# 2010年臺灣國際科學展覽會
# 優勝作品專輯

**編號：050005-03**

作品名稱

**Why Spiderman cannot do without his silk? —**

**The effects of dragline silk on jumping performance of jumping spider (Hasarius adanson)**

得獎獎項

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關鍵詞：**spider dragline silk、jumping performance、biomechanics**

# 作者簡介

我是陳永康，就讀於台中一中二年級。自幼常隨父母到郊外踏青，大自然這個豐富的寶庫時常提供我很多靈感。也因此啟發了做專題的興趣。

如果說我的高中生活因什麼而豐富,那一定是專題研究! 從踏進實驗室的第一步，到現在已是整整兩年。為了尋找屬於自己的原創性，題目換了又換。到這個專題為止已經是第三個了。或許這就是成為科學家的必經之路。很高興有機會參與國科會的高瞻計劃和科教館的青培計畫，教授和老師的督促及支持都使我受益良多。與學長姐和同學的討論，提供我更多創新的想法。最後，父母這一路走來對我的包容和鼓勵，成為我最大的支持。

# 摘要

由於蜘蛛絲複雜的分子結構及產生過程，長久以來一直被視為一個特殊的生物材料(高延展性，高韌性，和高強度)，此外，前人研究指出蜘蛛能自己調控絲的性質，並受到環境的影響。然而，大多數的研究多以結網性蜘蛛為主，只有極少數研究著重在探討非結網性蜘蛛，如:跳蛛。本研究中，以安德遜蠅虎為材料，分析跳蛛的跳躍行為，以及探討曳絲在跳躍過程時所造成的影響。我們初步的研究結果顯示: (一)曳絲在跳蛛跳躍過程中，對於安全降落扮演重要的角色，及(二)跳蛛會藉由改變身體的角度來維持身體的平衡。在跳躍過程中，蜘蛛的跳躍速度會因空氣阻力而減少，但是蜘蛛絲的彈性恢恢復力(根據虎克定律)會讓跳蛛跳躍速度更顯著的減少，並藉著身體的轉動與曳絲的作用達到身體平衡。對於一個非結網性蜘蛛是另外一個不可或缺的輔助工具。相對於其他跳躍動物，有絲的跳蛛具備另一項能減緩降落速度的工具以增加降落的安全性。

# Abstract

Spider silk has long been known as a remarkable material with great extensibility, strength, and toughness, which are thought to relate to its complex molecular structure and production process. Additionally, spider silk is found to vary with production conditions and its material properties can be controlled by the spiders. To date, most studies on spider silks were based on web-building spiders; however, few studies considered the silks produced by wandering spiders (e.g. jumping spiders), which cannot construct a web. In this study, we examine the jumping behaviors of jumping spiders *Hasarius adansoni*, and the effects of dragline silk on their jumping performance. Our results suggest that (a) dragline silk is necessary for the spiders to allow them land safely, and (b) jumping spiders can control their postures (e.g. body angles) to maintain its balance in the air. Our analyses show that although air resistance decreases spider's velocity, the dragline silk also plays a significant role in this process due to the resistant force from the stretched silk (as depicted by Hooke's Law). Therefore, besides controlling body postures like other jumping animals do, the jumping spiders also use dragline silk to ensure safe landing.

# 1. Introduction

Jumping spiders (salticids) are known for their acute vision, predatory strategies, and hydraulic mechanism without extensor muscles for jumping performances.[1, 2] They trail a dragline behind them to prevent dropping off from vegetation and broke the falling speed by dangle from it.[3] Therefore, it is also a called safety line or life line. According to previous studies, spider dragline silks are generated by major ampullate (MA) gland and minor ampullate (MI) gland, and they have different compositions of amino acids.[6] These differences were confirmed to influence mechanical properties and were determined by different spider silk genes (e.g. Masp2, Masp1 for major ampullate silk and Misp1, Misp2 for minor spider silk).[4, 5, 6]

After four hundred million years of evolution, these arachnid animals construct their unique material- spider silk.[6] Furthermore, there are lots of advantages (e.g. good extensity, high stress, and high toughness) than other artificial material (e.g. Kevlar, Nylon, and engineering steel).[5, 7] Liquid crystalline was converted to solid thread by spinning duct. [6, 8]And it depends on spinning conditions, reeling speed, body temperature and relative humidity. [9, 10, 11] Notably, every slight changes influence its properties significantly. The generating process is so complex that biomimetic materials couldn’t conform completely to natural spider silk.

The differences between naturally spun silk and forcibly spun one were also studied. It was regarded that forcibly spun silk was provided with a higher initial modulus but lower extensibility fiber.[12]In addition, there were also greatest differences between spider silk which was collected on horizontal surface and vertical one. The vertical one remained more superior properties and larger silk diameter to strengthen the safety function.[13]

Previous studies were mostly based on retiary (web building) spiders, however, there were few studies about wandering spiders, which was unable to spin a web. Regularly, the forcibly spun silk wouldn't perform in the excess of 0.3 (m/s),[12] on the other hand, the jumping velocity was usually in the excess of 1.0 (m/s). In addition, based on Ortlepp's results, spiders are able to control the tension and the properties of spider silk as they are drawn from the spinnerets.

Moreover, jumping insects all face challenges, including prevent rotation and reduce impact for landing.[14, 15] Most of jumping insects overcome challenges by their wings, however, spiders don't have wings; they have silk. Parry has indicated that dragline silk might influence spider's jumping trajectories[16]. In this study, we tried to study the role which spider dragline silk, a high performance material, plays during jumping performance. To understand more about the natural effect on spider, we then constructed an experiment which was analyzed by high speed camera and a set up for measuring the breaking force of spider dragline silk. Aside from that, we also studied that there were more than a single silk in one spider dragline silk, because there were two pairs of glands forming one spider dragline silk. It is interesting to study how do jumping spider survive in natural environment depend on these complex conditions; therefore we will try to explain the relations between gravity, air resistance, and spider dragline silk.

The procedures of this study are shown in figure 1. We hypothesize jumping spider could depend on the spider dragline silk and the behaviors adjusted by itself to land successfully and safely.

