# A High-Speed Launching Mechanism Inspired by a Slingshot Spider's Web

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## Abstract

Slingshot spiders use their conical webs to launch themselves at high speeds to catch prey. We built a launching mechanism inspired by the slingshot spider. Our launch mechanisms comprises a steel structure with eye bolts to hold a conical web made from latex rubber tubing. We pull the web by a winch using a lever arm. A quick-release mechanism connects the web to the winch using a tough-grid paracord. When we release the quick-return mechanism, the projectile material consisting of a steel ball achieved an acceleration of 5107 $m.s^{-2}$ or 521 times gravity, and a speed of 66.41 $m.s^{-1}$. The power per unit mass and energy per unit mass of our prototype was one tenth and one fifth that of the spider's web respectively. In particular, we found that web structure consisting multiple radial web elements reinforced with circumferential web elements provide enhanced stiffness; as a comparison our web had a stiffness of about 8 times that of traditional slingshot with a single radial web element. Our results suggest that adapting designs from nature can lead to potentially superior performance of man-made contraptions.

**Keywords:** Slingshot spider, Launching mechanisms, Catapult, Bioinspiration

# 1 Introduction

In the animal world, some species have developed remarkable responses either to capture their prey or evade predators. Some examples include, (1) the mantis shrimp has a saddle-shaped exoskeletal spring mechanism that it pulls and holds in place using muscles and is released to smash shells and impale fishes,[1] and (2) the web toed salamander and the golden wheel spider, both of which curl themselves into a circular shape and then roll downhill to escape predators.[2] The animals have inspired corresponding engineering imitations, the Ninjabot to mimic the Mantis Shrimp[3,4] and mobile manipulators based on the web-toed salamander and golden wheel spider.[5,6]

In this paper, our major interest is to recreate high speed launches inspired from biology. Broadly there are two distinct methods animals launch themselves at high speeds. One is to use appendages within the body, and two is to use external tools. Either of these solutions have more or less the same principle, an elastic element is wound up slowly and held in place using muscles. Then the muscles release the elastic element to generate large forces in a short amount of time.

In animals and humans, alike, the force-velocity relation in the muscles limits the maximum force and subsequently the maximum acceleration. The force-velocity relation suggests that one can achieve large forces at slow speeds or small forces at high speeds.[7] To overcome this, animals rely on elastic-like structures in their body (appendages) or external tools (e.g., spider's web). They use their muscles to apply large forces at slow speeds on the elastic element. This elastic element is held in place using a latch. Once the latch is let go, the elastic element takes over and launches the animal. However, it is important to note that the launch speeds still depend on the mass of the web; low mass and inertia favors a high launch speed for the same stretch in the elastic element.[8] One of the challenges is to scale the design to launch heavier and larger objects.

Most of the jumping robots rely on motor-spring-latch setup to overcome the force-velocity tradeoff of electric motors. A motor winds up a spring that is held in place by a latching mechanism. Once the latch is released, the robot jumps using the stored spring energy. Some examples, include the 24 gm, 5 cm Michigan State University (MSU) jumper that achieved a jump height of 27 times it own height,[9] a 49 g robot that can inspired by the click beetle that can jump 4 time body height using a torsional spring,[10] a 23 gm, 13 cm, locust-inspired robot that jumped 26 times its own height using a motor to wind-up a torsion-spring at the joints and held in-place using a tendon-like wire,[11] a 7 gm locust-inspired hopping robot that jumps 14 times its own height using a complex assembly of springs, cams, and lever,[12] a hopping robot based on a kangaroo that achieves hopping using elastic legs and an actuated tail,[13] a 5 cm, a 7 gm that can jump 27 times it height using four-bar linkage for legs and motors connected to a cam that load two torsional springs,[14] using free vibrations to hop vibration,[15] and hopping robots that use series or parallel springs for agile hopping.[16–18]

Pneumatic systems provide a high power to weight ratio. This has led to muscle-inspired pneumatics McKibben muscles. By stacking 6 pneumatic muscles, the robot Mowgli, inspired by the leg geometry of segmented animals like frogs, was able to jump 50% of its height.[19] The miniaturization of pneumatics is possible by 3D printing pneumatics actuators. One can achieve selective strengthening of high stressed parts by embedding metallic parts within 3D printed structures. The resulting 3D actuator was demonstrated in stand-alone jumping experiments and by embedding in a cartoon character of a hopping robot[20]

