Jumping performance of *Locusta migratoria* and relationship between jumping performance and ground roughness

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**ABSTRACT**

Locusts are famous for its excellent jumping performance. Jumping helps locusts avoid predators and initiate flight. In this paper, high-speed videos are recorded to analyze the jumping performance of *Locusta migratoria* Linnaeus from ground with different roughness. By the established simplified theoretical model, we calculated *L.* *migratoria* normally can get 1.8318 m/s takeoff velocity and maximum acceleration about 66.72 m/s² with takeoff angle at about 36°. Locusts are prone to slip when jumping from smooth surface especially for locusts with only one leg. The analyzed results show that locusts can increase their takeoff acceleration to get bigger takeoff velocity to adapt to different terrains, and takeoff velocity has no connection with takeoff angle while bigger takeoff angle have the possibility to help locusts to jump successfully with only one leg left or from smooth surface.

Keywords: jumping performance, *L.* *migratoria*, simplified model, surface roughness

**INTRODUCTION**

Animals have exceptional movement abilities (*Alexander, 2003; Pedley, 1977*). That inspires roboticists to design robots mimicking the locomotion of animals (*Kovac, 2010*). Jumping is an excellent way which allows several animals to overcome obstacles that are relatively large compared to their size (*Bonsignori et al., 2013; Bennet-Clark, 1975*). The biological observation results of *Alexander (2003)* shows that animals are prone to choose different locomotion modes as body size decreasing, and then jumping gradually substitutes walking, becomes the most suitable locomotion mode for small size insects.

*Burrows (2003)* classified animals jumping mechanism into 2 types: (1) lever principle used in animals with long legs like bush babies, kangaroos and frogs which can covert small force into big force and make the centroid get big acceleration; (2) catapult mechanism used by short leg animals. Insects exploit both designs: bush crickets use the leverage provided by long legs, fleas use stored energy to power their short legs, while lever principle combined with catapult used by locusts.

In order to escape from the predators or initiate flight, variety of insects evolved jumping ability (*Ritzmann, Quinn & Fischer, 2004*). *Bonsignori et al. (2013)* demonstrated that the acceleration of *Cicadella viridis Linnaeus* during the whole takeoff phase is almost constant by analyzing the centroid of leaffhopper with tacking software of a series of high speed video of jumping. A mathematical model is set up to calculate the propulsion force at the foot–ground interface, and the results shows the contact force is almost constant which differs from the force of other typical jumping models. *Sutton & Burrows (2011)* built a kinetic model to calculate the different possible velocities and accelerations of different jumping process, compared those calculation results with the kinematics movement measured from high-speed videos of natural jumping and got the conclusion that fleas realize jumping by apply force to the ground through the end of the tibiae. *Burrows (2006)* used the high speed camera to record the takeoff phase of froghopper and the calculation results showed that in the
best jumps by *Philaenus Stål*, take-off occurs within 0.875ms, with a peak velocity of 4.7 m/s and an peak acceleration of 5400 m/s², equivalent to 550 times gravity. Gvirsman, Kosa & Ayali (2016) demonstrated that the jumps’ azimuth and elevation angles are related with the initial body coordinates of position (relative to the hindlegs ground-contact points) and the flight initiation time is strongly connected with the jump pitch-angular velocity through analysis of directional jumping of locusts and dynamic computer simulation.

Insects are among the most proficient in jumping in the animal kingdom (Scholz, Bobbert & van Soest, 2006). In our study, locusts are chosen as model for the reasons below:

1. Locusts are famous for their high jumping performance (Bennet-Clark, 1975).
2. Body size is appropriate which makes taking videos and pictures easier, comparing to the average body size of flea which is only 1.8±0.19mm (Sutton & Burrows, 2011).
3. Take-off time is about 30ms which is moderate relative to flea with only 1.4±0.25ms (Sutton & Burrows, 2011; Bennet-Clark, 1975), so taking a video of locusts has lower requirement for the frame rate of high speed camera and the amount of data to be processed is moderate.
4. Jumping legs are very long comparing to forelegs and middle legs, which makes movement of hindlegs easy to observe (Albrecht, 1953).
5. The motor program of locust jumping includes both lever principle and catapult, which makes locusts different from other jumping animals (Burrows M., 2003).