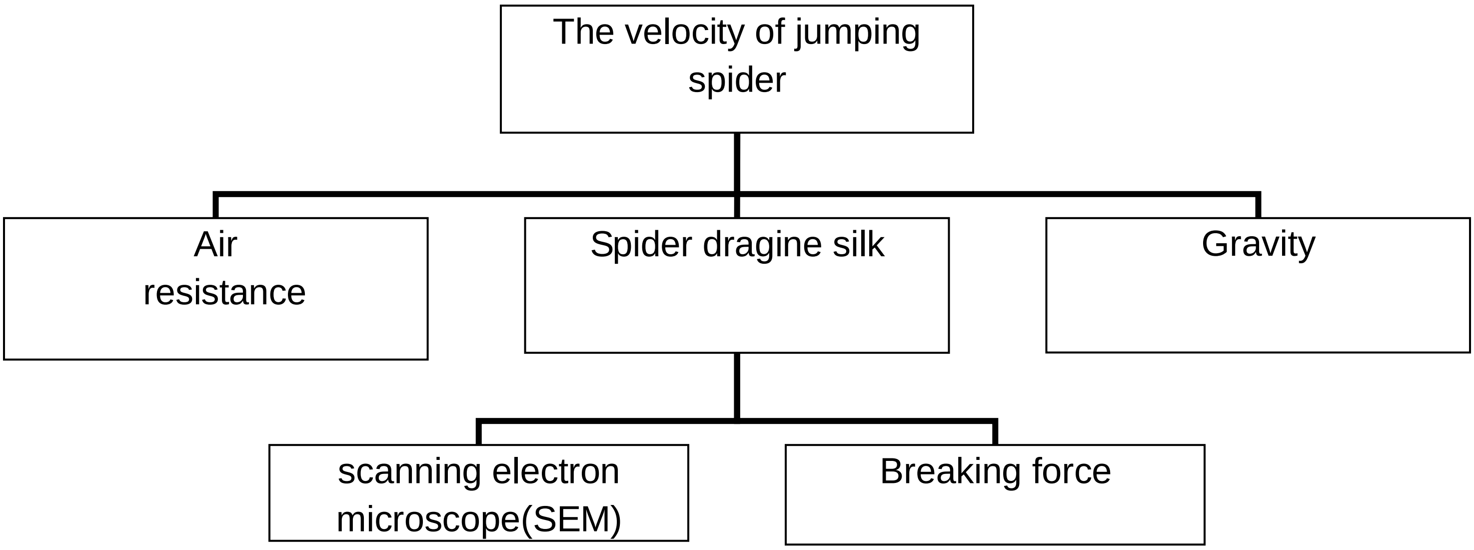



Fig. 1 Procedures of this study.

## 2. Materials & Methods

**Animals**. In this study, spiders of species 20 *Hasarius adansoni* were chosen and collected near Taichung (central Taiwan). And 15 could produce silk, 5 couldn't. They were fed with 3-4 fruit flies 2-3 times a week and supplied moderate water. The body length of a jumping spider is between 0.5-1 cm from head to tail (see Fig. 2).


Fig. 2 Jumping spider *Hasarius adansoni*.

**Experimental Set Up for Jumping Performance**. To keep track of the jumping performances of jumping spider, jumping spiders were filmed with high-speed camera. Jumping spider *Hasarius adansoni* was placed on (A) ascent to let it creep up to top. Since there was no way to retreat, the jumping spider would jump to the (B) destination. The whole process was filmed by (D) high speed camera (MotionPro X3) at 1000 frames per second with the (C) light source to illuminate, and a scale bar pasted on the lateral side of destination as a reference and calibration. The jumping sequences were then sent to (E) computer with the software Motion Studio (see Fig. 3). Only the sequences where the jumping spider jumped to the destination successfully were analyzed and we would then collect the spider dragline silk.

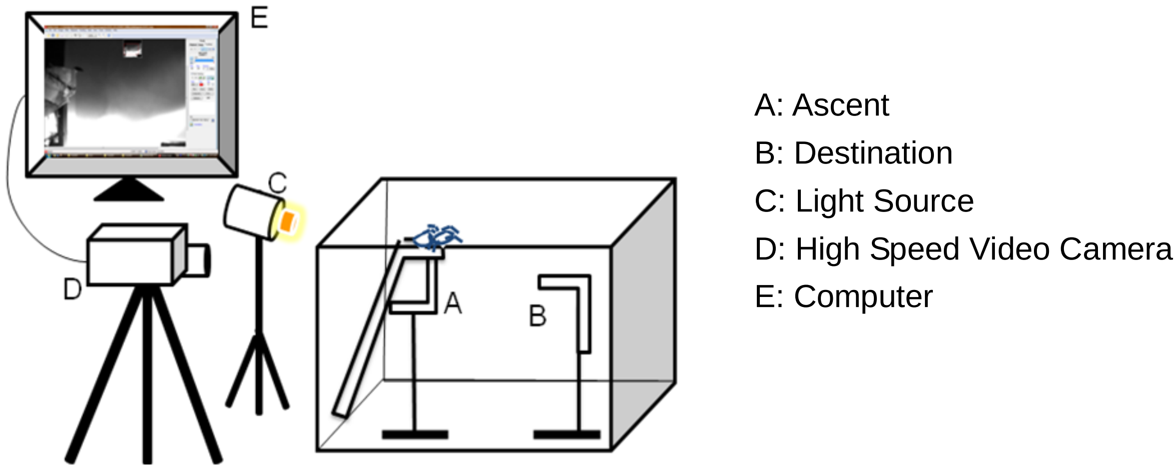



Fig. 3 The Experimental set up of jumping and high speed camera.

**Jumping Velocity and Force.** As to the calibration of the falling anesthetized jumping spider, some velocity fluctuations were made during tracking by Tema 2.6. To avoid the meaningless fluctuations, the jumping trajectories were smoothed by cubic polynomial by Origin 8. The smoothed positional data were differentiated to be the instantaneous velocity between two frames in SI units. According to Newton's second law, forced circumstances were equal to the product of mass and instantaneous acceleration. For Y coordinate, the maximum acceleration was 9.8 (m/s$^2$) which was completely forced by gravity only. To eliminate the effects without gravity, this can also be expressed as

$$F = m \cdot \sqrt{a_x^2 + \left(a_y - g\right)^2} \quad (1)$$

where $F$ is external force, $a_x$ is the instantaneous acceleration of X coordinate, $a_y$ is the instantaneous acceleration of Y coordinate, $m$ is the mass of the jumping spider, and $g$ is 9.8 (m/s$^2$) forced by gravity.

