How spiders hunt heavy prey: the tangle web as a pulley and spider's lifting mechanics observed and quantified in the laboratory

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Abstract

The spiders of the Theridiidae's family display a peculiar behaviour when they hunt extremely large prey. They lift the quarry, making it unable to escape, by attaching pre-tensioned silk threads to it. In this work, we analysed for the first time in the laboratory the lifting hunting mechanism and, in order to quantify the phenomenon, we applied the lifting mechanics theory. The comparison between the experiments and the theory suggests that, during the process, spider does not stretch the silk too much by keeping it in the linear elastic regime. We thus report here further evidence for the strong role of silk in spiders' evolution, especially how spiders can stretch and use it as an external tool to overcome their muscles' limits and capture prey with large mass.

Introduction

Spiders exhibit a large variety of behaviours(1) and, in this context, the ability to use silks has evolved over almost 400 million years to fulfil various functions(2) such as building webs(3) or cocoons(4), for courtship or ballooning(5). For these reasons most spider silks have high tensile strength, extensibility and toughness(6,7), as well as a strong stiffening at high deformations, which has recently been observed by Brillouin light scattering experiments(8,9). Among all the functions that are achieved through silk, the prey capture with webs has always intrigued scientists. As an example, the efficiency of orb webs in stopping flying prey requires high mechanical performances of the webs, which both absorb kinetic energy(10) and minimize the damage after impacts(9). Interestingly, spider silks and webs can also act as external power amplifiers because of the elastic energy stored in the material and the structure. For example, the spider *Hyptiotes cavatus* stretches its web by tightening an anchor line over multiple cycles of limb motion, and then releases its hold on the anchor line when an insect strikes the web, which rapidly tangles it(11). This is a quite rare feature in animals that commonly store the elastic energy in the organisms' own anatomical

structures(12–18). Another example of external power amplification could be given by the fascinating hunting behaviours of theridiid spiders(Figure 1a). These spiders use the particular structure of the cobweb, which has gumfoot threads that run from the substrate to the main frame (19). These threads are easily detached from the substrate when disturbed by walking prey and thus release the elastic energy stored in the main frame of the web(20). Consequently, if the prey is small (e.g. ant(21)), the gumfoot threads yank it upwards. In this way, small animals become suspended helplessly in the air. With the increase of the prey dimension, it may happen that more than one single gumfoot thread is involved in the suspension. More commonly, bigger sized preys are not completely lifted by a single thread, and theridiid spiders usually rush down and immobilize such prey using aciniform (wrapping) silk. In both these cases (likely the majority of hunt events in nature) spiders carry the prey back to the retreat on their spinnerets, as seen in practically all web spiders. On the other hand, if the prey is extremely large compared to the spiders (Figure 1b), it poses to it extreme conditions (with a large nutritional reward), and a different hunting behaviour, involving the investigated lifting mechanism, is displayed.

Once the large walking prey is attached to a capture sticky thread(22,23) of the 3-dimensional cob web (Figure 1c), the spider lifts it through sequential addition of pre-stretched silk threads produced by major ampullate gland(24) (Figure 1d-f). Between the addition of two threads, the aciniform silk as well as the venom is also used to further immobilize the prey. Again, the lifting prevents prey from escaping their web since it can no longer hold on to the underlying surface. Several records show that small reptiles and mammals are occasionally captured in this way (25,26). The first records published were the cases of a snake (about 55 gr) and a mouse that were not able to move and escape because they were lifted off the ground(27). Interestingly, during prey capture those spiders were continuously moving upward and downward with respect to the prey. This one was gradually lifted to a certain height (more than 10 cm). A subsequent more accurate description revealed that the spider attached to the animal silk threads and their length gradually decreased while the mouse was lifted(24). Mc Keown(28) associated this mechanism to the one used by other spiders (such as *Cyrtophora sp.*, *Olios sp.*, and *Phonognatha sp.*) to lift inanimate objects, e. g. leaves or empty shells that are typically used as a temporary den(29–32). Decary(33) observed that this lifting mechanism allows spiders of the genus *Olios sp.*(34) to lift snail shells that are more than 35 times the mass of the animal. As in theridiid spiders, *Olios coenobita* attaches silk threads, gradually shorter in length, to the object to apply a sum of tensions used to counteract gravity. Fage(34) suggested that the lifting of small stones in orb webs was due to the elastic silk threads, and not

done by the muscle power of the spider. The spider lifting (and dragging) mechanics was theoretically described by Pugno(35) who also showed how the natural (e.g. nonlinear) behaviour of the spider silk improves the efficiency of the lifting.

In this work, we studied experimentally for the first time the lifting mechanics used to hunt extremely large prey displayed by spiders of the family Theridiidae. To explain the phenomenon, we compared the experiments with the predictions of the theoretical model (here adapted)(35). The results are another strong example of the efficiency of the spiders in using silk and their web as external tools (i.e. like a pulley) that make them able to perform actions that would be impossible simply by using their muscles. Moreover, with the support of the mechanical model, we find that spiders apparently do not overstretch the silk threads used in the hunt. The lifting mechanism is, thus, another good example of the central role of silk in spider's evolution.

Material and Methods

The mechanical model

In order to rationalize the lifting observations, we apply the lifting mechanics theory developed by Pugno(35) (for the equations we refer to Figure 2).

At each step, the spider adds a thread, with a cross section area A, and the prey moves (if it does) till an equilibrium position. The vertical equilibrium is achieved through the sum of the vertical components of the threads' tensions that balance the weight of the prey. The horizontal equilibrium is achieved through the sum of the horizontal's components of the threads' tensions. For the sake of simplicity, we neglect the (nearly) horizontal threads only responsible for the horizontal equilibrium, which is here considered satisfied by definition.

The lifting of the prey did not occur immediately after the insertion of the first thread. In fact, only after a given number (N_l) of attached threads the prey started to be lifted. Then the count of the lifting's steps (j) started: only these N_l were considered in the vertical equilibrium of the suspended body prey. We named the weight of the prey W, the thread number with the index i and the lifting's step with the index j.

As suggested in Pugno(35) we considered two lifting strategies: all the inserted threads had the same unstretched length l_{i0} (first strategy, $l_{i0}=l_0$) or after the insertion of the l_{ij} all threads changed tension in order to reach the same level of strain ε_j (second strategy). Since spider silk presents an initial linear elastic regime and a subsequent nonlinear elastic regime (Figure S1), we considered the

situation of small deformations (linear regime) and large deformations (nonlinear regime). For the former we used the following constitutive law

$$\sigma = E\varepsilon$$

where E is the Young's modulus of the silk and ε its deformation. We used the following relation between ε and the initially inserted (l_{ij}) and undeformed (l_{i0}) lengths of the threads

$$\varepsilon_{ij} = \frac{l_{ij}}{l_{i0}} - 1$$

The nonlinear geometrical and constitutive regime were described by the following nonlinear constitutive law(35)

$$\sigma_{ij} = \frac{\sigma_u}{\varepsilon_u^{\alpha}} \ln^{\alpha}\left(\frac{l_{ij}}{l_{i0}}\right)$$

where σ_u is the ultimate strength of the silk, ε_u is the ultimate strain and α describes the power of the constitutive law: $\alpha = 1$ linear elasticity (in the limit of small strains), $\alpha > 1$ stiffening behaviour (commonly observed in natural material such as silk), $0 \leq \alpha < 1$ softening (usually observed in engineering materials).

The purpose of the lifting hunt mechanism is to avoid the prey escaping thanks to the lifting. For this reason, what matters the most is the vertical component of the motion of the prey.