Locusts are endowed with three pairs of legs (Chen et al., 2011). The hindlegs are jumping legs which can be divided into coxa, trochanter, femur, tibia, tarsus, and pretarsus (coxa, trochanter and pretarsus are neglected in our research for concision) as shown in figure 1 (Guo, Chen & Lu, 1991). The strong femurs of jumping legs and the slender tibiae make locusts have excellent jumping ability. The takeoff phase consisted of cocking, co-contraction and triggering phase (Han et al., 2013). During cocking and co-contraction phase, locusts store energy in extensor and semi-lunar process which is similar as a torsion spring by the coordinated movement of femur and tibiae (Brown, 1967). Through triggering phase, by rapid release of stored energy, locusts realize jumping while middle legs and fore legs play an important role mainly in adjusting take-off angle and elevation direction (Heitler & Burrows, 1977; Santer et al., 2005).

Due to the distinguished jumping ability of locust, there are numerous researches focused on locusts. Locusts have ability to control their jump performance by adjusting elevation angle, takeoff velocity and azimuth angle (Sutton & Burrows, 2008). Elevation angle is set by the orientation of the hindlegs relative to the body and is close to the angle of the straight line connecting the distal end of a tibia with the proximal end of a femur (Sutton & Burrows, 2008). Takeoff velocity is decided by the amount of energy stored inside the extensor muscles and semi-lunar process of knee joints of hindlegs during the contraction phase (Bennet-Clark, 1975). Azimuth angle is controlled by changing the direction of the body with the front and middle legs (Santer et al., 2005). Forelegs movements help locusts control their azimuth angle independent of the hindlegs position which contributes to the takeoff velocity and elevation angle, which makes it possible to change the azimuth angle after the hindlegs are cocked and makes the movement of locusts more agile. As the reference before, we can conclude that locusts can make targeted jumping under different situations while there are little reference how the parameters of locusts itself influence the jumping
performance. Edward P. Snelling tested the effect of the temperature and body mass on the jumping performance by a series of experiments which shows that temperature has no significant effect on the jumping performance while jump energy in juvenile locusts increases disproportionately with body mass (Snelling, Becker & Seymour, 2013). In this paper, with the help of high speed video recording, a mathematical model is established to analyze the dynamics and jumping performance during takeoff phase of adults *L.migratoria*. The effect of surface roughness on the jumping performance is investigated by comparing the takeoff time, velocity and elevation angle of a series of jumping from both rough foam plate and smooth acrylic plate. The relationship between different jumping parameters is concluded based on the experiment results.

Materials and Methods

As illustrated in figure 1, *L.migratoria* adults were reared in the Creative Engineering Design lab at the BioRobotics Institute of Scuola Superiore Sant’Anna of Pisa, Italy. Experiments were conducted under laboratory environment in December 2016. Specimens were reared in the laboratory within cylindrical transparent plastic box (50mm in diameter and 70mm in length) and fed with fresh vegetables and wheat. A total of 9 locusts are tested in our experiment for jumping behavior observation and video recordings. Temperature were maintained at 26±2°C and relative humidity at 40±5% during experiments. The platform for locust jumping experiment is a foam box with size of about 30×20×30mm of which the front is a transparent acrylic board and the back is attached with coordinate paper. During the experiment a soft plastic bar was used to stimulate locusts to jump from a small hole at the upside of the foam box. The take-off phase videos were took using a HotShot 512 SC high-speed video camera(NAC Image Technology, Simi Valley, CA, USA), the exposure frame rate exceeding 8000 frame/sec. Sequential images from each jump were captured at a rate of 1000 frames/sec with an exposure time of 1ms. The HotShot 512 SC video camera stores images with a resolution of 512×512 pixels directly to its internal memory. These images were downloaded into a dedicated computer for data analysis. The area where insects were expected to jump was lit with four LED illuminators (RODER SRL, Oglianico, TO, Italy) that emit light (420 lm each) at k=628 nm. Red light was chosen because it matches the maximum absorption frequency of the camera and because it does not impair the visual apparatus of the locusts due to locusts are blind under that wavelength (Briscoe & Chittka, 2001; Bonsignori et al., 2013).

