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Aiming and Vaulting: Spider Inspired Leaping for Jumping Robots

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Abstract— **Jumping spiders are capable of targeted jumps by using their front legs to guide the release of energy from their rear legs. In this paper, we present a simplified model of the jumping spider based on the anatomy of the real spider. The immediate goal of this model is to understand how the geometry of the legs affects the jumping motion, with the further goal of using this geometry in the future development of jumping robots. Through a set of simulations, dynamic analysis, and experiments with a physical realization of our model, we identify several features of the spiders' jumping mechanism, most notably that "vaulting" with the front legs allows the system to generate flatter take-off trajectories than could be achieved by simple aiming of a spring-release mechanism.**

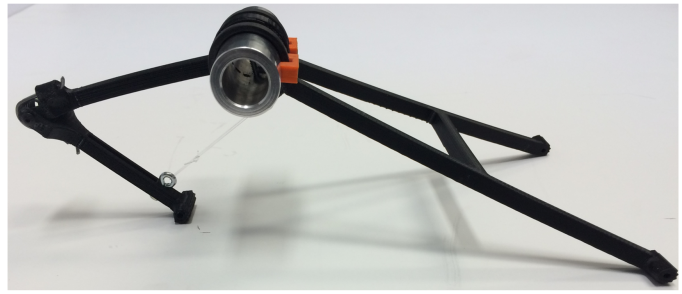

Fig. 1: The jumping spider mechanism.

I. INTRODUCTION

Jumping can serve multiple functions for animals and robots: Escape from a predator or other dangerous situation, efficient locomotion over rough terrain [1], and launching at a target. Achieving these goals requires a combination of fast energy release and a structure to channel this release in a desired direction. This aiming is especially important for purposeful locomotion and targeted launching.

Jumping spiders provide an interesting example of an aiming mechanism that is employed by animal feeding strategy involves precision pounces on often-airborne insects. The spiders use their legs to adjust the direction and velocity of the jump. The rear legs provide the required reaction force to propel the spider and the front legs in jumping spider act as a lever to control the direction of the jump [1].

In this paper, we present a simplified model of the jumping spider robot based on the anatomy of the real spider. The main contribution of this paper is to investigate the geometry of the jump and how the presence of the vaulting leg affects the resulting motion; this focus on how energy is *channeled* is in contrast to most other jumping studies' focus on questions of energy storage capacity and rate of release. In our model we implement the main legs of the spider which can contribute in the targeted jump as identified in [1]: the hind leg that supplies the energy for the jump, and the front leg which acts as a guide for the energy release. We use dynamic simulations to investigate the influence of parameters including front leg angle, front leg length and spring stiffness on the height, travel distance, velocity and direction of the jump. These simulations were corroborated via experiments on a physical implementation of our model, illustrated in Fig. 1 and the accompanying video.

A key insight that we gained from this investigation is that the vaulting leg allows the system to jump along flatter trajectories than would be possible with a simpler aiming mechanism. This effect persists even as the spring stiffness is increased, indicating that this increased range of launch angles is a fundamental geometric effect, and not tied to a slow release of jumping energy.

II. BACKGROUND

This paper draws on prior research efforts regarding jumping spider anatomy and jumping mechanism. Researchers have worked on many robots with jumping ability [2]–[7] for which the main concerns are overcoming high obstacles, designing good energy storage mechanisms, and efficiently releasing the energy [8]. In [9], a 7g jumping mechanism was developed to overcome large obstacles. The major focus of that study is on the height and the travel distance of the jumping robot. In order to generate a high jump, Kovac, et.al designed the mechanism such that the force profile starts with small force to prevent the system from launching before the maximum energy has been released from the spring into the system. The 7g jumping mechanism was later improved by adding the ability to steer the take-off in the horizontal plane [10].

Some investigations of jumping designs that have taken advantage of an assistive leg to jump [11], [12]. The assistive leg can help the robot to steer itself and jump with a desired elevation. In recent study of jumping robots, the [12] presented a soft robot which takes advantage of combination of pneumatic and explosive actuators to perform a jump. The robot proposed in study is capable of targeted jump, with the height and travel distance adjustable by its legs. In these works, however, the legs have been treated primarily as an aiming device for the energy release mechanism, and their effects on the launch dynamics have not been considered.