<u>Linear regime I strategy</u>

Following Figure 2 we wrote the vertical force equilibrium between the weight of the prey and the overall vertical component of the tension generated by the threads for each lifting's step (see supplementary information). Then, following ref(35), we worked out the height of the prey at step n as a function of the measured thread angles (θ_{in}, see figure 2a)

$$H_n = y_0 - y_n = y_0 - \frac{l_0}{E(N_I + n)}\left(\frac{W}{A} + E\sum_{i=1}^{N_I}\cos\theta_{in} + E\sum_{i=1}^{n}\cos\theta_{in}\right) \quad (1)$$

<u>Linear regime II strategy</u>

In this case, the length l_0 was not known but the overall strain of all the threads at each step j was known (ε_j). Again, we analysed step by step (see supplementary information) and thus obtained the height of the prey at step n as

$$H_n = y_0 - \frac{1}{E(1+\varepsilon_n)}\left(\frac{W}{A} + E\left(\sum_{i=1}^{N_I}\cos\theta_{in} + \sum_{i=1}^{n}\cos\theta_{in}\right)\right)\left(\sum_{i=1}^{N_I}\frac{1}{l_{in}} + \sum_{i=1}^{n}\frac{1}{l_{in}}\right)^{-1} \quad (2)$$

Nonlinear regime II strategy

For the sake of simplicity, we did not consider the I strategy for the nonlinear regimes.

Following the previous logic and the process step by step (see supplementary information) we computed the height at step *n*

$$H_n = y_0 - \frac{W}{A}\frac{\varepsilon_u^{\alpha}}{\sigma_u}\frac{1}{\ln^{\alpha}(1+\varepsilon_n)}\left(\sum_{i=1}^{N_I}\frac{1}{l_{in}} + \sum_{i=1}^{n}\frac{1}{l_{in}}\right)^{-1} \quad (3)$$

Process' efficiency

An efficiency was associated to the lifting process. In particular, we used a lifting velocity (final height divided by the lifting time), a step efficiency $\eta = \frac{1}{n+N_I}$ (4), and a gravitational efficiency (energetic efficiency) defined by Pugno(35) as following

$$\eta' = \frac{WH}{N_I wH + w\sum_{i=1}^{j} y_i} \quad (5)$$

where *w* was the weight of the spider and *H* was the final height. The lifting velocity was calculated as

$$v = \frac{H}{t} \quad (6)$$

where *t* was the time of the whole process.

Fit the model

To fit the model, we used experimental values and we inserted them in the equations (1-3) by means of some assumptions. The parameters inserted in the equations (1), (2) and (3) (i.e. $E, \sigma_u, \epsilon_u, , \alpha$ and A) were estimated through the measure of the mechanical properties of the supporting threads (lifting threads produced by major ampullate gland). The lengths and the angles of the threads were measured by means of the recorded videos. For the parameter *α*, we extrapolated it by fitting the nonlinear regions of the stress strain curves (Figure S1). Since it was impossible to measure l_{i0}, we calculated it using

$$\varepsilon = \frac{l_{ij}}{l_{i0}} - 1$$

where for *ε* we assigned two constant characteristic plausible values: one characteristic of the linear elastic regime and the other of the nonlinear one, respectively 0.05 and 0.25. By fitting the model, we were able to see which kind of constitutive law regime was more representative for the silk during the lifting and possibly which strategy was preferred.

Spiders, their cages and prey

The spiders under study belonged to the family of Theridiidae. We used five animals: one *Steatoda paykulliana* and four *Steatoda triangulosa*. All of these animals were kept in plastic boxes covered with black paper inside at room temperature (20-23 °C and 30-39% RH) (Figure 2b,c). This was done to highlight the contrast between the silk of the webs and the surrounding and thus facilitate the measurements of the thread lengths and geometry. The selected prey was *Blaptica dubia*, a cockroach from Central and South America. This was selected since its strength and weight (higher with respect to the spider). In this context, the lifting of this animal represents a challenge for the spiders under study. Each animal was weighted before the test with a high-resolution scale.

Silk Mechanical properties

From the cobwebs, we cut the trapping thread above the region covered with glue droplets. Then, we glued (with a double side tape) the silk samples on a paper frame provided with a square open window of 1 cm side. For tensile tests, we used a nanotensile machine (Agilent technologies T150 UTM) with a cell load of 500 mN. The applied strain rate was 1%/s. We computed the engineering stress dividing the measured force by the cross-sectional area of each tested thread. The diameter of the fibres was measured with the support of a light microscope(36), and the cross sectional area of the thread (which can be composed of more fibres) was calculated using the sum of the fibres cross sectional area. We present the data with the mean value and standard deviation. For *Steatoda paykulliana* we measured ten samples of silk. For *Steatoda triangulosa* 32 (8 for each animal).

Scanning Electron Microscopy

A FE-SEM (Zeiss-40 Supra) was used to investigate the morphology of the web's junctions and threads. We used a Zeiss – 40 Supra. The metallization was made by using a sputtering machine Quorum Q150T and the sputtering mode was Pt/Pd 80:20 for 5 minutes.

Measure of the thread length

The lifting predation was recorded with a high-resolution Sony Camera. In order to estimate the silk thread length and the height of the prey, we stopped the video when the spider attached the thread to the prey and measured the length and the angles through the support of ImageJ software analysis(37) (Figure 2b-c). Each parameter was measured 5 times and its mean value and standard

deviation computed; then we used the average for the fit. All the threads lengths and angles as well as their uncertainties are reported in Supplementary data sheet. Among all the attempts in filming the lifting mechanism, we selected the best five videos (see supporting videos), where these were the only ones that allowed us to perform the previous mentioned quantitative analysis.

At each step, in this way, we had the static situation in an equilibrium point (measures of the threads' lengths, their inclination, and anchorages' threads heights) that was used to fit the theoretical model.

Results

Structure of the webs

The structure of the 3d cob web was complex as depicted in Figure 3a. However, some of the web's components could easily be identified. With the supporting threads (Figure 3b), the spider produced the main structure of the web (upper part) and it protected the den by creating a shell of these threads in the frontal part of the web(19,38,39). In order to join two or more of these threads, piriform and aggregate silks were used (Figure 3f) to create strong junctions(22,40). Moreover, the spiders of the family Theridiidae used aggregate silk to cover capture threads with glue(41). The threads were fixed to the surfaces by means of attachment discs produced by the piriform silk (Figure 3d-e)(42,43). In all cases the spiders under analysis built the webs with the capture threads near the bottom of the enclosure.

Mechanical properties of the silk

Figure S2 and Table 1 show the mechanical properties of the major ampullate silk (extracted from supporting threads) of the spiders that were studied. The typologies of fibres are two: one for the species *S. paykulliana* and one for *S. triangulosa*. We chose this type of silk because is supposed to be used during the lifting(35). The silks that were analysed presented remarkable mechanical properties, comparable with the ones reported in literature(44). The species of analysed spiders were *Steatoda triangulosa* and *Steatoda paykulliana*. Respectively, the measured strengths were 205 ± 106 MPa and 409 ± 356 MPa. The strain at break was respectively 0.42 ± 0.13 and 0.26 ± 0.15. The Young's modulus was respectively 1.7 ± 1.5 GPa and 3.9 ± 3.3 GPa. The toughness modulus was respectively 50 ± 39 MJ/m^3 and 49 ± 41 MJ/m^3. The α parameter was respectively 1.5 ± 0.5 and 1.2 ± 0.2. By considering the aim of our analysis, we were interested in the ultimate stress (σ_u, i.e. strength) and ultimate strain (ε_u) that were inserted in the equations (1-3). Thus, we used the

obtained mean values of these parameters for the application of the theoretical model to our experimental setup. In particular, for *Steatoda triangulosa* $\varepsilon_u = 0.42$ and $\sigma_u = 205\ \mathrm{MPa}$ were used, whereas for *Steatoda paykulliana* $\varepsilon_u = 0.26$ and $\sigma_u = 409\ \mathrm{MPa}$ were used. Moreover, the cross-sectional area *A* was computed by summing the cross-sectional area of the fibres that composed the thread (usually 2-3), which were computed using the mean value of the fibres diameters (Table 1). Furthermore, in the equations the parameter $\varepsilon_n = \varepsilon = const$ is present, which defines the strain of the inserted thread. Up to the model that we considered, i.e. large or small deformations, the values associated to this parameter were different. In particular, for *Steatoda paykulliana* we used $\varepsilon = 0.15$ and $\varepsilon = 0.05$ respectively; and for *Steatoda triangulosa* we used $\varepsilon = 0.25$ and $\varepsilon = 0.05$ respectively. These parameters were chosen on the base of the related stress strain curves as representative of large or small deformations. In this regard, for large deformation we considered the middle part of the second stiffening phase as the level of strain of the inserted fibre. For small deformation, on the other hand, we chose the mean value of the yielding point.