**Body Angle.** In order to quantify the variation of motions, we then use different vectors to describe. Owing to the images which were filmed by high speed camera, jumping spider would change the body angle between cephalothorax and abdomen. Therefore, to analyze the changes of the body angle, the jumping spider was divided into three parts- tail, middle, and head (see Fig. 4)

Vector middle – tail (represented abdomen) was tail coordinate minus middle coordinate, and vector middle-head (represented cephalothorax) was head coordinate minus middle coordinate. Additionally, to understand the changes of each part, we then calculated vector direction angle. Vector direction angle was defined as generalized angle from 0$^o$ - 360$^o$ (0-2π radians).

To obtain the body angle $\theta$ (defined as included angle), we used the following equation:

$$\vec{a} \cdot \vec{b} = |\vec{a}||\vec{b}| \cos\theta = x_1 x_2 + y_1 y_2 \quad (2)$$

where $a$ is vector middle-tail, $b$ is vector middle-head, $\theta$ is the body angle, $(x_1,y_1)$ is vector $a$'s coordinate, and $(x_2,y_2)$ is vector $b$'s coordinate.

To clarify the significance of angle changes, vector bisector was calculated by adding two unit vectors, and it could clearly tell us the exact changes between vector middle – tail and vector middle-head.

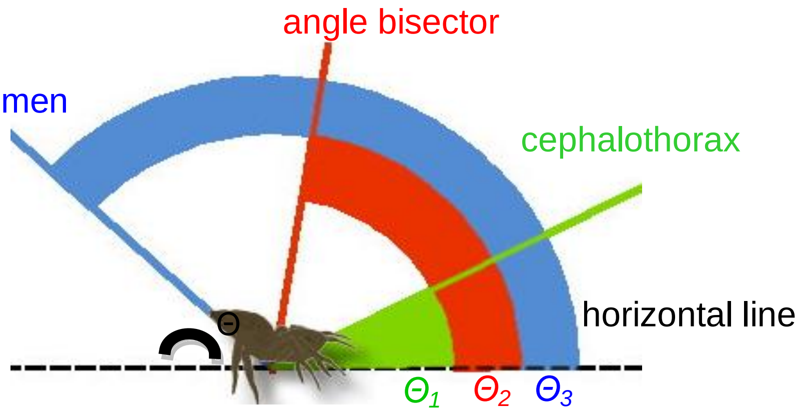



Fig. 4 Three different body angles, including different body directions. $\Theta_1$ represents the angle of cephalothorax's direction (green), $\Theta_3$ represents the angle of abdomen's direction (blue), $\Theta_2$ represents the angle of angle bisector's direction (red). $\Theta$ represents the angle between abdomen and cephalothorax.

**Angle between abdomen and dragline silk.** Angle between silk and abdomen is quantified by using vector dots equation (see Fig. 5).

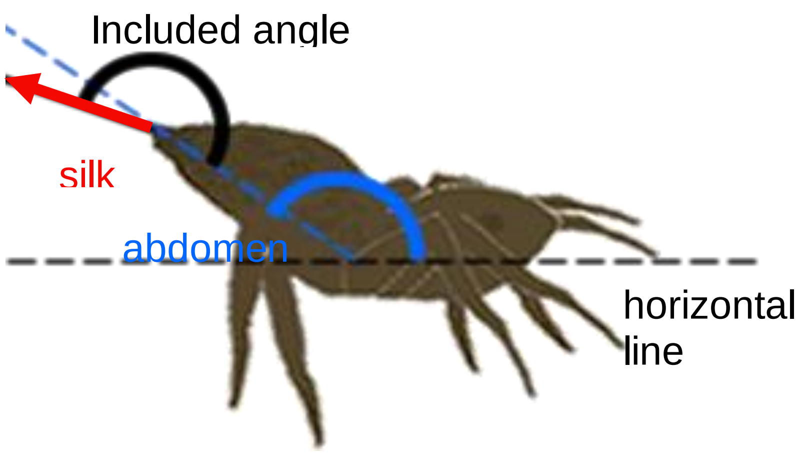



Fig. 5 Angle (black) between silk (red) and abdomen (blue)

**Air Resistance.** A physic model was made to describe an ideal jumping performance which was forced by gravity and air resistance without spider dragline silk. When jumping spider completely departed from jumping stage, the air resistance was influenced by the immediate jumping velocity, and it would also lead to a new jumping velocity because of an immediate acceleration next.

Air resistance can be calculated as follows:

$$D = \frac{1}{2} C_d \rho A V^2 \quad (3)$$

Where $D$ is the pressure drag, $C_d$ is the drag coefficient (=0.5-1N-$s^2$/kg-m), $\rho$ is the mass density of air (=1kg/$m^3$), $A$ is the reference area ($m^2$), and $V$ is the velocity of jumping spider (m/s).

**The Morphology of Spider Dragline Silk.** The spider dragline silk of jumping spider *Hasarius adansoni* was collected after it jumped. Spider dragline silk was adhered on depart point and terminal point by itself , and the silk samples were pasted on the paper cards which were divided into five parts for 1 cm each to do Scanning electron microscopy tests and force strain tests. That was done at a stable temperature (24.01667°±1.60177° C) and relative humidity (60.15±13.40951 % RH) with an air conditioner to control the conditional factors. The scanning electron microscopy (SEM) images were taken by using a FEI Inspect at 25 KV with a resolution of 1.5 nm. The silk samples were pasted on electrical tape, and they were coated with 30 nm gold layers by EIKO Engineering IB-2 afterwards (see Fig. 6)