Selected videos were edited with NAC HSSC Link software (NAC Image Technology) in order to contract the take-off portion from the whole video. Some videos were analyzed in advance with the native NAC software of the high-speed camera, which requires manual tracking of an area at a time. ProAnalyst suite (Xcitex, Cambridge, MA, USA) software was chosen to track object movement and results show negligible errors in the trajectories of tracked areas.

Definitive video tracks were analyzed, using automatic tracking with ProAnalyst suite, to mark out the motion of the center situated between middle legs and hindlegs. The tracking methodology was based on the selection of a distinct feature and the determination of its frame-by-frame motion characteristics (i.e. position, velocity and acceleration) over time,
with respect to the image plane. During automatic tracking, the user selects the feature location in a single initial frame. This feature is defined as a rectangular region of pixels in the initial frame. The software then examines subsequent frames and automatically finds and automatically tracks the feature. ProAnalyst suite software was carefully focaly observed by operator to assure that the resultant auto-tracked paths corresponded to the actual raw image sequence. To avoid errors, we tracked every video four times and calculated average pixels of centroid during take-off.

We checked every chosen videos frame by frame and find the configuration just before the jump and defined this time as \( t_0 \) and define the end of take-off phase when hindlegs just lose contact with ground as \( t_{fin} \). With the tracked centroid pixels of every videos and coordinate paper behind the platform behind locusts, we can easily change pixel positions into displacement in millimeter then we import those data into Matlab and use the polynomial regression method to analyze trajectories and instantaneous velocities. The displacement coordinates were extracted from locust jumps whose trajectory lay in a plane very close to perpendicular with respect to the longitudinal axis of the video camera.

**Model description**

In order to better understand the jumping mechanism of locusts, the important joint angle of hindlegs like \( \theta_1 \) between tibiae and ground, knee joint angle \( \theta_2, \theta_3 \) between body and femur during take-off phase are recorded based on the high speed takeoff video. Because the jumping mainly relates to the hindlegs, the fore legs and middle legs are omitted in the simplified model and the quality of the fore legs and mid legs are merged into the body mass. In the simplified mathematical model, the body is simplified as a rigid body; the centroid is located in point \( S \); femur is connected with the body by the joint \( C \). The femur and tibiae are simplified as rigid bars, and simplify the knee joint as hinge \( B \). In the take-off phase, the tarsus keeps contacting with ground so we simplify the tarsus with ground as a whole, the joint between tarsus and tibiae as hinge \( A \). Simplified theoretical model is shown in figure 2.

![Locust morphology](image1.png)  
**Figure 1.** Locust morphology  

![Theoretical model of locust movement](image2.png)  
**Figure 2.** Theoretical model of locust movement

The X-Y reference coordinate systems is established on ground according to the D-H method, as shown in figure 2, and base coordinate system \( x_0y_0 \) is built up in the fixed hinge \( A \) while base coordinate axes are parallel to the reference coordinate system. The base coordinate system is fixed due to hinge \( A \) is fixed on ground. Dynamic coordinate systems \( x_1y_1, x_2y_2, x_3y_3 \) in the joints \( B, C, centroid \( S \) are established respectively, of which the x-axis
positive direction is the direction of rods; z axis is perpendicular to the paper plane outward, and the joint angle positive direction is determined based on right hand rule. $\theta_1$, $\theta_2$, $\theta_3$ represent the angles between the links respectively. $l_1$, $l_2$, $l_3$ represents the length of femur bar $AB$, tibiae bar $BC$ and the length between point $C$ and centroid $S$ respectively, as illustrated in figure 2.