The lifting

During the predation, the spiders displayed different behaviours, which can be due to the fact that the prey were alive and this affected the observation.

In all the five selected videos (see supporting videos) when the spiders reached the prey, they started to wrap it with aciniform silk(45). Moreover, when the prey reached the main frame of the tangle web, the lifting was strongly affected by the presence of numerous obstacles, i.e. frame threads. In this context we observed that the spiders somehow removed these obstacles. For the fourth sample the prey climbed for few centimetres the wall of the cage. The lifting occurred when it fell down and the spider started to wrap it.

For calculating the distance between the anchorage and the prey (namely y_j) we measured the length of the inserted thread and the (cosine of the) angle between the thread and the vertical axes (Figure 2). All the lengths and angles values as well as their uncertainties are reported in Supplementary data sheets. The height *H* of the prey is the distance between the cockroach and the ground level. These measurements were performed for each set of threads for all taken videos.

In all the cases the lifting did not occur immediately after the insertion of the first thread. On the other hand, they started after N_l threads, which are listed in Table S1. During the predation behaviours, as depicted in Figure S3, the inserted fibres were all different in term of lengths for all the spiders and no apparently regularity was observed (for the values and the uncertainties see

supplementary data sheet). In this regard, Table S1 shows the number of threads used to lift the prey ($n+N_l$, which was considered in the theoretical model), their mean length and the final height reached by the prey. For the cases under study, i.e. *Steatoda triangulosa* I, *Steatoda triangulosa* II, *Steatoda triangulosa* III, *Steatoda triangulosa* IV, and *Steatoda paykulliana* we observed respectively $n+N_l$ equal to 29 (N_l=5), 73 (N_l=13), 47 (N_l=11), 34 (N_l=3), and 17 (N_l=13). Respectively, the masses of the spider (and relaetd prey) were 0.14 ± 0.01 g (0.31 ± 0.01 g), 0.04 ± 0.01 g (0.34 ± 0.01 g), 0.02 ± 0.01 g (0.34 ± 0.01 g), 0.01 ± 0.01 g (0.50 ± 0.01 g), and 0.22 ± 0.01 g (0.36 ± 0.01 g). Furthermore, it is interesting to notice the final height of the lifted prey. Comparing it with respect to the height profile of the tangle web main structure (Figure S4) it is possible to notice that the final height was quite close to the height profile of the main structure, but not higher. In particular, the final heights that we detected were respectively 5.70 ± 2.39 cm, 4.30 ± 2.07 cm, 3.00 ± 1.73 cm, 5.40 ± 2.30 cm, 0.80 ± 0.35 cm (Table S1). The reason of this could be the dense net of silk fibres in the main frame of cob webs, which obstructed the lifting.

During lifting, spiders used different anchorages where they secured the threads. Equations (1), (2), and (3) require that the value of the anchorages' height is constant. In Figure S5 the measured height of the anchorages and the height of the prey are depicted and it is possible to see that the height of the anchorages did not change considerably during the process.

The predation was considered finished when the spiders stopped its lifting activity.

The mechanics of lifting: theory compared to experiments

To compare the experimental and theoretical results we neglected, for the sake of simplicity, the viscoelastic relaxation of the silk for. This could be considered a reasonable ansatz since the low timing of the lifting, i.e. ~10 minutes.

We have analysed the lifting mechanics firstly by considering the real efficiency described in equation (4) with the gravitational efficiency described in equation (5). Moreover, the mean lifting velocity has been associated to every lifting experiment (equation (6)). Table 2 shows the values of these parameters and also the mass of the spiders and the cockroaches that were lifted.

In particular, the spider that shown the highest absolute efficiency $\eta$was the *Steatoda paykulliana* (0.06). On the other hand, *Steatoda triangulosa* presented comparable values (namely 0.04, 0.02, 0.03, 0.03). In term of gravitational efficiency, the obtained values were more inhomogeneous, and respectively we obtained 0.11, 0.06, 0.08, 0.32, and 0.08. The fourth spider had the highest gravitational efficiency because it was the spider that lifted, relatively speaking, the heaviest prey.

In particular, the weight of the quarry was 50 times the spiders. The slowest lifting process (lifting velocity, i.e. equation (6)) was the one of *Steatoda paykulliana* (the lowest final height was observed for this spider). Respectively, the obtained velocities were 0.0046 cm/s, 0.0021 cm/s, 0.0039 cm/s, 0.0117 cm/s, and 0.0007 cm/s.

To compare the theoretical model with the experimental data we used equations (1), (2) and (3). We firstly measured the mechanical properties of the spider silks involved. Then, at the end of each step (equilibrium state), we measured the threads length, their inclination and the height of the prey. The obtained data were inserted in the previous mentioned equations that were compared to the actual lifting experiments. The comparison among the theoretical models (i.e. linear regimes I and II, and nonlinear regime II) and the experimental data is depicted in Figure 4 and Figure S6. The difference between the two strategies in the linear regimes was small and no major differences occurred. A discrepancy between the predicted linear models and the experimental values was noticed at high step's number. This discrepancy (as well as the decrease in height) is due to the fact that in the theoretical model the experimental thread lengths and angles values were inserted. These are affected by uncertainties (see supplementary data sheet) and thus our comparison is not a best fit.

As highlighted in Pugno(35), the nonlinear regime improves the efficiency of the lifting especially in the first lifting's steps. With the exception of the last case (*Steatoda paykulliana*), we noticed that the assumption of the linear regime of the silk fitted better the experimental results. This means that *Steatoda triangulosa* did not stretch the silk's threads till large deformations and only the assumption of the linear regime was self-consistent with the experimental observations. It is possible that this occurs because silk threads deformed and kept in the linear elastic regimes are better in bearing loads cycles, with a small hysteresis(46–49). This is beneficial for hunting mechanisms that involved extremely large prey that usually do not die immediately and, thus, fight for their lives.

Discussion and Conclusion

Some spiders lift objects, to build den(29,31,32,34), and animals to feed(20,21,25). Theridiid spiders (Figure 1a) are able to catch prey much larger and stronger than them (e.g. small lizards, small mammals or big insects) by lifting them and, thus, making them immobilized since unable to hold on to the underlying surface(24,25) (Figure 1b). Whilst this mechanism is not used for small (medium) sized prey, which are lifted by using only the gumfoot threads and the elastic energy

stored in it and in the related part of the cobweb(20,21,42), it represents an interesting example of how spiders are able to outperform their muscles limits. Nevertheless, in the case of extremely large prey, the elastic energy stored in the cobweb and the gumfoot threads may be not sufficient for the lifting and thus a multiple step lifting mechanisms is adopted.