Miniature robots at the micro-scale that jump several times their height have been created using micro-electromechanical systems or MEMs actuators. For example, nanoporous silicon produces gas when ignited that achieved jumping to 11 times its height[21] and using a compliant elastomer structures in-plane with traditional silicon MEMs thermal actuator microrobotic platform reached a jumping height of 80 times its height.[22]

To avoid being limited by the force-velocity trade-off in electric motors, combustion-based launching robots have been created. Some examples include a jumping robot that uses combustion between butane and oxygen to generate high thrust,[23] and a mobile robot retrofitted with an actuator that generates high thrust using combustion between propane and nitrous oxide.[24]

An interesting idea for velocity amplification without using springs, motors, or combustion is to rely on collision of disparate masses. This is a physics demonstration and consists of stacking a small ball (e.g., a tennis ball) on top of a bigger ball (e.g., basketball) and letting them fall under gravity. There are two collisions, one between the big ball and the ground and subsequently between the big and small ball, the latter collision leads to the small ball bouncing much higher than its initial drop (see explanation in[25] Section 10.5, pp 546). One can achieve additional velocity amplification by stacking multiple balls with disparate masses.[26]

In contrast to these past works, the slingshot spider uses the energy stores in its web (an external tool) to generate a high-speed acceleration.[27] The spider weaves a conical web. Then pre-loads it using a tension-line. When it senses a prey, the spider releases the tension-line to fling itself and the web toward the prey. In doing so, it achieves a peak velocity of 4.16 $\mathrm{m.s}^{-1}$ and peak acceleration of 1163 $\mathrm{m.s}^{-2}$ or 120 times gravity. We demonstrate a launching mechanism inspired by the slingshot spider's web. The main novelty is that this is the first reported adaptation of the slingshot spider's web to design a launching system. We show that the web material, the web structure, and the catch and release mechanism are all central to achieving high speed/high acceleration launches. Our design achieved a launch speed of 66.41 $\mathrm{m.s}^{-1}$ and a peak acceleration of 5107 $\mathrm{m.s}^{-2}$ or 521 times gravity.

The paper is organized as follows. The Section 2 is the materials and methods section which discuss the bioinspired design including simulation, experimental setup, and data analysis. The Section 3 is on results and discussion, and finally the Section 4 is the conclusion.

# 2 Materials and Methods

## 2.1 Bioinspiration

Although the slingshot spiders build a conventional web, there is a distinct way in which they use their web to catch their prey. These spiders attach a tension line to the center of the web. Then they use their four rear legs to hold on to the web while using the four front legs to load the web by pulling onto the tension line as shown in Fig. 1. They hold onto the stretched tension line using their pedipalps, which are secondary appendages (to legs) that are part of their jaw. When the spiders sense a prey, they release the tension line, flinging both themselves and the web at speeds of around 4.2 $\mathrm{m.s^{-1}}$ and accelerations of 1163 $\mathrm{m.s^{-2}}$ or 120 times gravity.[27]

We hypothesized that the following aspects are key to the high speeds of the slingshot spider, (1) the conical structure of the web, (2) the high elasticity and high tensile strength of the web, (3) the mechanism to draw and hold the tension line, and (4) effective release of the tension line. Inspired by these key observations, we describe the construction and testing of our high-speed launching mechanism.

## 2.2 Bioinspired Design

Figure 2 shows the overall setup of the launch mechanism. The setup includes a steel support frame, a winch to load the projectile, a quick-release mechanism, and eye bolts to hold the web on the steel frame. We describe these next.

**Support structure:** The support structure needs to be strong enough to bear the forces generated during the projectile loading and release. We used steel plates as shown in Fig. 2 which were welded together. Then a grinder equipped with a sanding wheel was used to smooth out the welds. Finally, we painted the welded frame with a primer to apply a protective coating to prevent corrosion. We show the finished product in Fig. 2. It has a total length of 50.8 cm, a width of 20 cm, and a height of 17.4 cm.

