in figure 11(a). In particular, the torque-angle curve has a positive slope for this case and this might partially explain why the pitch angle of the cricket increases during the ascent (see Fig. 12). Frame 9 is in the transitory phase as the cricket begins to assume the stable posture and while the curve shape is quite distinct from others, it does have a slightly negative torque-angle slope. Finally, Frames 31 and 38 are in the descent phase and they both show stabilization behavior: small torque magnitude with a negative torque-angle slope. Thus, Fig. 12 clearly shows that only the posture adopted during descent is highly stable to pitch.

CONCLUSIONS

High speed videogrammetry experiments and aerodynamic models have been employed to explore the hypothesis that the wingless spider cricket uses its limbs to aerodynamically stabilize its posture during the aerial phase of their long jumps. The study shows that the animals adopt a streamlined posture during the initial portion of the jump so as to increase jump distance but then transition to the stabilization posture during the descent. This stabilization allows them to land on their powerful hind quarters and enables them to quickly prepare for subsequent jumps. Jumping as a form of locomotion provides some advantages over crawling and flying and the current research could be useful in the development of small jumping robots that could be used for a variety of purposes.

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