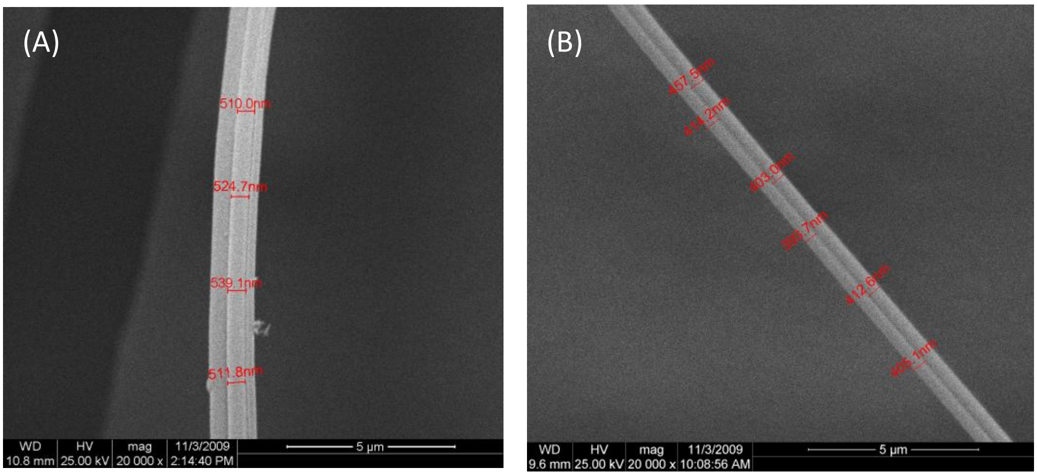



Fig. 6 The scanning electron microscopy(SEM) images. (A) shows there were three silks in one dragline, and (B) shows two silks in one.

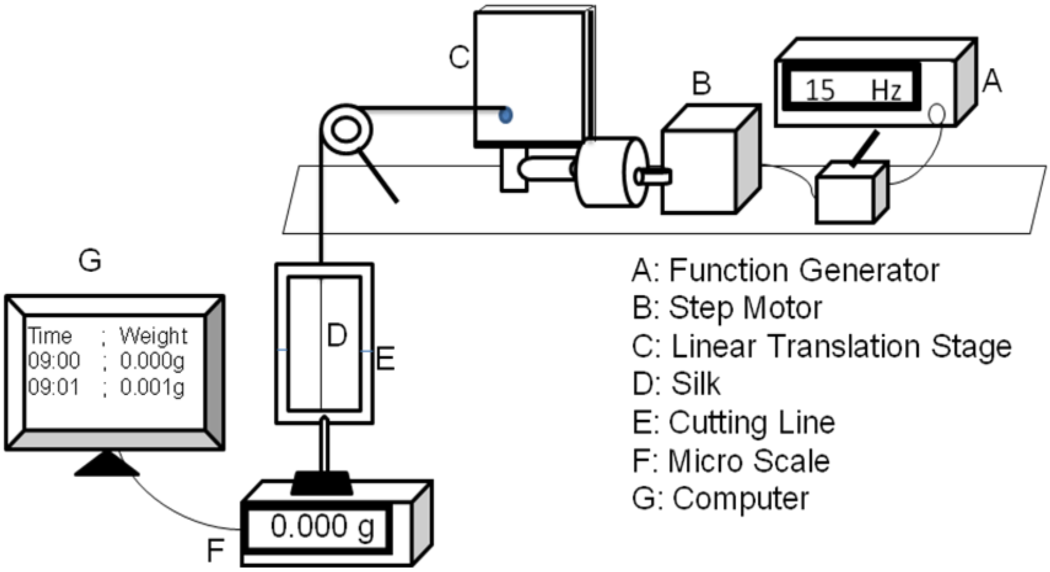


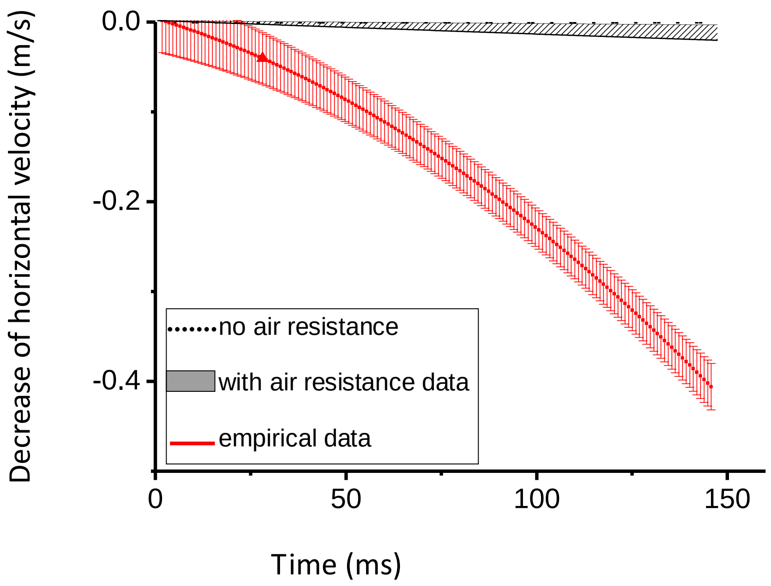

Fig. 7 An Apparatus to measure mechanical properties of spider dragline silk.

**The Experimental Set Up for Force Measurement**. The apparatus was designed to measure breaking force of spider dragline silk at a constant extension rate. The whole apparatus was propelled by (B) step motor with (A) function generator at 15Hz. The rotation of step motor (VEXTA 5-PHASE ) would later drive (C) linear translation stage (Newport M-423 Series) to move backwards. After the (D) spider dragline silk which was pasted on a paper card was cut off (E) , the paper card was departed in halves. As the linear translation stage moving backwards, it would lead to the values of (F) micro scale (Precisa XS 625M) to decrease. The different weight and time were sent to (G) computer afterwards (see Fig. 7).