The transformed rotational matrix of coordinate system $x_2-y_2$ relative to coordinate system $x_1-y_1$ is:

$$\begin{bmatrix}
\cos(\pi + \theta_2) & -\sin(\pi + \theta_2) & 0 & l_2 \cdot \cos(\pi + \theta_2) \\
\sin(\pi + \theta_2) & \cos(\pi + \theta_2) & 0 & l_2 \cdot \sin(\pi + \theta_2) \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

Therefore, centroid coordinates in coordinate system $x_0-y_0$ can be expressed as:

$$p_0 = 0T_1 \cdot 1T_2 \cdot p_2 = \begin{bmatrix}
-l_3 \cdot \cos(\theta_1 - \theta_2 - \theta_3) + l_2 \cdot \cos(\theta_1 - \theta_2) - l_1 \cdot \cos\theta_1 \\
l_3 \cdot \sin(\theta_1 - \theta_2 - \theta_3) - l_2 \cdot \sin(\theta_1 - \theta_2) - l_1 \cdot \sin\theta_1 \\
0 \\
1
\end{bmatrix}$$

So centroid position at take-off phase can be expressed as:

$$\begin{cases}
x_s = -l_3 \cdot \cos(\theta_1 - \theta_2 - \theta_3) + l_2 \cdot \cos(\theta_1 - \theta_2) - l_1 \cdot \cos\theta_1 \\
y_s = l_3 \cdot \sin(\theta_1 - \theta_2 - \theta_3) - l_2 \cdot \sin(\theta_1 - \theta_2) - l_1 \cdot \sin\theta_1
\end{cases}$$

The displacement $L_s$, velocity $v_s$ and acceleration $a_s$ of centroid can be solved by the above formula:

$$\begin{cases}
L_s = \sqrt{x_s^2 + y_s^2} \\
v_s = \frac{dL_s}{dt} = \frac{2}{2} \sqrt{(x_s')^2 + (y_s')^2} \\
a_s = \frac{dv_s}{dt} = \frac{2}{2} \sqrt{(x_s'')^2 + (y_s'')^2}
\end{cases}$$

Results

Takeoff phase of locust jumping L.migratoria

With the video of locust takeoff phase of 1000 frames every second, we use the ProAnalyst suite (Xcitex, Cambridge, MA, USA) software to track object movement and results show negligible errors in the trajectories of tracked areas. The average morphology parameters of locust hindlimbs are illustrated in Table 1. Locust morphology is shown in figure 1.

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hindlimb, femur</td>
<td>22.55±1.06</td>
</tr>
<tr>
<td>Hindlimb, tibiae</td>
<td>20.11±0.06</td>
</tr>
<tr>
<td>Hindlimb, tarsus</td>
<td>6.25±0.50</td>
</tr>
<tr>
<td>Body</td>
<td>43.30±0.54</td>
</tr>
</tbody>
</table>
As illustrated in figure 3, the black and red bars represent the tibiae and femur of locust, respectively. The blue point, red point and black point represent hip, knee and tarsus of locust respectively. During the whole takeoff phase, the tarsus keeps in contacting with ground and the knee joint is extended during the whole takeoff phase.

By the analysis results of experimental data, it can be known that take-off phase lasts about 35.5ms. At take-off phase, fore legs and middle legs left the ground first, the joints of hindlegs will continue to rotate until the hindlegs leave the ground. The angle variation trend during the takeoff phase is illustrated in figure 4. It is concluded from the analysis result that $\theta_1$ changes from 44° to 115°, $\theta_2$ changes from 13° to 134°, $\theta_3$ keeps unchangeable in the first 20ms and gradually increases to 140~180° in some videos. With the increase of $\theta_2$, femur muscle is fully contracted and drives the movement of tibiae. Variation range of $\theta_3$ will be different with the take-off angle changing.