In this work, we observed and quantified in the laboratory the lifting mechanism in its extreme condition, which was observed before only in situ and for inanimate objects(27). The process requires the use of silk with good mechanical performances(6,7) (Table 1) and the support of a robust 3D cobweb(20) (Figure 3). In fact, by attaching pre-tensioned silk threads (probably produced by major ampullate gland), the spider is able to apply a sum of tension that wins the prey's weight (Figure 1c-f). The lifting is not abrupt and it requires many steps, forcing the spider to continuously going upward and downward the web. Also, the aciniform silk(45) as well as the venom are used to further immobilize the quarry during the process. This ended when the prey was close to the main frame of the tangle web, where the den of the spider lies but the dense silk fibres' network obstructs the movements of the quarry. This could be a reason why in the case of *Steatoda paykulliana* less steps and lower final heights were observed, since the main structure of its cobweb was particularly low (Figure S4). Moreover, since also part of the cob web (and not only the threads that are directly involved in the lifting) is indirectly involved in the hunt by releasing the related stored elastic energy(20), we do not exclude that a denser and larger mesh would improve the lifting mechanism. A comparison between the experimental results and the theoretical model of spider lifting mechanics(35) was performed under two main different hypotheses, i.e. small linear or large nonlinear deformations, suggesting that in our experiments the threads are working in linear regime.

In the lifting of objects (such as shells or leaves or living preys), spiders may achieve higher lifting efficiency because of the nonlinear constitutive law of silk (i.e. large deformations)(35). However, in our work with living prey, we observed that the linear strategy seems to be more compatible with the observations especially for *Steatoda triangulosa* (Figure 4). Thus, the silk used during the lifting by these spiders is probably kept in the linear elastic regimes (i.e. small deformations) (Figure S1). In this way, the threads are able to recover and restore better the original mechanical properties during loads cycles (due to the prey movement and lifting)(46,50). Interestingly, this seems in countertrend with respect to the passive hunting mechanisms of the orb webs(10), in which nonlinear behaviours are beneficial for both absorbing the kinetic energy of the prey and for reducing the damage in the web after the impacts(9).

Thus, it seems that Theridiid spiders are able to use the web and their silk as an external tool to hunt, which can be tuned by the arachnid. In this context, the use of silk as an external tool to store elastic energy is not limited to Theridiid spiders. *Hyptiotes cavatus*, for example, uses its web as a power amplification to capture flying prey, which offers many advantages over the muscles limitations(11).

Although the experimental results are affected by large uncertainties as well as the theoretical model compare simple strategies, we provide the first quantitative observation of this spider lifting mechanisms for hunting living large preys. In conclusion, the spider lifting is emerging as another key mechanism of the spiders that use naturally pre-stretched silk as an external tool (here like a pulley) to perform actions that are impossible only with their muscles. Thus, also for lifting, the silk threads seem to have a central role in spider's life and evolution.

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Author Contributions

G.G. performed the experiments, acquired the data and wrote the first draft of the paper. N.M.P. suggested the idea, supervised the work, helped in the data's analysis and in the writing of the manuscript. All authors viewed and approved the final manuscript and had the opportunity to comment on earlier drafts.

Additional Information

Competing Interests: The authors declare that they have no competing interests.

Data availability: The authors declare that the data supporting the findings of this study are available within the article and its supplementary information files.

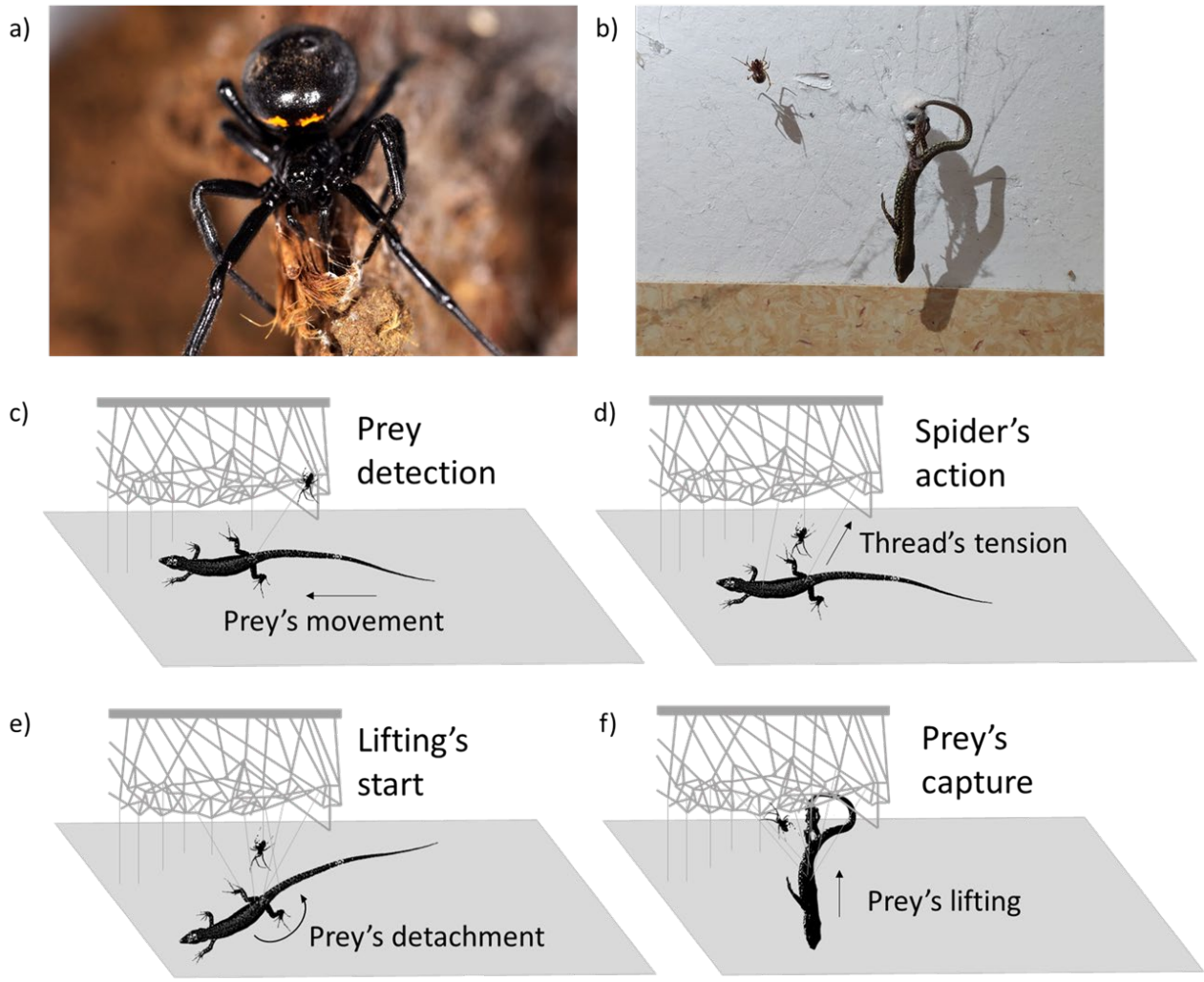


Figure 1: a) An adult Steatoda paykuliana female of the family of Theridiidae (courtesy of Alessandro Kulczycki, Aracnofilia – The Italian Association of Arachnology). b) A Steatoda triangulosa that captured a Lizard (Podarcis muralis) by using lifting technique (courtesy of Emanuele Olivetti). Schematic of the technique used to lift the prey. c) the prey is detected by the capturing threads and, once it is, d) the spider starts to attach pre-tensioned threads to it. e) When the weight of the prey is won by vertical component of the sum of the tensions the prey detaches from the surface and f) starts to be lifted.