# 3. Results and Discussion

**Influence of Air Resistance.** Based on the shape of the jumping spider, drag coefficient was supposed to range from 0.5-1 (N-$s^2$/kg-m). In an ideal horizontal motion of projectile, the jumping process could be regarded as being forced by gravity only; hence, the maximum acceleration should be 9.8 (m/$s^2$). To compare the influence of silk between spider with silk and without silk, the expected range of horizontal velocity (see Fig. 8) was used according to air resistance equation which is without the influence of viscous force other than pressure drag. The maximum values (red) referring to the drag coefficient values of 0.5 and the minimum values (blue) referring to the drag coefficient values of 1.0. Obviously, there is a significant difference between spider with silk and without silk. For the one with silk (see Fig. 8 A), there is a great gap between the expected values and measured ones. However, the one without silk (see Fig. 8 B) is just about the range of expected one. It shows that the influence of silk is greater than the influence of air resistance on horizontal velocity. That is to say, if a spider wants to decelerate its great landing velocity, it not only needs the air resistance but also relies on the drag of force more. Because the Renald's number of spider is approximately 1000, we only consider the influence of pressure drag and neglect the viscous force. Due to the influence of viscous force, horizontal velocity of spider without silk has a difference between empirical data and with air resistance ones.

(A)




(B)

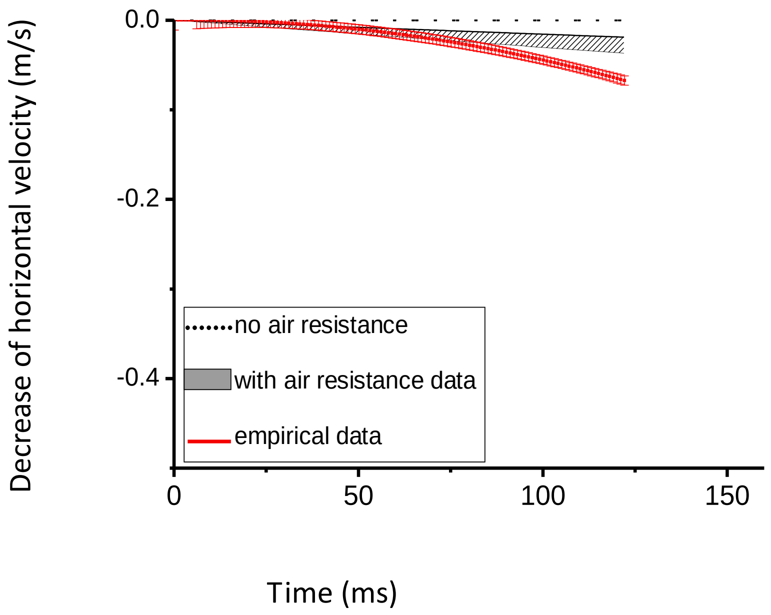
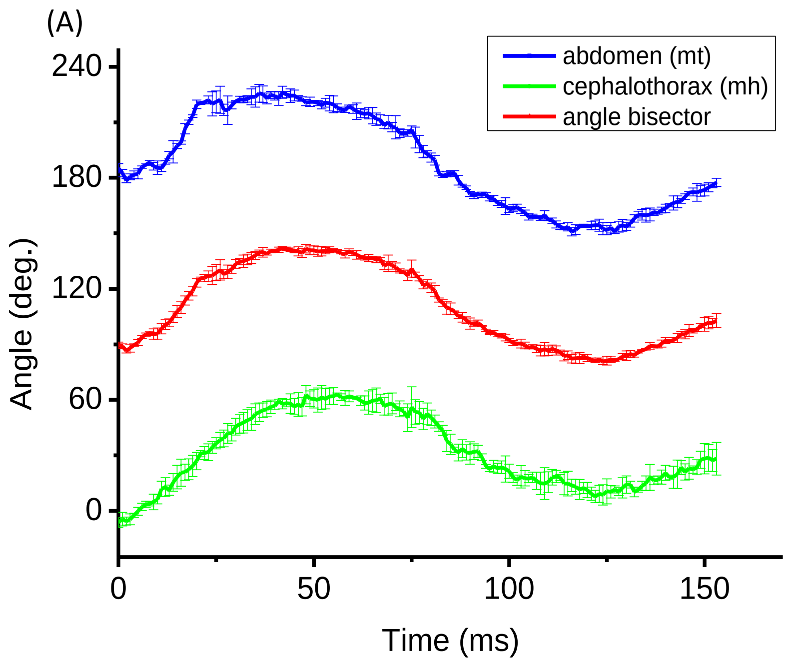
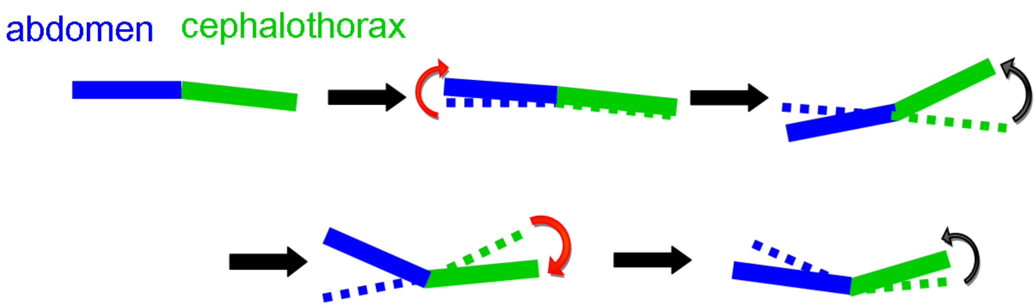



Fig. 8 The decrease of horizontal velocity of spider (A) with silk and (B) without silk over time. No air resistance data represents a constant velocity without influence of any forces. Wish air resistance data (dense area) represents the values which are only influenced by air resistance only. The empirical data was both influenced by dragline silk and air resistance.

**Body Angles.** However, the jumping performance of the jumping spider wasn't as simple as we thought. Vector middle-tail represents the direction of abdomen, vector middle-head represents the direction of cephalothorax, vector bisector represents the overall body direction (see Fig. 4). In the jumping performance, spider starts to rotate dorsally in abdomen, afterwards it seems to experience some sort of force to change the position. On the other hand, it seems that there is just a single trend for a spider without silk to rotate dorsally. And what the mechanism is that a jumping spider utilizes its silk to balance its body.