The jumping process also has been studied from biological point of view. Jumping spider characteristics in different jump situations have been considered in [1]. In this research, photographs were used to measure the spider jumps. The

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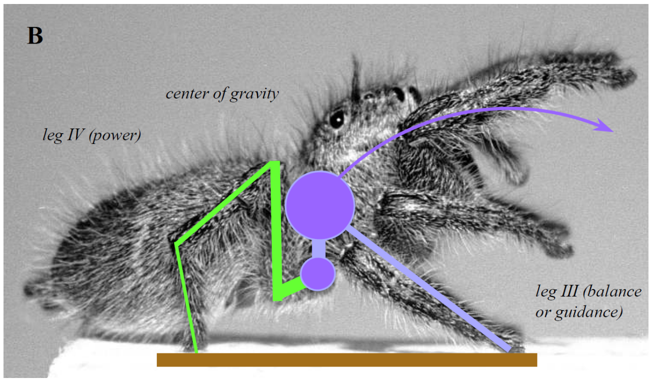

Fig. 2: Description of fundamental legs of jumping spider for a complete jump [1].

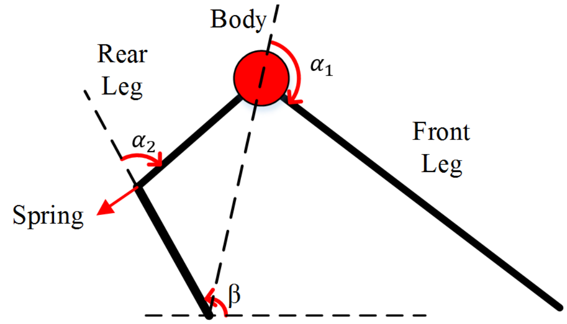

Fig. 3: The spider model.

focus was mainly on the ability of spiders to select their take-off velocity and direction to account for prey position and gravity. Other related works have studied on hydraulic leg extension. Parry and Brown [13] concentrated on jump mechanism of jumping spiders and mentioned that there are no extensor muscles at the hinge joints of spider leg and the extension is due to haemocoelic blood pressure [14]. The directional jump also has been studied for other insects. Card studied the fruit flies behavior of the jump [15] and showed why they are so hard to swat. She demonstrated that the flies can change the center of mass (COM) of their body by combination of leg placement (changing legs position) and leaning (shifting the body position). This center of mass movement helps them to jump in different directions. Her study revealed that most of the COM repositioning in forward and backward direction comes from leg placement whereas, the leaning movement mostly contributes in lateral repositioning. In the other study, Burrows investigated the grasshopper jump and the role of its legs during the jump [16]. He identified three different phases where the jump takes place and in the second phase the body angle is adjusted by changing the front leg position.

III. SPIDER ANATOMY AND MODELING

There are two main legs that play key roles in launching the jumping spider. The rear leg (labeled IV in [1] and in Fig. 2) provides most of the propulsion force for a jump. The front leg (labeled III) contributes a stabilizing force to stop the spider from falling over before the jump and serves to guide the direction of jumping [1]. The rear leg has several links, which straighten from initial folded position under internal pressure [14].

Based on the information gained from the anatomy of the spiders, we model our jumping spider as a planer system consisting of rear and front legs in which both front leg and rear leg have no-slip contact with the ground, and thus serve as pivots while there is a positive reaction force. The, rear leg in our model is composed of two segments which are equal in length and are joined together. The front leg length is equal to the length of summation of rear legs. We model the legs as massless links, corresponding to the concentration of mass in the body of a real spider [14].

The resulting system is a four-bar linkage. We model the body as a point mass, the front leg as freely pivoting around the body, and the leg energy storage as rotational spring at the joint that provides leg extension as shown in Fig. 3.

The spiders jump occurs in four phases. Fig. 4 shows three stages of jumping and one stage of flying. In each stage, the trajectory of the body mass is displayed as the trailing path.

- Stage (1) is when spring is released from an initial resting configuration.
- Stage (2) shows the spider as it has begun to increase in its velocity in an upward direction, pivoting around the front foot. This stage only appears during vaulting jumps.
- Stage (3) shows when the reaction force of the front leg becomes zero, the system enters into the unsupported phase. In an aiming jump, the system enters this stage directly from stage 1.
- Stage (4) shows the spider at flying phase. When both legs have zero reaction force, the system enters its flight phase.