**Geometric structure of the web:** In order to understand the role of the geometric structure of the web on the elastic storage capacity, we modeled four structures in finite element analysis software ANSYS as shown in Fig. 3. The strands of the web were modeled as silicon rubber with a density of 1120 kg.m$^{-3}$ and had a fixed diameter of 0.127 cm ($0.05''$). The four structures were: the traditional slingshot with a single radial cross wire shown in Fig. 3 (a), the simple web with multiple radial lines joined at a central loading place shown in Fig. 3 (b), the complex web with multiple radial lines connected with circumferential wires shown in Fig. 3 (c), and our prototype web with quadrilateral shaped web shown in Fig. 3 (d). Each of the designs had a hexagon support structure that was anchored to the ground using a fixed support boundary condition. We used the default meshing in ANSYS as it got acceptable results, but had to increase the mesh resolution for the complex web and our prototype web to produce acceptable stress results. All these structures were loaded with a force of 45 N at the central line.

The traditional slingshot had the most deformation; the simple web was next with a deformation of 0.33 that of the simple web; the the complex web was next with a deformation of 0.15 that of simple web; finally, the our prototype web had the least deformation of 0.13 that of the simple web. Consequently, if the traditional slingshot has a stiffness of $k$ then the stiffness of the simple web is $3k$, the complex web is $6.67k$, and our prototype is $7.7k$. Also, note that our prototype design uses less material than the complex web, and is marginally stiffer.

These numerical simulations suggest several things. (1) Adding more strands increases the stiffness, thus slingshot is least stiff compared to the web type structure. (2) Adding circumferential lines to existing radial lines doubles the stiffness. (3) Including small quadrilateral type structures as seen in our prototype increases the stiffness slightly compared to the complex web. These results suggest that slingshots designed from nature's solutions have larger force carrying capacity.

**High elasticity and high tensile strength of the web:** We used latex rubber tubing as the web material. Latex rubber tubing has a tensile strength of 24 MPa (3500 psi) and we can stretch it to 200 to 750 percent of its original length. It is easily available as tubing to be used in creating the web. Our web, which is based on Fig. 3 (d), is shown in Fig. 4. The size of the web is 16 cm × 16 cm, the inner and outer diameters of the tubing is 0.2 cm and 0.5 cm respectively. W e manually wrapped the latex rubber tubing on the eye bolts and used cable ties.

**Winch and quick-release mechanism:** We attached a pouch to the center line, which would hold the projectile element. We used an off-the-shelf slingshot release device which is shown in Fig. 2. The quick-release mechanism is used to hold the pouch using a spring-loaded trigger line that is manually locked into place. We then attached the quick-release mechanism to a winch using the tension line made out of tough-Grid paracord of diameter 0.48 cm (3/16″). The winch consists of a drum with a diameter of 10.8 and a hand crank with a length of 17.78, both of which give sufficient leverage to draw the tension line without substantial effort. We attached a string line to the trigger mechanism to enable it to be pulled while staying a safe distance from the launching mechanism.

**Projectile material and launch:** In order to have uniformity across trials, we used off-the-shelf projectile material consisting of quarter-inch steel ball, each weighing 90 gm. We manually release the quick-release mechanism using a string line.

## 2.3 Testing Setup and Data Analysis

Figure 5 shows the experimental setup. We placed the support structure on a cinder block to elevate its height. It has sufficient weight to resist the horizontal recoil motion of the web. However, to provide extra support, we used duct tape to secure the structure to the cinder block. We placed the launching mechanism against a visual field with a white background with black scale markings which were 0.305 m ($\sim 1''$) apart. At the end of this visual field, we put a target block consisting of a cardboard box with a plywood backing to absorb the projectile and to keep the vicinity safe. For each trial, we manually loaded the projectile, attached it to the quick return mechanism, and released it. By controlling the amount of windup, we could increase the amount of tension in the line. We placed a high-speed camera capable of shooting up to 1000 frames per second in the view of the projectile. We tried multiple trials with increasing tension. We report the runs with maximum tension to achieve the most speed and acceleration.

We analyze the video footage is using the video and motion analysis software Tracker.[28] In Tracker, we need to indicate an origin, the projectile location at every frame, the frame rate, and the length scale to convert the pixels into a distance measurement. The visual scale in view provides the distance calibration. The Tracker software can provide global coordinates of the projectile which we use for kinematic and dynamic analysis. Figure 6 shows 6 successive frames and projectile location processed by the Tracker software.