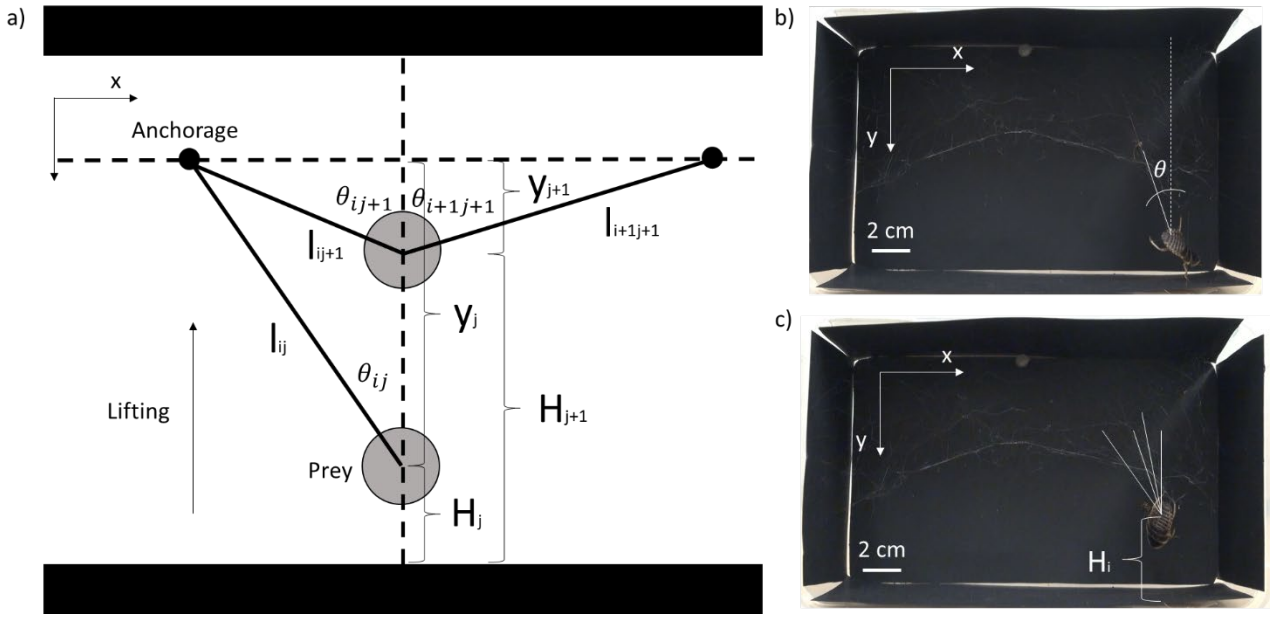


Figure 2: a) Schematic of the lifting process. b) First step of the lifting process with the frame. c) After several steps the prey is lifted and the final height is H_i. This is achieved by using various threads.

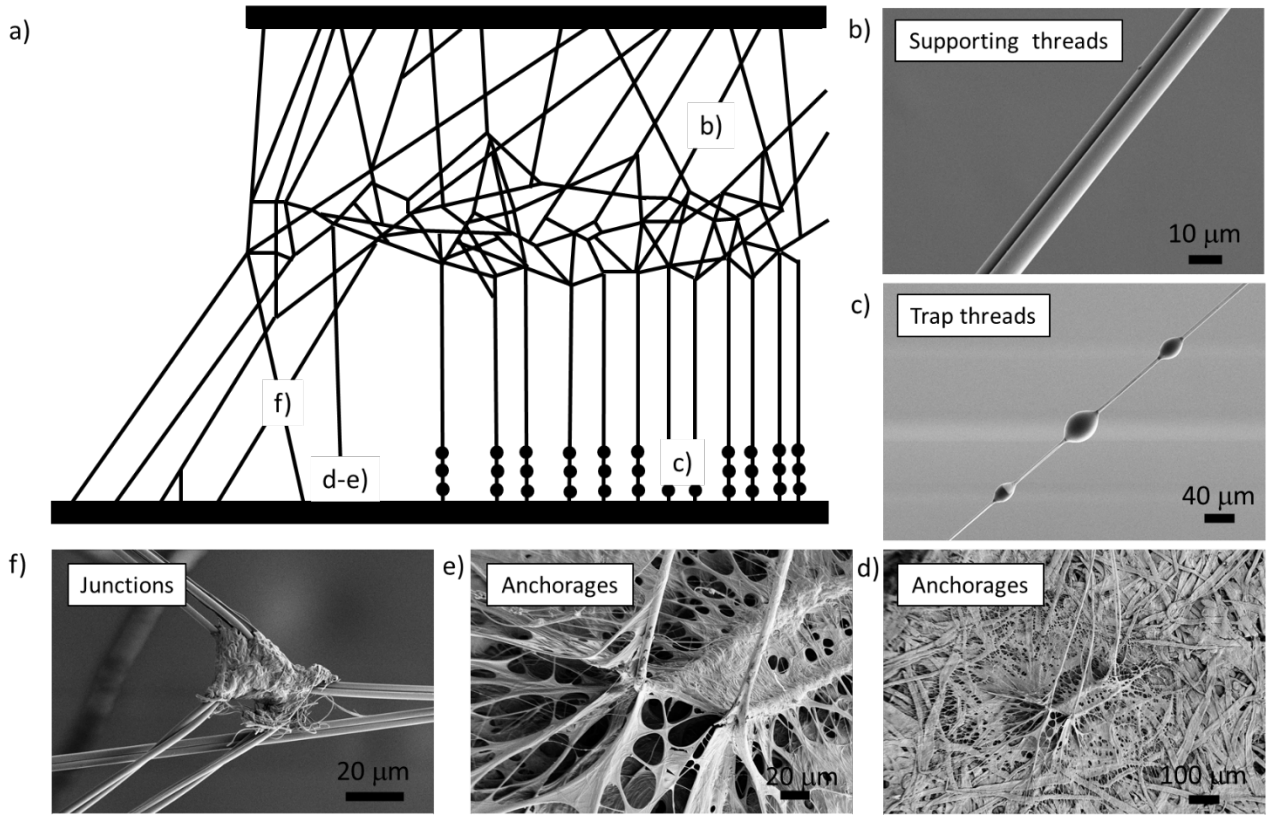


Figure 3: a) Typical structure of a cob web produced by the spiders of the family Theridiidae (adapted from (51)*). b) Supporting threads are produced mainly by using Macro Ampullate gland. c) Trapping threads of the web placed close to the ground in order to catch the prey. The glue is produced by aggregate gland and the main thread by major ampullate gland. d) The anchorage of the webs with the paper and e) a detail of the anchorage. f) Junctions that connect different frame threads on the web produced by piriform and aggregate gland.*

Table 1: The mechanical properties of the catching thread (without glue) of the three species of spiders studied.

Species	Nr. Samples	Fibre diameter (µm)	Strain at break (mm/mm)	Strength (MPa)	Young's modulus (GPa)	Toughness modulus (MJ/m^3)	Alpha α