The jumping spider jumps by starting in a configuration with the back leg spring pre-loaded to jump. When it is released, it continues until the rear leg angle α_2 becomes close to 0°angle (stage 3) and after that it enters to the stage (4) with the initial velocities taken from the previous stage.

Note that the Fig. 4 shows a vaulting jump. In some cases (the *unsupported jumps* described below), the mechanism lifts off directly, without pivoting around the front leg.

IV. TYPES OF JUMP

There are three different jumps may happen for spiders: unsupported Jump, aiming and vaulting.

- **Unsupported Jump:** The initial reaction force is what determines an unsupported jump, and that in the limit of high stiffness, it would be an aiming jump, but that for lower stiffnesses, the jumper would "fall over" as it launches.
- **Aiming jump:** Is the theoretical limit of unsupported jump when the jump occurs very fast. Therefore, the system launches along the initial body angle.
- **Vaulting:** In a vaulting jump, the mechanism pivots around the front foot, re-aligning the rear leg's line of action prior to take-off.

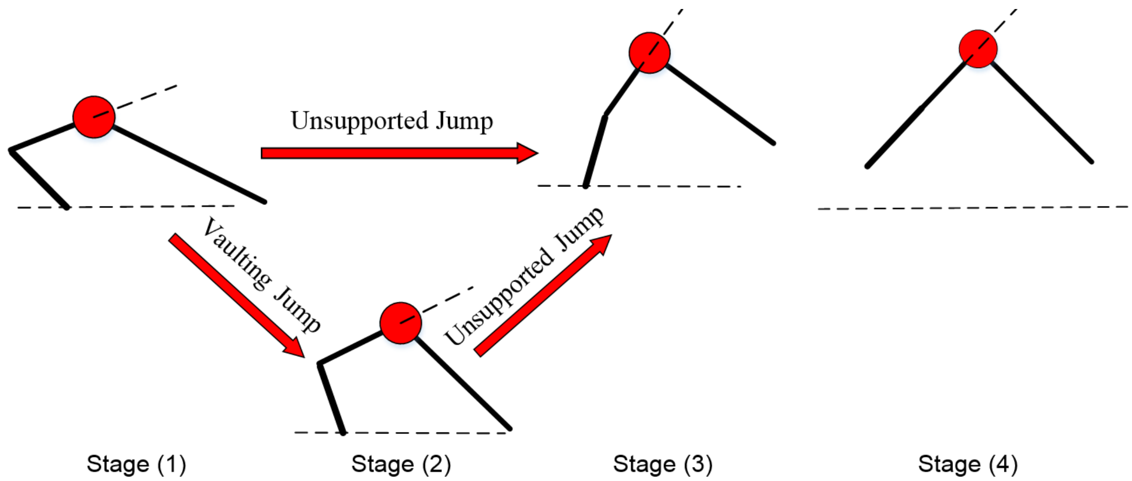

Fig. 4: Stages of the jump. (1) initial configuration, (2) pivoting around front foot, (3) launching off of rear leg, and (4) flight phase.

Given this categorization of jumping, we can then ask:

- What is the role of the mechanism's geometry in the jump?
- Under what conditions does an unsupported jump occur?
- Under what conditions does vaulting occur?
- How does vaulting affect the kinds of jumps that the mechanism can make?

V. SIMULATION AND RESULTS

To investigate the system's jumping behavior, we carried out a series of simulations. The fixed parameters over these simulations are the lengths of the leg segments, $L_1 = L_2 = \frac{L_3}{2}$ and initial angle of the back leg joint (i.e., the compression of the spring) at $\alpha_2 = 2.2$ radians. In our parameter explorations, we evaluate the effect of initial front leg angle α_1, non-dimensional stiffness

$$\rho = \frac{\omega_n{}^2}{\ddot{\theta}} = \frac{k}{m} \cdot \frac{L_1 + L_2}{g} \tag{1}$$

relating the time scale of spring release and falling forward, and front leg length. In each series of simulations, we fixed one of the variables, took a coarse sampling of a second, and a fine sampling of a third, resulting in three plots of data each, as illustrated in Fig. 5, 6, 7 and described below.