# 3 Results and Discussion

We manually loaded the mechanism by pulling the lever on the winch. We measured the displacement of the web from the resting position to the maximum loading position and it was $d = 0.432$ m. We used a weighing scale to measure the force in the web and it was

$F = 125$ N. The total energy stored in the web is

$$E = 0.5Fd, \tag{1}$$

and is 27 J. We found the energy per unit mass, $\hat{E}$, by dividing the energy with the mass of the web $\sim 0.04$ kg and is $\hat{E} = 0.675$ kJ.kg$^{-1}$.

Figure 6 shows six successive frames for one launch and a video is provided in the references [29]. The distance scale between the black markers in the background is 0.305 m ($\sim 1''$). The Tracker software[28] is used to mark the projectile position at different frames. The red filled dot shows the projectile location at the current frame. The red unfilled diamond shows the projectile location at the previous frames. Tracker software uses the frame rate, the distance scale, and converts the pixel information into projectile coordinates. Since the launch is almost horizontal and since there is no acceleration or deceleration in the horizontal direction, we can compute the projectile velocity at release using the distance between projectile position in successive frames, $d_{\text{frame}}$, and time interval $t_{\text{frame}}$. Thus

$$v_{\text{release}} = \frac{d_{\text{frame}}}{t_{\text{frame}}} \tag{2}$$

We used a camera with a frame rate of 500. Thus, $t_{\text{frame}} = 2$ ms. We used multiple frames to find the velocity and then average the value. We computed $v_{\text{release}} = 66.41 \pm 2.5$ m.s$^{-1}$.

We compute the acceleration just before release assuming that it is constant throughout the time it travels along the slingshot

$$a_{\text{web}} = \frac{v_{\text{release}}^2}{2d} \tag{3}$$

which was found to be 5107 m.s$^{-2}$ or 521 times gravitational acceleration.

We can also find the time between opening of the quick-release mechanism and launch of the projectile as

$$t_{\text{web}} = \frac{v_{\text{release}}}{a_{\text{web}}} \tag{4}$$

which is found to be 13 ms.

Finally, we compute the power per unit mass $\hat{P} = \frac{\hat{E}}{t_{\text{web}}}$ where $\hat{P}$ and $\hat{E}$ are power and energy per unit mass. The power per unit mass was found to be $\hat{P} = 51.9$ kW.kg$^{-1}$.

All these results are summarized in Tab. 1 and compared with slingshot spider metrics. Comparing, our design has energy per unit mass 0.675 $\sim$ 1/6th and the power per unit mass is 1/10 th of the slingshot spider's web. Thus, when scaled to the spider's size, the energy and power density are modest. Fig. 7 compares the energy per unit mass and power per unit mass of our design against the slingshot spider, and other biological and synthetic materials.

As seen earlier, our results when scaled to the slingshot spider's mass are quite modest. The two most significant drawbacks in our slingshot are to do with the material and the structure of the web. First, the spider's web is known to have high strength, excellent elasticity, and toughness which is incomparable to other synthetic fibers including the latex rubber tubing used here; it is five times stronger than steel and two times more flexible than nylon per unit weight.[30] Second, the spider can weave a net with numerous radial and tangential lines which increases the elasticity and strength by several orders of magnitude.[31] However, in our case, the relatively large diameter of the latex rubber tubing prevents us from increasing the number of radial and tangential lines for a given cross-sectional area for the web. Though increasing the cross-sectional area is possible, adding more latex tubing would increase the mass of the web, reducing the benefits of higher elasticity.

The launching mechanism has application in creating better slingshots. For instance, we have shown the superiority of having the conical web with radial and tangential lines over the traditional slingshot with a single line in the amount of energy stored for a pre-load (see Fig. 3). Another application of high-speed launching mechanism is for launching small aerial vehicles, especially fixed-wing aircraft.[32]

The force-velocity profile of actuators enables high speed at low torques or vice versa.[7] This is the main deterrent in the realization of high-speed movements using muscles and motors. This is overcome by using spring-like mechanisms. The spring-like mechanisms are loaded using large forces at slow speeds, then stored in a latch mechanism, and finally released. However, this reasoning works only when the springs are light. Once the springs become heavy, they have high mass and inertia and thus limit the amount of velocity achievable using spring-like mechanisms. Thus, it is quite challenging to scale the device to launch heavier objects such as full-size airplanes on ships. These launches generally use pneumatic or hydraulic systems.[33]

One of the major limitations of this work is that our system cannot achieve comparable acceleration to the slingshot spider when scaled for mass because of the relatively poor strength and elasticity of man-made material compared to the spider's web. Another limitation is that after the release of the tension line, our system needs to be manually re-set. This is in contrast to the slingshot spider that only releases a part of the tension line and then pulls on this line to reset the trap.