The values of angle $\theta_1$, $\theta_2$, $\theta_3$ in the formula (3) are substituted based on the results calculated from high speed video, and centroid trajectory and displacement of centroid during the whole takeoff phase are calculated based on formula (4). The calculation results of two typical jumping are shown in figure 5. During the whole take-off phase, the trajectory of centroid of locusts is approximately a straight line. And the displacement of centroid during the
takeoff phase is about 35.4 mm, takeoff angle is about 36°. The velocity and acceleration curves during take-off phase are shown in figure 6. Normally, after the takeoff phase, *L.migratoria* can get a takeoff velocity of 1.8318 m/s, and get the maximum acceleration at 20.5±2.5m/s after the beginning of takeoff, about 66.72 m/s², as illustrated in figure 6. Based on this, it is concluded that the propulsion force increased gradually to maximum value and then decreased. This variation trend makes locust jumping efficient, smooth and steady and good for decreasing the pressure between tarsus and ground during takeoff, which is consistent with the research results in animal experiment conducted before (*Bennet-Clark, 1975*).

![Figure 5](image1.png)

**Figure 5.** (a) centroid trajectory  
(b) displacement of centroid

![Figure 6](image2.png)

**Figure 6.** (a) velocity  
(b) acceleration

In summary, there are slight difference between the centroid position and displacement curve calculated from simplified model and that of animal model, but the variation trends are consistent. The error maybe caused by the following two factors: (1) there are errors in points marking of locust joints in jumping video processing; (2) the simplified model supposed centroid position is fixed relative to body while centroid position is changing because hindlegs change from curling up to stretching in locust jumping.

**Locust jumping from surface with different roughness**

Experiments were conducted inside a box with a transparent screen. High speed camera was used to take the video of locusts jumping from ground with different roughness. Inside the box, one half of ground is made of foam coefficient of which friction is bigger than that of the other half which is made of smooth acrylic sheet. With the data, the parameters of...
different jumping like slipping or not, takeoff angle, takeoff velocity, and the time takeoff phase lasts were analyzed and the strategy locusts used to adapt to surface with different roughness and relationships between different parameters are summarized.

<table>
<thead>
<tr>
<th>Number of locust</th>
<th>Total number of jumping</th>
<th>Surface material</th>
<th>slip</th>
<th>Success takeoff total</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 with two legs</td>
<td>4</td>
<td>acrylic sheet</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>foam</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>#2 with one legs</td>
<td>10</td>
<td>acrylic sheet</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>foam</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>#3 with two legs</td>
<td>21</td>
<td>acrylic sheet</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>foam</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>

* “slip” means that during the extension of hindlegs of locusts, the tarsus slip on the surface and the body of locust fail to detach with surface; “success takeoff” means that the locusts get a takeoff velocity through the propulsion from surface and turn into flying phase.

As table 2 shows that locust 2 with only one leg can hardly jump from the smooth surface but can successfully jump from the rough surface. Comparing with the jumping performance of locust 1 and 3, it is easy to find that locusts with two legs are easy to easily slip during jumping both on foam and acrylic sheet. This result convinced us that the importance of two leg for the jumping of locusts. What’s more, by analyzing the video of takeoff phase, we noticed that locusts that jump with only one leg are prone to yaw after takeoff maybe due to the unbalance caused by unilateral jumping force. Locusts with two legs like locusts 1 and 3 meet no difficulty jumping from both smooth and rough surface, these results convince us that intact locusts have the ability to adapt to different terrain and adjust the jumping performance.

Locusts slip easily on the smooth surface when taking off from smooth surface especially locust only with one leg. Roughness of surface is very important to the jumping performance of locusts. We choose videos whose trajectory lay in a plane very close to perpendicular with respect to the longitudinal axis of the video camera to analyze the takeoff parameters. The results are listed in table 3 and illustrated in figure 7. The first number in the first column in table 3 represents the number of locust which is the same as table 3 and the left two numbers represent the number of jumping of the same locust.