A. Front Leg Angle (α_1) and Stiffness (ρ)

The first set of simulations consider the effect of the front leg angle on the launch angle, at low, medium and high stiffness. As illustrated in Fig. 5, increasing the front leg angle increases the launch angle. For low stiffness, the hypothetical unsupported jump is very close to the vaulting jump. As the spring stiffness becomes higher the take-off angle for the unsupported jump approaches that of the aiming jump, while the vaulting jump maintains a significantly lower angle. When the front leg increases, the spider's body tends toward the back leg and causes the reaction force to get close to the vertical direction which decreases the load over the front leg and instead put more load on the back leg. Therefore, the spider experiences unsupported jump.

B. Spring Stiffness (ρ) and Front Leg Angle (α_1)

The second set of simulations considers the effect of the stiffness on the launch angle, at small, medium and large front leg angle. As shown in Fig. 6, increasing the stiffness increases the flying angle to some extent and this is noticeable that the rate of increase in flying angle is much higher when spider is doing aiming jump than when it is doing vaulting jump (Fig. 6 c). Similar to the results from the front leg angle, it is shown here that for any given stiffness, in some angle the spider only performs unsupported jump and in some others does the vaulting angle. The figure states that for small front leg angle, the difference of flying angle between hypothetical unsupported jump and vaulting jump is more. That is because vaulting takes longer time before switch to unsupported jump. (Vaulting jump usually starts with vault and then during the jump when spider loses the front leg contact, switches to the unsupported jump). As expected also, increasing the stiffness has a direct effect on the travel distance and the height of the jump regardless of what the front leg angle is, and increases both height and travel distance. Also, as the stiffness increases the speed of the jump increases.

C. Front Leg Length (L_3) and Spring Stiffness (ρ)

Finally the third set of simulations considers the effect of the front leg length on the launch angle, at low, medium and high stiffness. Increasing the front leg length, increases the flying angle regardless of the type of the jump (Fig. 7). For larger front leg angle, higher spring stiffness and larger front leg, the spider does unsupported jump. On the other hand, for smaller front leg angle, lower spring stiffness and smaller front leg, the spider does the vaulting jump. As the leg length increases for the same configuration, the body of spider moves toward the back leg. Therefore, the reaction force on the rear leg tends to the vertical direction which causes the front leg loses its contact with ground at the beginning of the jump and performs unsupported jump.

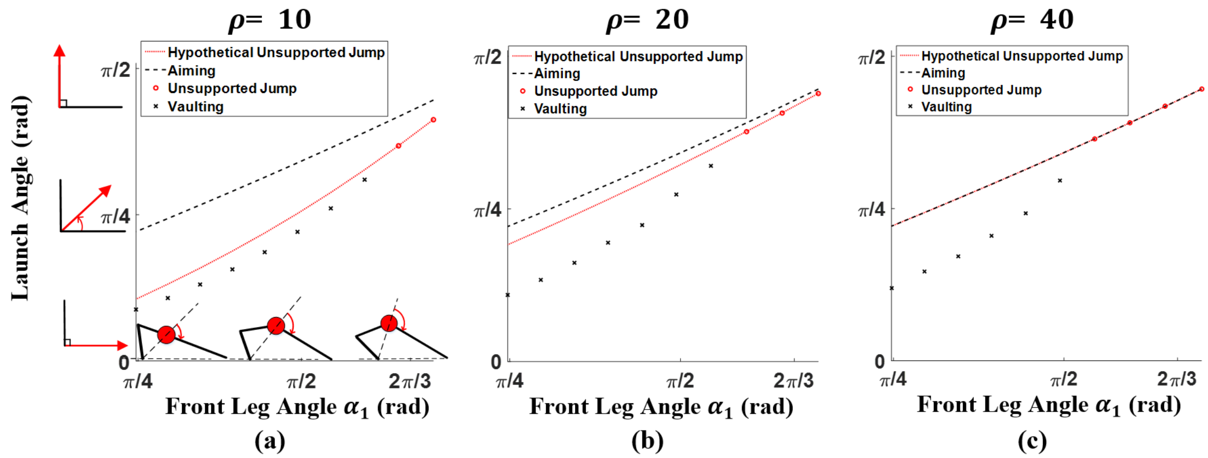

Fig. 5: Launch angle and type as a function of stiffness and front-leg angle. As the stiffness increases, unsupported jump converges to the aiming jump and vaulting stays as lower launch angle.