## 4 Conclusion

We have created a high-speed launching mechanism inspired by the slingshot spider. We wrapped a highly elastic and strong latex rubber tubing, manually, to eye bolts on a steel support structure to resemble the conical structure of the spider's web. We used a winch with a drum and a lever arm to pull a trigger line made of Tough-Grid paracord resembling the dragline of the spider. We held the trigger line in place using an off-the-shelf quick-release mechanism copying the anchoring provided by the legs of the spider. When the trigger mechanism was let go, the projectile material consisting of a quarter-inch steel ball achieved an acceleration of 5107 m.s$^{-2}$ or 521 times gravity and speed of 66.41 m.s$^{-1}$. When these numbers are appropriately scaled and compared with the spider, we have modest energy per unit mass and power per unit mass, but substantially better than the traditional slingshot. Our conclusion is that the high-speed launching mechanism inspired by the slingshot spider's web is promising, but web materials with significantly higher elasticity and higher tensile strength per unit mass are required to further improve their performance.

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# Declarations

## Conflict of interest

The authors declare that they have no conflict of interest.

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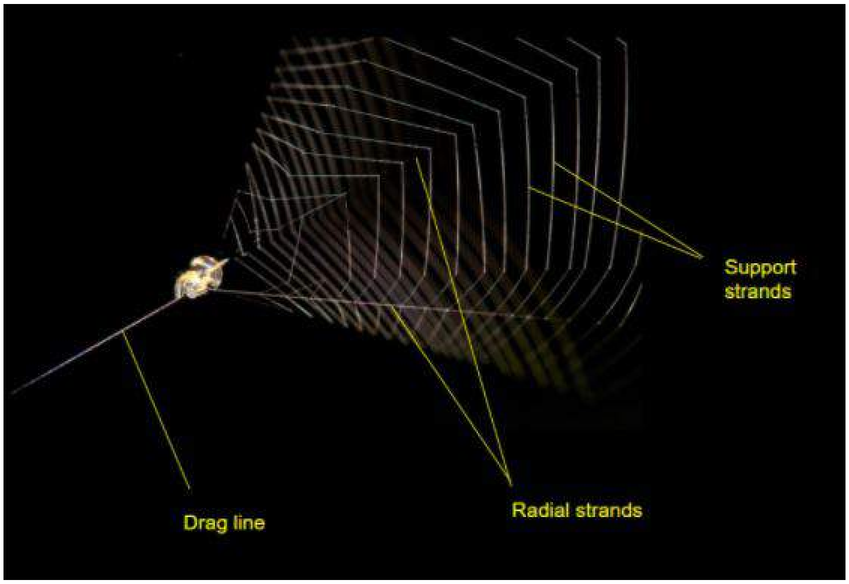

Figure 1: A slingshot spider ready to strike having loaded its conical web[27]