We can conclude when the takeoff time is close, locusts jumping from foam can get bigger takeoff velocity than locusts jumping from acrylic sheet as shown in figure 7(1). From figure 7(3), we can conclude that there is no obvious connection between takeoff velocity and takeoff angle. Based on the results shown in table 3 and figure 7(4), we can conclude that there is obvious relation between takeoff velocity and takeoff acceleration both in the jump from smooth and rough surface. The bigger the takeoff acceleration, the bigger the takeoff velocity, this can be explained by that bigger acceleration means surface provide locust more propulsion force during the takeoff phase, so the locust can get bigger takeoff velocity.
Figure 7. Relationships between different takeoff parameters

(Blue “*” stands for jumpings from acrylic sheet and red “+” stands for jumpings from foam)

Table 3. Parameters of different jumping videos

<table>
<thead>
<tr>
<th>number</th>
<th>material of</th>
<th>time/</th>
<th>displacement/</th>
<th>velocity/</th>
<th>acceleration/</th>
<th>angle/*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>ms</td>
<td>mm</td>
<td>m/s</td>
<td>(m/s^2)</td>
<td></td>
</tr>
<tr>
<td>207</td>
<td>foam</td>
<td>46</td>
<td>24.8377</td>
<td>1.1001</td>
<td>28.1899</td>
<td>80.7253</td>
</tr>
<tr>
<td>302</td>
<td>acrylic sheet</td>
<td>35</td>
<td>26.1951</td>
<td>1.4559</td>
<td>76.4864</td>
<td>38.1893</td>
</tr>
<tr>
<td>303</td>
<td>foam</td>
<td>34</td>
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<td>1.6663</td>
<td>70.5341</td>
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<tr>
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<td>47.4788</td>
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<tr>
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<td>foam</td>
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<td>1.7984</td>
<td>109.4974</td>
<td>39.6435</td>
</tr>
<tr>
<td>309</td>
<td>acrylic sheet</td>
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<td>31.4848</td>
<td>1.9912</td>
<td>73.0474</td>
<td>45.3066</td>
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<tr>
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<td>foam</td>
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<td>19.3889</td>
<td>1.2761</td>
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<tr>
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<td>acrylic sheet</td>
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<td>27.1509</td>
<td>1.5176</td>
<td>77.6370</td>
<td>49.4077</td>
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<tr>
<td>313</td>
<td>foam</td>
<td>27</td>
<td>19.2681</td>
<td>1.2176</td>
<td>79.5069</td>
<td>47.0241</td>
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<td>314</td>
<td>acrylic sheet</td>
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<td>19.1751</td>
<td>1.4857</td>
<td>66.7524</td>
<td>58.0622</td>
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<td>17.8876</td>
<td>1.0481</td>
<td>59.5394</td>
<td>60.2231</td>
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<tr>
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<td>1.2085</td>
<td>55.8374</td>
<td>61.9776</td>
</tr>
<tr>
<td>318</td>
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<td>28.9664</td>
<td>1.1962</td>
<td>50.0516</td>
<td>50.0392</td>
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<tr>
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<td>acrylic sheet</td>
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<td>22.2170</td>
<td>1.0699</td>
<td>52.9634</td>
<td>55.3587</td>
</tr>
<tr>
<td>321</td>
<td>acrylic sheet</td>
<td>43</td>
<td>19.0321</td>
<td>0.7717</td>
<td>38.2735</td>
<td>56.1221</td>
</tr>
</tbody>
</table>

*“displacement/mm” means the displacement of the center during takeoff; “velocity/(m/s)” means the maximum velocity when the locust left ground; “acceleration/(m/s^2)” means the maximum acceleration during the takeoff; “angle/*” means the elevation angle of the center during the takeoff.

From the locust with only one leg that jump successfully from the rough surface with takeoff angle of 80.7253 °, there is the possibility that locusts can enlarge the takeoff angle.
to overcome the disadvantage during takeoff like the lack of one leg and smooth surface. The experiment we taken cannot convince this point, maybe in the later we can conduct experiment to proof this view. From the data above, we can conclude that locusts have excellent jumping performance and locusts have the ability to adjust their takeoff time, velocity and angle to adapt to different terrains.