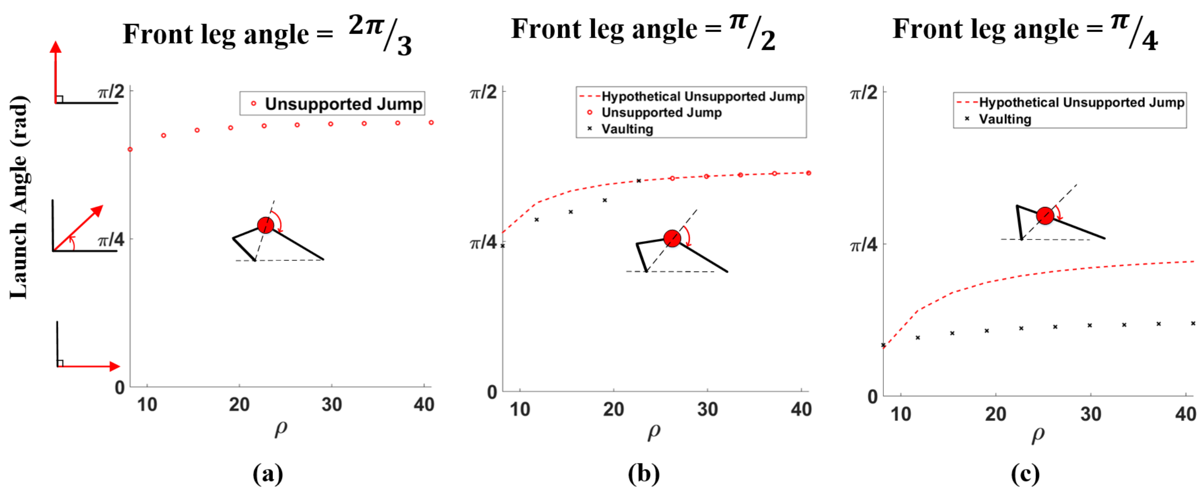

Fig. 6: Launch angle and type as a function of front leg angle and spring stiffness. Lower stiffness corresponds to the vaulting behavior and the front leg angle decrease results in vaulting behavior over a greater range of stiffnesses.

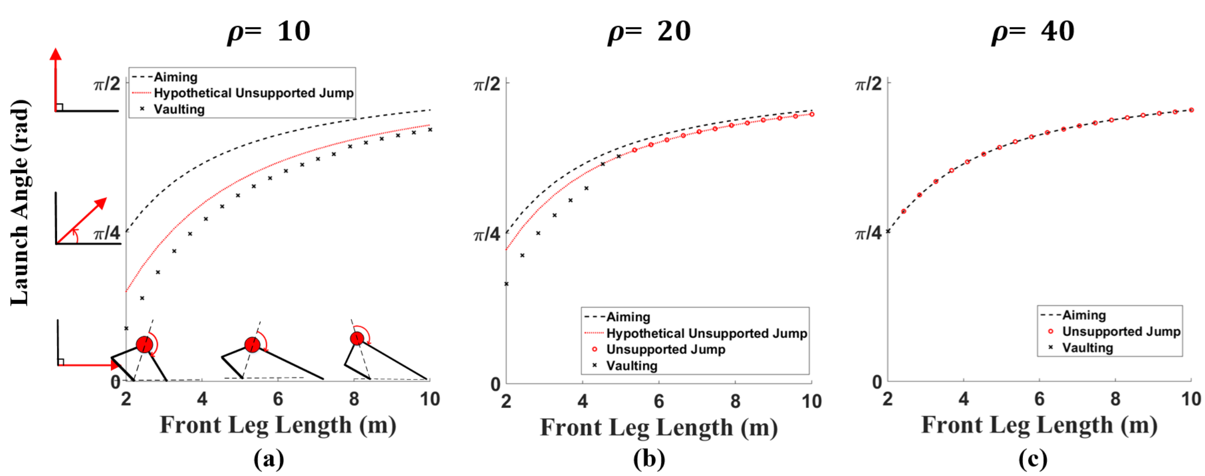

Fig. 7: The behavior of the jump for $\alpha_1 = 30°$and front leg length variation are depicted. Increasing the front leg length increases the launch angle and can change the type of jump (b).