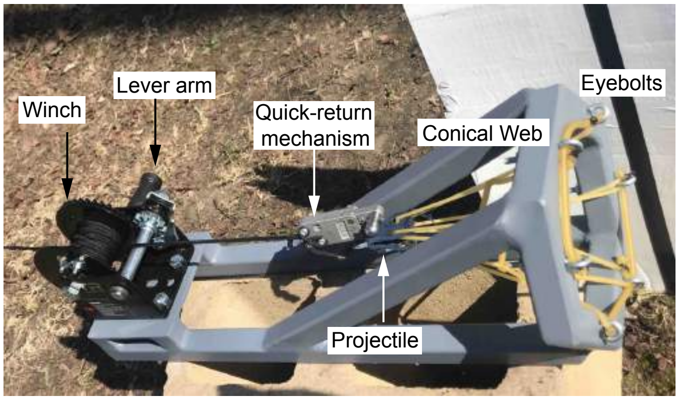

Figure 2: Launching mechanism inspired from the slingshot spider

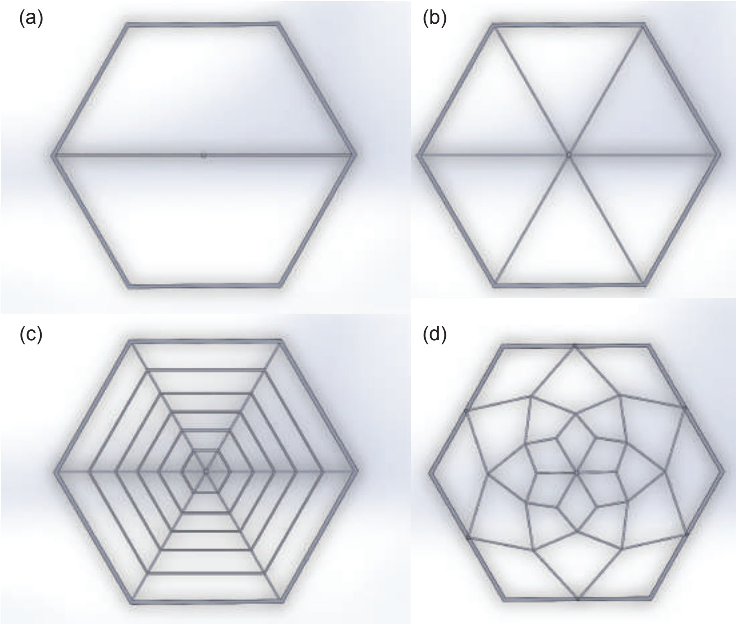

Figure 3: Different web designs: (a) slingshot, (b) simple web, (c) complex web (similar to spiders web), (d) prototype web (our design).

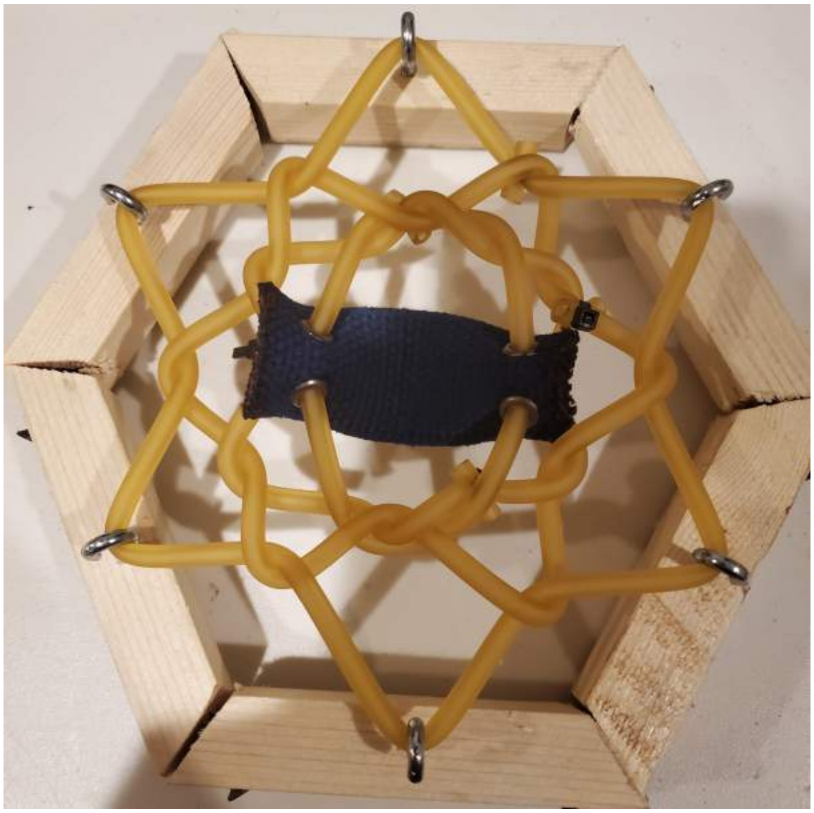

Figure 4: Prototype web is made up of latex rubber tubing and is manually attached to the setup.