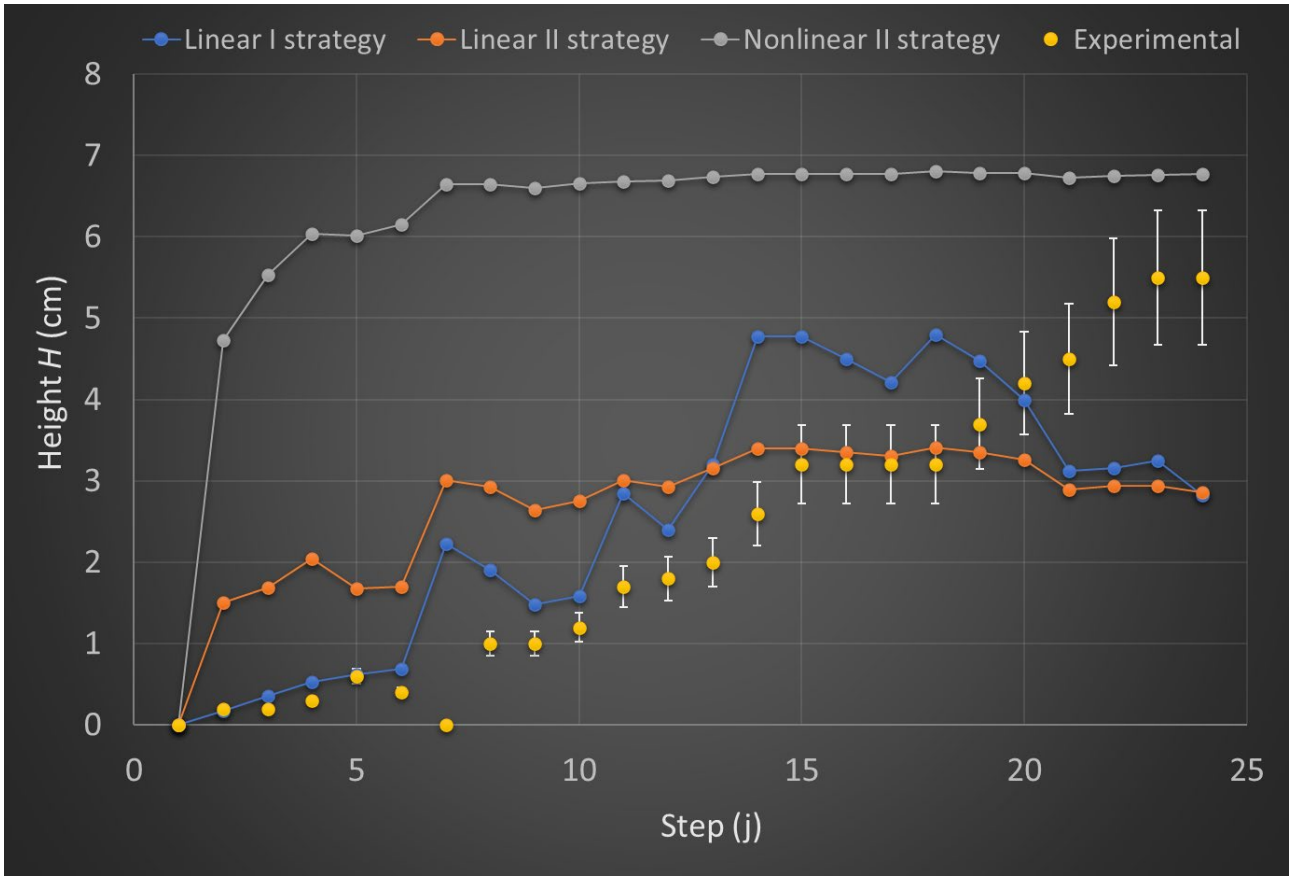
Steatoda triangulosa	32	5±2	0.42 ± 0.13	205 ± 106	1.7 ± 1.5	50 ± 39	1.5 ± 0.5
Steatoda paykuliana	10	7±2	0.26 ± 0.15	409 ± 356	3.9 ± 3.3	49 ± 41	1.2 ± 0.2

411

412 *Table 2: The efficiencies and velocities of the lifting of the different cases analysed in this study. η indicate the process' efficiency and*
413 *η' indicate the gravitational efficiency and V the lifting velocity.*

Spider	Mass of the spider (g)	Mass of the *Blaptica dubia* (g)	η	ηˈ	*V* (cm/s)
Steatoda triangulosa 1°	0.14 ± 0.01	0.31 ± 0.01	0.04	0.11	0.0046
Steatoda triangulosa 2°	0.04 ± 0.01	0.34 ± 0.01	0.02	0.06	0.0021
Steatoda triangulosa 3°	0.02 ± 0.01	0.34 ± 0.01	0.03	0.08	0.0039
Steatoda triangulosa 4°	0.01 ± 0.01	0.50 ± 0.01	0.03	0.32	0.0117
Steatoda paykulliana	0.22 ± 0.01	0.36 ± 0.01	0.06	0.08	0.0007

414



415
416 *Figure 4: Representative comparison among the theoretical model and the experimental data of the lifting. Grey lines = nonlinear*
417 *elastic regime (II strategy); blue lines = linear elastic regime (I strategy); orange line = linear elastic regime (II strategy); yellow line =*
418 *experimental data.*

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Supplementary information

How spiders hunt heavy prey: the tangle web as a pulley and spider's lifting mechanics observed and quantified in the laboratory

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The mechanical model (detailed description)

Linear regime I strategy

Following Figure 2 we wrote the vertical force equilibrium between the weight of the prey and the overall vertical component of the tension generated by the threads for each lifting's step[21]:

1) $\frac{W}{A} = \sum_{i=1}^{N_I} \sigma_{i1} \cos\theta_{i1} + \sigma_{11} \cos\theta_{11} = \sum_{i=1}^{N_I} \left(E\left(\frac{l_{i1}}{l_0} - 1\right) \cos\theta_{i1} \right) + \cos\theta_{11}\, E\left(\frac{l_{11}}{l_0} - 1\right) =$

$\sum_{i=1}^{N_I} \left(E\left(\frac{y_1}{\cos\theta_{i1} l_0} - 1\right) \cos\theta_{i1} \right) + \cos\theta_{11}\, E\left(\frac{y_1}{\cos\theta_{11} l_0} - 1\right)$

$$\Rightarrow y_1 = \frac{l_0}{E(N_I + 1)} \left(\frac{W}{A} + E \sum_{i=1}^{N_I} \cos\theta_{i1} + E \cos\theta_{11} \right)$$

where A is the cross-sectional area of the silk thread (considered constant during the process) and y_i is the vertical distance between the prey and the anchorage of the thread. The first sum (till N_I) of vertical components of the threads' tensions was related to the silk fibres inserted prior to lifting. The next step was described as follow[21]:

2) $\frac{W}{A} = \sum_{i=1}^{N_I} \sigma_{i2} \cos\theta_{i2} + \sigma_{12} \cos\theta_{12} + \sigma_{22} \cos\theta_{22} = \sum_{i=1}^{N_I} \left(E\left(\frac{l_{i2}}{l_0} - 1\right) \cos\theta_{i2} \right) +$

$\cos\theta_{12}\, E\left(\frac{l_{12}}{l_0} - 1\right) + \cos\theta_{22}\, E\left(\frac{l_{22}}{l_0} - 1\right) = \sum_{i=1}^{N_I} \left(E\left(\frac{y_2}{\cos\theta_{i2} l_0} - 1\right) \cos\theta_{i2} \right) +$

$+ \cos\theta_{12}\, E\left(\frac{y_2}{\cos\theta_{12} l_0} - 1\right) + + \cos\theta_{22}\, E\left(\frac{y_2}{\cos\theta_{22} l_0} - 1\right)$

$$\Rightarrow y_2 = \frac{l_0}{E(N_I + 2)} \left(\frac{W}{A} + E \sum_{i=1}^{N_I} \cos\theta_{i2} + E(\cos\theta_{12} + \cos\theta_{22}) \right)$$

…

n) $y_n = \frac{l_0}{E(N_I + n)} \left(\frac{W}{A} + E \sum_{i=1}^{N_I} \cos\theta_{in} + E \sum_{i=1}^{n} \cos\theta_{in} \right)$

If the height of the anchorages is constant during the process, we calculated the height of the prey at the lifting's step *n* by using[21]:

$$H_n = y_0 - y_n = y_0 - \frac{l_0}{E(N_I + n)}\left(\frac{W}{A} + E\sum_{i=1}^{N_I}\cos\theta_{in} + E\sum_{i=1}^{n}\cos\theta_{in}\right) \quad (1)$$