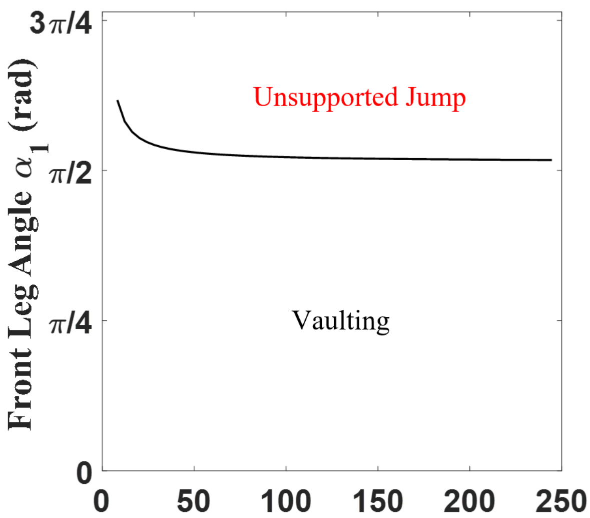

Fig. 8: Separated regions where the vaulting jump or unsupported jump occurs.

D. Analysis of Results

The vaulting and aiming motions are distinguished by the presence or absence of a vertical reaction force on the front foot when the spring is released. We calculate this reaction force by assuming a zero-displacement constraint on the motion of the front foot, and then extracting the vertical reaction force from the resulting trajectory of the body as

$$F_R = \frac{m(\ddot{y}x + g) - m\ddot{x}y}{L} \tag{2}$$

where x, y, $\ddot{x}$, $\ddot{y}$ are the position and acceleration of the body respectively. L is the toe's distance of the front and back legs. If $F_R > 0$, then the zero-displacement condition is consistent with the spider vaulting with some weight supported on the front foot. If $F_R \leq 0$, then this means that the spring has sufficient vertical force to immediately lift the spider in an aiming jump.

The Fig. 8 illustrates that even for high stiffness spring (explosive-actuated system) the system vaults at some angles, and that the division converges to the angle of α_1 at the initial configuration as ρ increases, where γ is the angle of the reaction force and (x, y) is the position of the center of mass. if $\alpha_1 > 90°$, an unsupported aiming jump occurs. On the other hand, if $\alpha_1 \leq 90°$ the system vaults instead (Fig. 10).

VI. EXPERIMENTS

To demonstrate the aiming and vaulting motions on a physical system, we built a proof-of-concept mechanical model, illustrated in Fig. 1. This model consists of four main parts: The front and rear legs, main body, and the leg stoppers. The front and rear legs are of equal length (165mm) and 3D printed with ABS plastic. The main columns of the legs feature a c-channel design in order to save weight and provide the appropriate strength. All three ground contact points for the legs have small extruded spikes to ensure there is no slipping during the jumping motion. The front legs are fixed together with a cross brace to ensure even tracking and increase rigidity. The rear leg features a joint at the midpoint which is fitted with a torsional spring to actuate the jumping motion.

The spring is loaded manually, then secured with fishing line using the 2 eyebolts located at opposite ends of the rear leg. The string is then cut to release the energy stored in the spring to actuate the jumping motion. The main body of the mechanism was constructed using a single hallow tube of aluminum. The use of aluminum against plastic creates a low friction interface allowing the front legs to rotate, as well as providing enough weight to keep the center of mass close to concentric with main body. The lateral center of the main body features 12 tapped holes that are drilled at 30°degree increments around its circumference. These holes allow for the angle between the front and rear legs to be adjusted by removing the eyebolt at the top of the rear leg, and rotating the leg around the body. The leg stoppers are set at a fixed position on the main body and serve to ensure the front legs are at the proper angle before the jump is executed. Fig. 9 and the attached video illustrate the result of our experiment for both vaulting and aiming jump.

VII. CONCLUSIONS

In this paper, we investigated a model of the aiming mechanism used by jumping spiders. Through parameter exploration and dynamic analysis, we identified three critical jumping regimes: unsupported jumps, aiming jumps and vaulting jumps. Unsupported jumps were those for which the front leg lifted off the ground immediately at the beginning of the jump, and for which the final take-off angle was determined by the relative rates of energy release from the spring and the system falling forward under the influence of gravity. In the limit of fast energy release, these unsupported jumps converged on an “aiming” behavior, in which the take-off angle was the same as the initial line of action of the spring.