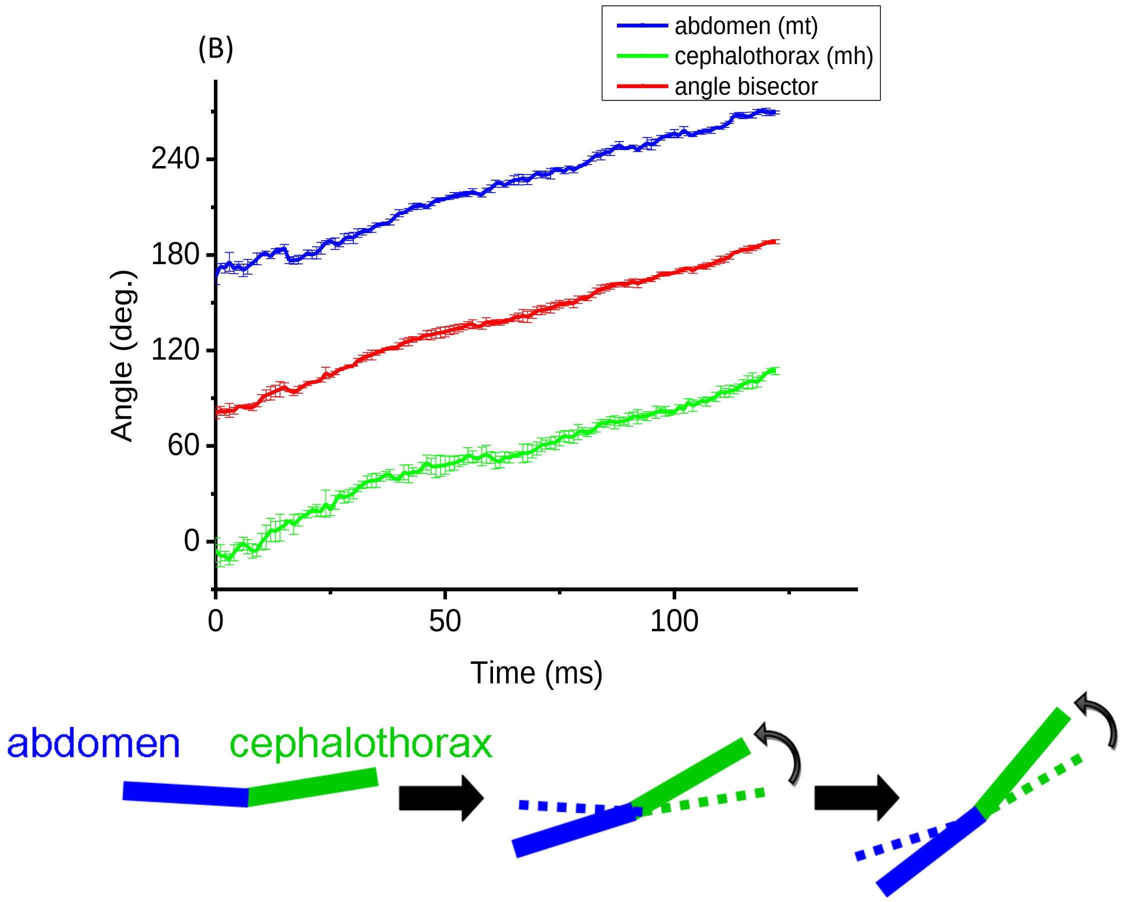



Fig. 9 Body angles over time show the change of direction of body positions of (A) with silk and (B) without silk. Green line represents the direction of cephalothorax, blue line represents the direction of abdomen, and red line represents the overall body direction. For a spider with silk, seems to have different trend during jumps. The trend of angle is started in ventral way to dorsal way. On the other hand, the trend of a spider without silk seems to have a single rotating trend.

**Angle between abdomen and cephalothorax.** To examine the difficulty whether jumping spider will rotate during the jump, angle between abdomen and cephalothorax is quantified here because the moment of inertia is strongly connected to the angle. Results show that spider which can produce silk will decrease body angle to create an optimum posture and have a safe landing. By contrast, since spider without silk doesn’t have any other forces to counteract with and also inertia will make spider rotate, spider without silk will keep a high body angle which leads to a great moment of inertia, and can prevent over-rotation. However, without adjusting body angle, spider without silk can’t make an optimum posture. That is to say, it will easily rotate in its landing phase.