**Discussion**

Locusts are good models to investigate jumping behavior because of its excellent jumping performance and moderate size and takeoff time (*Bennet-Clark, 1975*). During the whole take-off phase, the trajectory of centroid of locusts is approximately a straight line which coordinates with the results that the angle of elevation at take-off is set by the orientation of the hindlegs relative to the body and is determined by the line connecting the distal end of a tibia with the proximal end of a femur (*Sutton & Burrows, 2008*). This angle is set by rotation at the coxae before the tibiae start to extend.

In our work, the centroid of *L. migratoria* keeps straight during takeoff with takeoff angle at about 36°. Normally, at the end of the takeoff phase, *L. migratoria* can get a takeoff velocity of 1.8318 m/s, and get the maximum acceleration of 66.72 m/s². Based in our results, it is concluded that the contact force increased gradually to maximum value and then decreased. Our results are similar to *Schistocerca gregaria* Forsskål that *S. gregaria* can get velocity of 3.2 m/sec with elevation angle of 50° is reached and the peak acceleration is about 180 m/s² after takeoff (*Bennet-Clark, 1975*).

*L. migratoria* in our experiment, the jump impulse lasts 26-42ms while the jump impulse of *S. gregaria* lasts 25-30ms (*Bennet-Clark, 1975*). And the impulse force during the whole takeoff phase shows the same trend, increasing from the beginning and then decreasing after reach the peak force. *L. migratoria* attains the maximum impulse force at 20.5±2.5ms after the beginning of takeoff while *S. gregaria* reaches the peak acceleration at 21ms (*Bennet-Clark, 1975*). During takeoff, the displacement and velocity curve of centroid also show the same variation trend which demonstrates that the motor programs of jumping are similar for locusts of different species. It is concluded that the jumping performance of different species locusts varies while the motor programs of jumping are similar.

The roughness of surface has an obvious effect on the locust jumping performance and locusts are prone to slip on the smooth surface especially for the locusts with only one leg. The experiments result shows that locust with only one leg can hardly jump from smooth surface but it has the possibility to successfully take off from the rough surface with elevation angle about 81°, which shows the increase of the elevation angle has the possibility to help locust jump successfully with smaller propulsion force due to lack of one hindleg. The fact locusts that with only one hindleg left or intact locust but one hindleg slipping during takeoff can still have the possibility to jump successfully shows that asynchronous extension of the two hindlegs or lack of one hindleg do not affect the trajectory of natural jumps. This is consistent with previous observations that asynchronous leg extension or even the complete absence of one hindleg can jump successfully also but cause little difficulty in jumping (*Santer et al., 2005; Bennet-Clark, 1975*). Because elevation is determined by the initial
position of hindleg, and remains constant throughout the jump, asynchrony of the forces between the left and right hindlegs does not lead to a catastrophic failure of elevation control. But through observation of the takeoff videos, we find jump with only one hindleg (lack of one hindleg or one hindleg slipping during takeoff) always accompanies with deflection instability of body after takeoff.

The experiment results show that jumping from the foam can get bigger takeoff velocity than jumping from the acrylic sheet when the takeoff time is close. This conform that the surface of foam is rougher than acrylic sheet so foam can provide more friction during takeoff.

At the same time, figure 7(3) shows that there is no obvious connection between the takeoff velocity and takeoff angle both in smooth surface and rough surface. Locusts can jump with different velocities at the same take off angle and jump with different takeoff angles at the same takeoff velocity. This result is consistent with the conclusion that speed is controlled by using the extensor tibiae muscles to store and release the appropriate amount of energy within the elastic processes of a hindleg (Bennet-Clark, 1975).

The experiment results show that locusts can get bigger takeoff velocity with bigger acceleration both jumping from smooth surface and rough surface. The takeoff velocity is proportional to takeoff acceleration because locusts can get bigger propulsion force during the takeoff phase. Due to the limited number of samples, we cannot conclude a precise mathematical expression between takeoff time and takeoff velocity while the connection between two parameters is obvious as illustrated in figure 7(4).

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Reference