Vaulting jumps, in which the mechanism pivots around the front leg before launching, exhibited a different, and unexpected convergence behavior. Because the spring force pushes into the front leg during “low-aimed” jumps, its release rate is slowed; this allows the system more time to pivot forward, and results in a trajectory that is even flatter than its initial aimed direction. Unlike the unsupported jumps, these jumps do not converge to the “aiming” behavior with increased stiffness, and so can be considered a distinctly geometric effect.

In our future work, we will seek to enhance our model by adding more segments to the legs and incorporate rotation of the jumper’s body, as observed for spiders in [1]. Jumping spiders have also been observed to use anchored draglines to achieve maneuvering capabilities while in the air [18]; we aim to take advantage of our study of tethered projectiles in [19] and [20] to add similar capability to our jumping spider mechanism, additionally drawing on parallel work in [17].

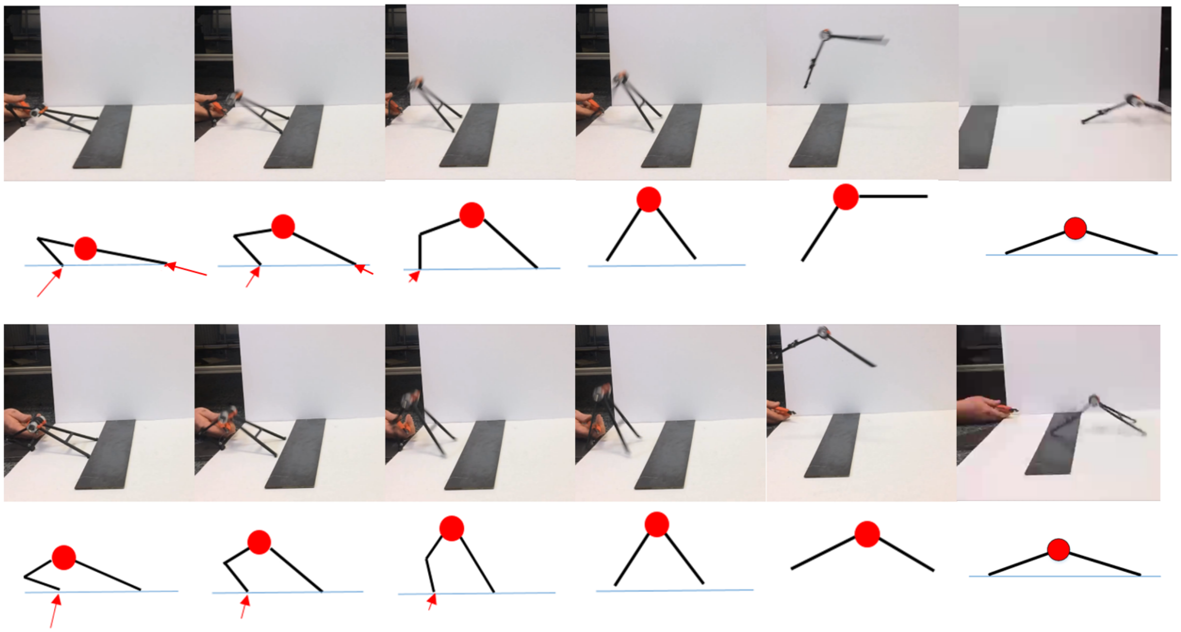

Fig. 9: Experimental validation with two different front leg angle (0°and 45°) that cause vaulting and aiming respectively. The cartoons below the pictures demonstrate the reaction forces on the feet. In vaulting, the spider start jumping by assisting from the front leg and when the reaction force becomes zero, the jump switch to the aiming jump. For the aiming jump it is shown that there is no reaction force on front leg at the beginning.

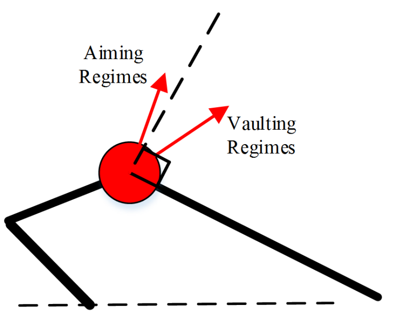

Fig. 10: Description of aiming and vaulting jump

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