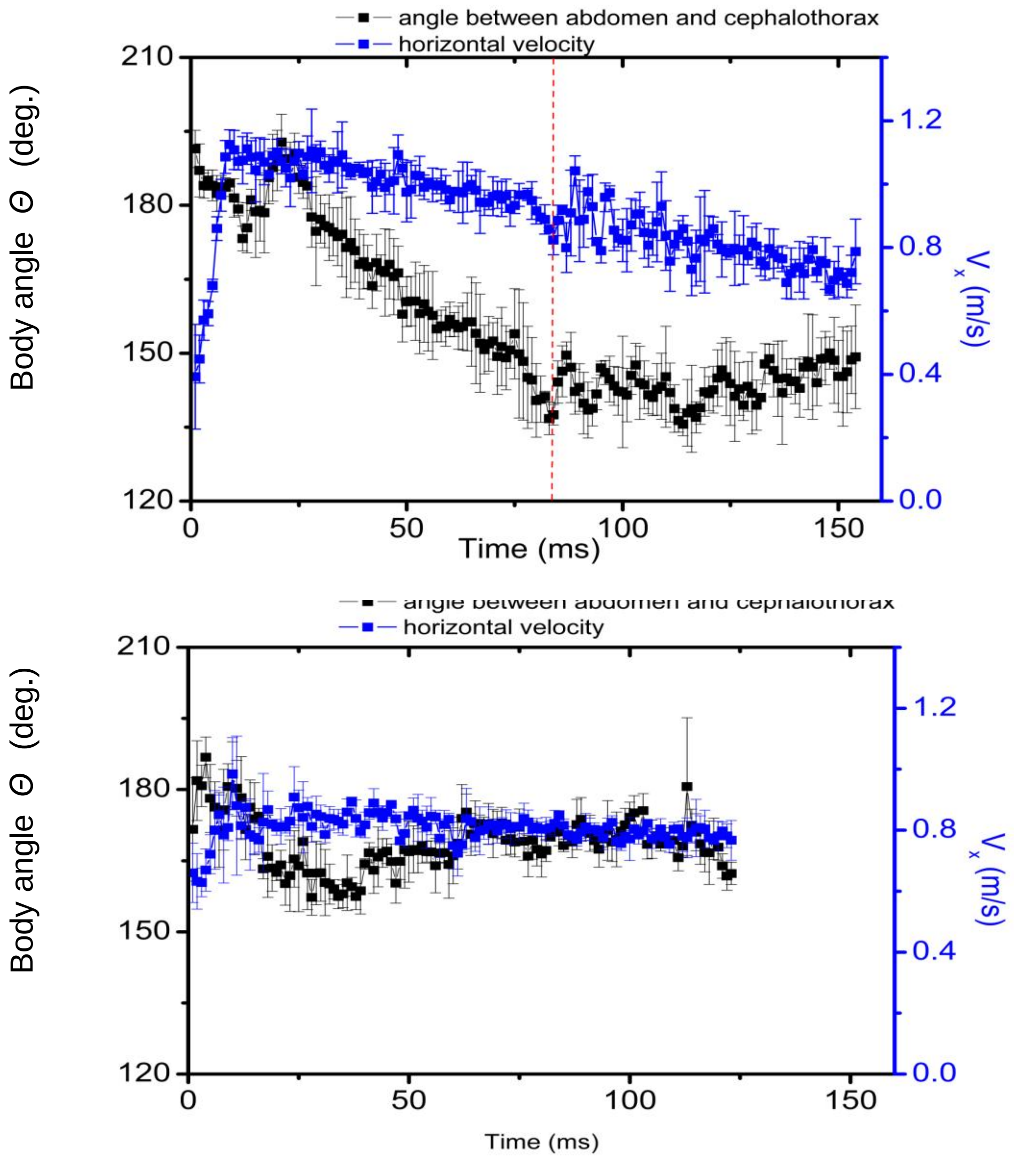



Fig. 10 Angle between abdomen and cephalothorax and horizontal velocity over time of (A) with silk and (B) without silk.

**Compare of Landing Motions Between Spider with Silk and without silk**. In our recorded experiments, jumping spiders with spider dragline silk (see Fig. 11 A) could stop safely due to the assisting of the friction brake caused by spider dragline silk. Also, by mean of the forth pair of legs which spiders use to cushion the great landing impact, the spider could land safely. On the other hand, there are unpredictable landing motions for spider without silk. For a spider without silk (see Fig. 11 B), it can rely on its abdomen to reduce the impact during landing. In addition, On account of there were no external force to eliminate the dorsal torque caused by itself, it needed to rely on the friction brake or it would rotate obviously. Qualitatively saying, if a jumping spider wants to reach the target accurately and safely, it does need the spider dragline silk to decrease the huge momentum by the frication break in the instant and accompany with its fourth pair of legs.

(A)

(B)

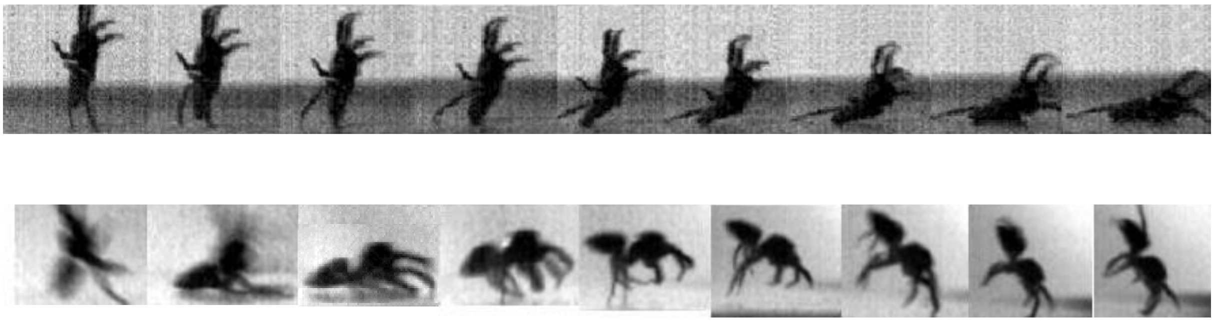
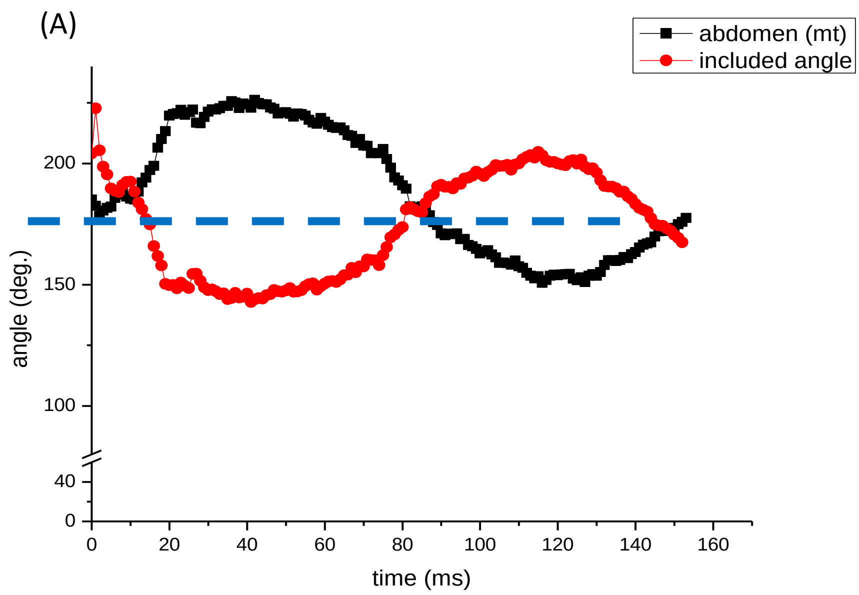


Fig. 11 Different landing motions of jumping spider (A) shows the normal spider landing with silk. It stopped stably and didn't slip through destination by its legs' buffer and the effect of spider dragline silk. (B) shows the spider without silk in contrast. Apparently, it couldn't stop purely by its legs or friction brake on destination, and it counteracted the huge momentum by rotating or slipping.