Linear regime II strategy

We proceed by following the previous logic scheme. However, this time the length l_0 was not known but the overall strain of all the threads at each step *j* was known (ε_j). Again, we analysed step by step and thus we obtained[21]:

1) $\frac{W}{A} = \sum_{i=1}^{N_I}\sigma_{i1}\cos\theta_{i1} + \sigma_{11}\cos\theta_{11} = \sum_{i=1}^{N_I} E\cos\theta_{i1}\left(\frac{l_{i1}}{l_{i0}} - 1\right) + E\cos\theta_{11}\left(\frac{l_{11}}{l_{10}} - 1\right) =$

$\sum_{i=1}^{N_I}\frac{Ey_1}{l_{i1}}(1+\varepsilon_1) - E\sum_{i=1}^{N_I}\cos\theta_{i1} + \frac{Ey_1}{l_{11}}(1+\varepsilon_1) - E\cos\theta_{11}$

$$\Rightarrow y_1 = \frac{1}{E(1+\varepsilon_1)}\left(\frac{W}{A} + E\left(\sum_{i=1}^{N_I}\cos\theta_{i1} + \cos\theta_{11}\right)\right)\left(\sum_{i=1}^{N_I}\frac{1}{l_{i1}} + \frac{1}{l_{11}}\right)^{-1}$$

where first sum (till N_I) of vertical components of the threads' tensions is related to the silk fibres inserted prior to lifting. The next step is described as follow[21]:

2) $\frac{W}{A} = \sum_{i=1}^{N_I}\sigma_{i2}\cos\theta_{i2} + \sigma_{12}\cos\theta_{12} + \sigma_{22}\cos\theta_{22} = \sum_{i=1}^{N_I} E\cos\theta_{i2}\left(\frac{l_{i2}}{l_{i0}} - 1\right) +$

$E\cos\theta_{12}\left(\frac{l_{12}}{l_{10}} - 1\right) + E\cos\theta_{22}\left(\frac{l_{22}}{l_{20}} - 1\right) = \sum_{i=1}^{N_I}\frac{Ey_2}{l_{i2}}(1+\varepsilon_2) - E\sum_{i=1}^{N_I}\cos\theta_{i2} + \frac{Ey_2}{l_{12}}(1+$

$\varepsilon_2) - E\cos\theta_{12} + \frac{Ey_2}{l_{22}}(1+\varepsilon_2) - E\cos\theta_{22}$

$$\Rightarrow y_2 = \frac{1}{E(1+\varepsilon_2)}\left(\frac{W}{A} + E\left(\sum_{i=1}^{N_I}\cos\theta_{i2} + \cos\theta_{12} + \cos\theta_{22}\right)\right)\left(\sum_{i=1}^{N_I}\frac{1}{l_{i2}} + \frac{1}{l_{12}} + \frac{1}{l_{22}}\right)^{-1}$$

…

n) $y_n = \frac{1}{E(1+\varepsilon_n)}\left(\frac{W}{A} + E\left(\sum_{i=1}^{N_I}\cos\theta_{in} + \sum_{i=1}^{n}\cos\theta_{in}\right)\right)\left(\sum_{i=1}^{N_I}\frac{1}{l_{in}} + \sum_{i=1}^{n}\frac{1}{l_{in}}\right)^{-1}$

If the height of the anchorages is constant during the process, we can compute the height of the prey at the lifting's step *n* by using[21]:

$$H_n = y_0 - \frac{1}{E(1+\varepsilon_n)}\left(\frac{W}{A} + E\left(\sum_{i=1}^{N_I}\cos\theta_{in} + \sum_{i=1}^{n}\cos\theta_{in}\right)\right)\left(\sum_{i=1}^{N_I}\frac{1}{l_{in}} + \sum_{i=1}^{n}\frac{1}{l_{in}}\right)^{-1} \quad (2)$$

Nonlinear regime II strategy

For the sake of simplicity, we do not consider the I strategy for the nonlinear regimes.

Following the previous logic and the process step by step we obtained[21]:

1) $\frac{W}{A} = \sum_{i=1}^{N_I} \sigma_{i1} \cos\theta_{i1} + \sigma_{11} \cos\theta_{11} = \sum_{i=1}^{N_I} \cos\theta_{i1} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha\left(\frac{l_{i1}}{l_{i0}}\right) + \cos\theta_{11} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha\left(\frac{l_{11}}{l_{10}}\right) =$

$\sum_{i=1}^{N_I} \frac{y_1}{l_{i1}} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha(1+\varepsilon_1) + \frac{y_1 \sigma_u}{l_{11} \varepsilon_u^\alpha} \ln^\alpha(1+\varepsilon_1)$

$$\Rightarrow y_1 = \frac{W}{A} \frac{\varepsilon_u^\alpha}{\sigma_u} \frac{1}{\ln^\alpha(1+\varepsilon_1)} \left(\sum_{i=1}^{N_I} \frac{1}{l_{i1}} + \frac{1}{l_{11}} \right)^{-1}$$

where first sum (till N_I) of vertical components of the threads' tensions was related to the silk fibres inserted prior to lifting. The next step was described as follow[21]:

2) $\frac{W}{A} = \sum_{i=1}^{N_I} \sigma_{i2} \cos\theta_{i2} + \sigma_{12} \cos\theta_{12} + \sigma_{22} \cos\theta_{22} = \sum_{i=1}^{N_I} \cos\theta_{i2} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha\left(\frac{l_{i2}}{l_{i0}}\right) +$

$\cos\theta_{12} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha\left(\frac{l_{12}}{l_{10}}\right) + \cos\theta_{22} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha\left(\frac{l_{22}}{l_{20}}\right) = \sum_{i=1}^{N_I} \frac{y_2}{l_{i2}} \frac{\sigma_u}{\varepsilon_u^\alpha} \ln^\alpha(1+\varepsilon_2) + \frac{y_2 \sigma_u}{l_{12} \varepsilon_u^\alpha} \ln^\alpha(1+\varepsilon_2) +$

$\frac{y_2 \sigma_u}{l_{22} \varepsilon_u^\alpha} \ln^\alpha(1+\varepsilon_2)$

$$\Rightarrow y_2 = \frac{W}{A} \frac{\varepsilon_u^\alpha}{\sigma_u} \frac{1}{\ln^\alpha(1+\varepsilon_2)} \left(\sum_{i=1}^{N_I} \frac{1}{l_{i2}} + \frac{1}{l_{12}} + \frac{1}{l_{22}} \right)^{-1}$$

…

n) $y_n = \frac{W}{A} \frac{\varepsilon_u^\alpha}{\sigma_u} \frac{1}{\ln^\alpha(1+\varepsilon_n)} \left(\sum_{i=1}^{N_I} \frac{1}{l_{in}} + \sum_{i=1}^{n} \frac{1}{l_{in}} \right)^{-1}$

If the height of the anchorages is constant during the process, we can compute the height of the prey at the lifting's step *n* by using[21]:

$$H_n = y_0 - \frac{W}{A} \frac{\varepsilon_u^\alpha}{\sigma_u} \frac{1}{\ln^\alpha(1+\varepsilon_n)} \left(\sum_{i=1}^{N_I} \frac{1}{l_{in}} + \sum_{i=1}^{n} \frac{1}{l_{in}} \right)^{-1} \qquad (3)$$