Figure 5: Experimental setup

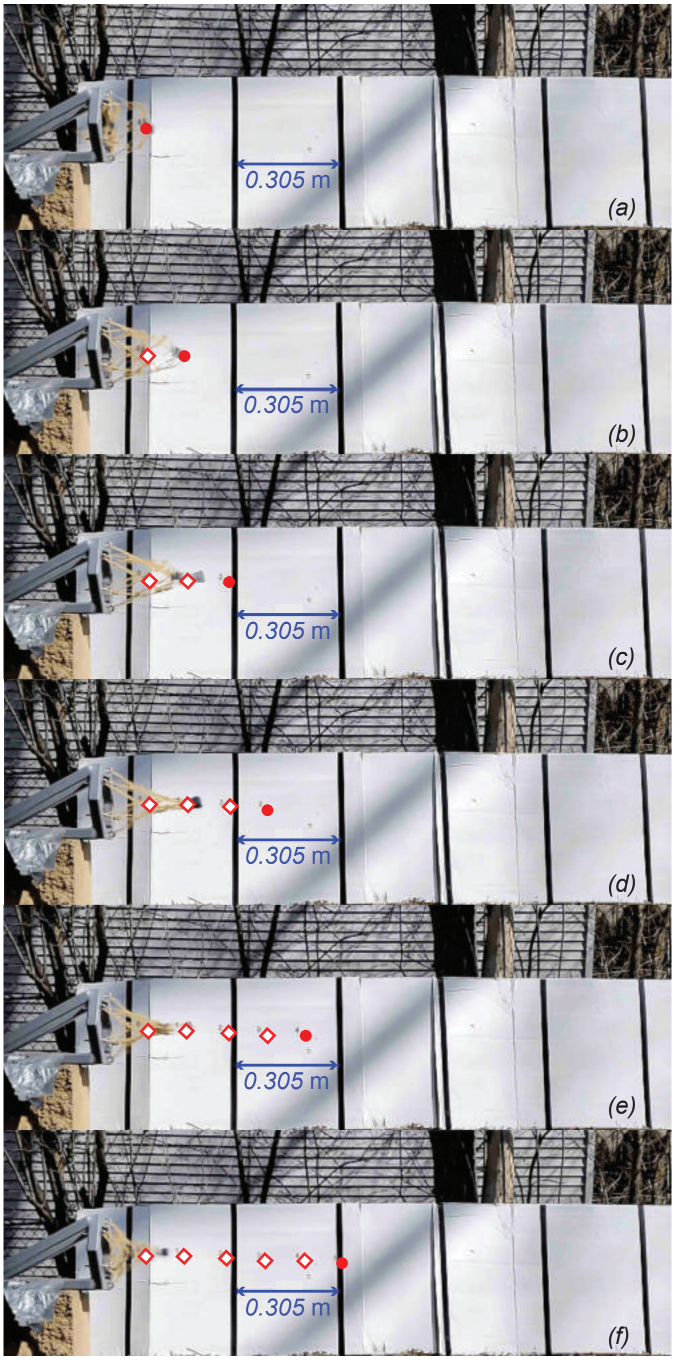

Figure 6: Six successive frames during testing of the slingshot. The red dot indicates current location of the projectile and the white diamond with red outline indicates past locations of the projectile.

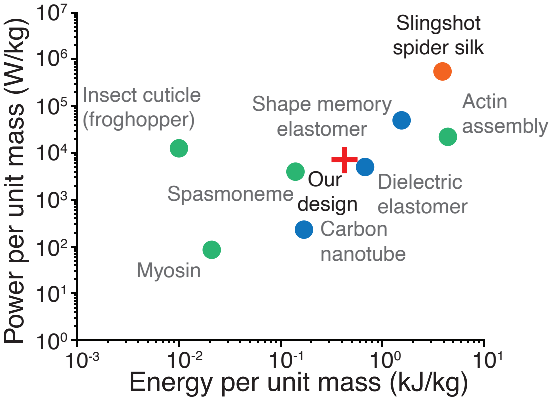

Figure 7: Comparing the power per unit weight (W.kg$^{-1}$) and energy per unit weight (kJ.kg$^{-1}$) of slingshot spiders web (orange dot) with biological materials (blue dots), synthetic materials (green dots), and our design (red cross). Figure taken and redrawn from.[27]

| | Slingshot spider | Our design |
|---|---|---|
| Displacement (m) | 0.0268 | 0.432 |
| Velocity ($m.s^{-1}$) | 4.16 | 66.41 |
| Acceleration ($m.s^{-2}$) | 1163 | 5107 |
| Acceleration in gs ($m.s^{-2}$) | $130g$ | $521g$ |
| Energy / mass ($kJ.kg^{-1}$) | 3.92 | 0.675 |
| Power / mass ($kW.kg^{-1}$) | 550 | 51.9 |

Table 1: Comparing our design with slingshot spider data[27]