**Mechanism that spider controls its silk to adjust body positions.** The mechanism interests us is how they utilize dragline silk to adjust its body angles and postures. We use the change of angle between dragline silk and abdomen to demonstrate the torque which causes the adjustment of body angles. The angle between silk and abdomen is compared to the change of the direction of abdomen. Also, to compare the effect of this mechanism of with silk (see Fig. 12 A) and without silk (see Fig. 12 B), we assumed the spider without silk experiencing the force of silk, and compare its rotation with the torque caused by dragline silk. The angle between abdomen and silk seems to have a counteracting trend to the direction of abdomen. In addition, the angle is fluctuating up to down in the cross of hundred and eighty degrees. The mechanism indicated that the spider will rotate dorsally first due to its initial inertia, however, when the angle is lower than hundred and eighty degrees, the dragline silk will cause a ventral torque to adjust spider's body posture and make it rotate ventrally. In the process, whenever abdomen rotates to the hundred and eighty degrees line, the silk will influence its translation momentum only because that means the starting point, tail and middle point are in a straight line. Furthermore, the inertia which keeps spider's first rotation will drive it to rotate and cross the hundred and eighty degrees. Gradually, the first rotation will stop to rotate the reversing way due to the torque of silk. On the other hand, the rotation of spider without silk will rotate in a same trend and hasn't been crossed the hundred and eighty line. The angle seems to be no influence by the torque of silk which we assumed. That is to say, the silk which we assume is meaningless and doesn't exist. The mechanism which we found out was unique among those animals which can jump. According to the special geometry of jumping spider like a dumbbell, a spider can easily adjust its body posture with a company by the silk. And the mechanism is the motivation of dragline silk to balance spider's body and make it land safely.



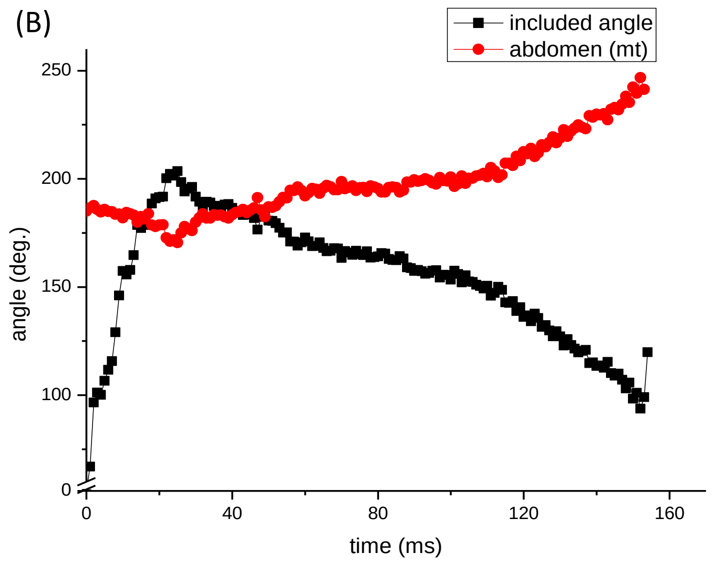




Fig. 12 Angle between abdomen and silk and angle of abdomen's direction over time of spider (A) with silk and (B) without silk.

**The Breaking Force of dragline silk.** On the other aspect of jumping performances, when the natural spun silk forcing on the jumping spider, the average breaking force could apply up to approximately 0.35 body weights. However, the average breaking force of the silk was approximately 2.4 body weights. This would then lead to the silk tension less than 15％ breaking load during jumping performance. And this was quite similar to Ortlepp's results. Our study indicates that spider dragline silk was spooled with small tension and took an important place in jumping performance. The effect of the spider dragline silk is an important factor of decreasing the jumping speed and avoiding spider's rotation.

Furthermore, we have tested dragline silk by another apparatus which has a different extension rate and more accurate micro balance. The results show dragline silk can withstand up to 1.7 body weights. Additionally, we have calculated the external forces in first half of jumping process and second one. Results show that the second half's breaking force is 1.7 times greater than the first one. Since scientists have indicated that spiders can actively control the property of silk, we believe the silk's property is changed during the jump and it was controlled by jumping spider. Also, safety factor of dragline silk shows it's unlikely to break during a jump.

Tab. 1 External force of air and drag shows the second half of jump is much greater than the first one. By mean of external force and breaking force of silk in average, a safety factor is quantified. Both first and second show silk is safe enough for a jump.

| **External force (EF) = air + <u>silk</u>** | | | **Breaking force (BF) of dragline silk** | **Safety factor (BF/EF) > 1 considered "safe"** | |
|---|---|---|---|---|---|
| $1^{st}$ half of jump | | $2^{nd}$ half of jump | whole jump (average) | $1^{st}$ half of jump | $2^{nd}$ half of jump |
| 0.25 body weight (BW) | < | 0.43 BW | 1.73±0.58 BW | 6.9 | 4.0 |

## 4. Conclusions

In our study, we suggest that spider dragline silk is not only a safety line, but also a necessary assistance tool. It plays an important role in jumping performances. In addition, there are three kinds of motions- jumping, landing and pre-landing in jumping performances. To balance the body, abdomen and cephalothorax lifted up consistently to decrease the torque caused by dragline silk. Spider dragline silk acted on spider to decrease the landing velocity. Without the help of dragline silk, jumping spider would rotate significantly after it landed, the importance of dragline silk was proved again . These results show that spider dragline silk could reduce landing velocity and function with spider jumping motions. The control of angle and spider dragline silk then promoted a succession of jumping performance. Jumping spider with dragline silk provided with another tool for decreasing landing velocity to make it land safely..

The SEM images show that there were more than one silk in a spider dragline silk, which is believed to be spinned by two pair of glands (major ampullate and minor ampullate gland). In the future, we will try to examine the regulation of silk production by adjusting two different glands.

## 5. Acknowledgements

We thank Prof. M.-C. Shih for discussion throughout the course of this project, and the members of the Shih-Roan-Chi Joint group at the Physics Dept. & Biophysics Inst. at NCHU for discussing the experiments. We thank Prof. I.-M. Tso and the members at the Tso’s lab for providing information on the animals. We thank H.-Y. Tseng for assisting SEM work on silk morphology. We also thank S.-T. Hsieh for teaching us the feeding methods of fruit flies.

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