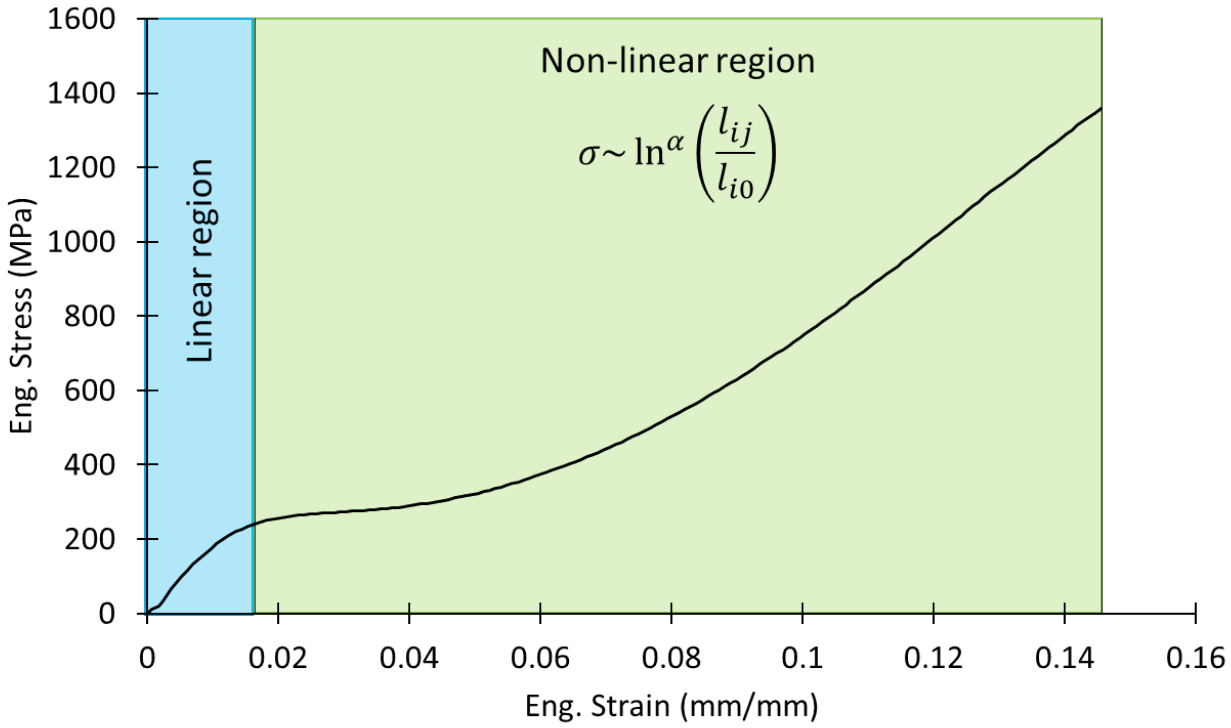

Figure S1: A typical stress strain curve of a spider silk fibre. In order to compute α, we fit the nonlinear region with the indicated equation. The first region, on the other hand, is the linear one.

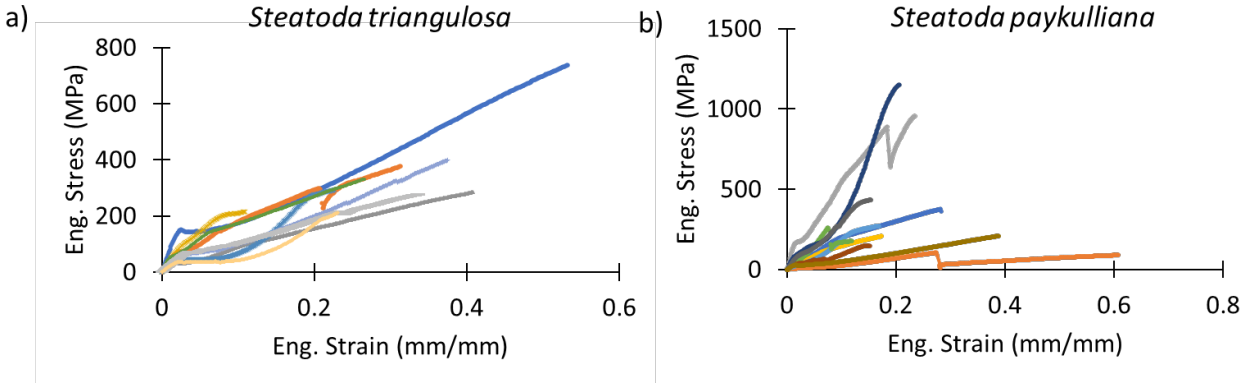

Figure S2: The mechanical properties of the catching thread (without glue) of the two species of spiders that were studied. a) Stress-strain curves of the species Steatoda triangulosa, b) stress-strain curves of the species Steatoda paykulliana.

Table S1: The number of threads used (whole process) to lift the prey, their mean length and the final height at which the prey is lifted at the end of the process. N_I is the number of threads inserted prior the lifting and n is the number of threads inserted during the lifting.

Spider	Number of used threads		Final Height (cm)
	N_I	n	
Steatoda triangulosa 1°	5	24	5.70 ± 2.39
Steatoda triangulosa 2°	13	60	4.30 ± 2.07
Steatoda triangulosa 3°	11	36	3.00 ± 1.73
Steatoda triangulosa 4°	3	31	5.40 ± 2.3
Steatoda paykulliana	13	4	0.80 ± 0. 35

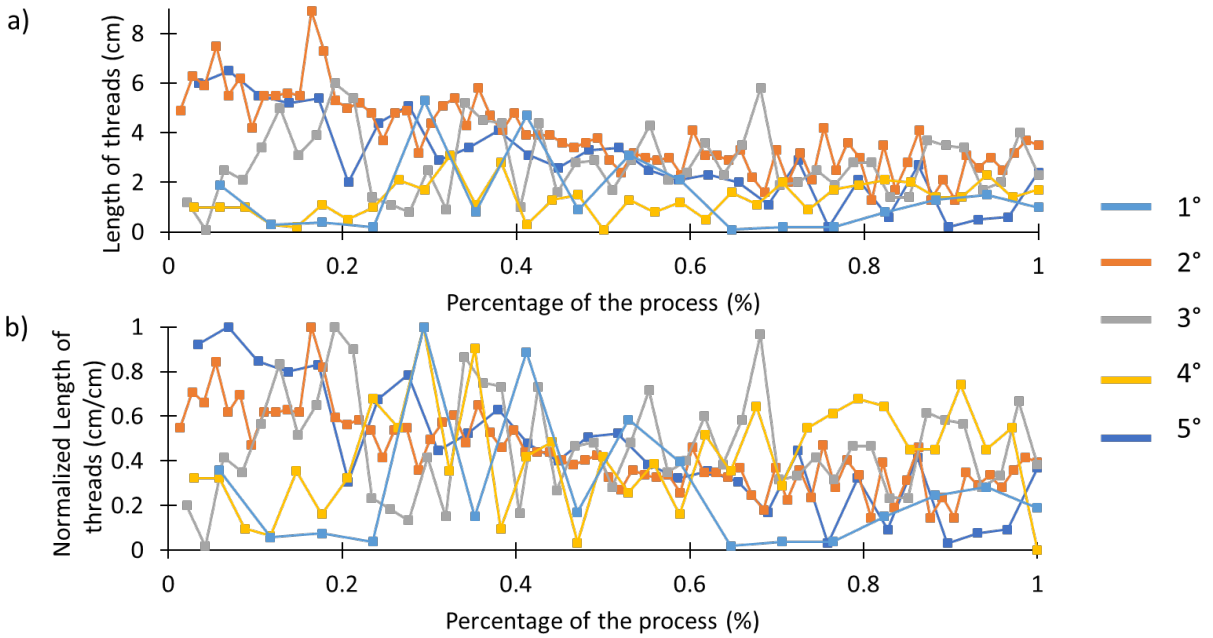

Figure S3: a) Length of the inserted threads vs the step of the lifting mechanisms (express in percentage). b) Normalized length of the thread (with respect to the longest) vs the step of the lifting mechanism (expressed in percentage). No particular regularity is observed. The percentage of the process means the state of the hunt with respect to its end (i.e. when the spider stops to spin). It is simply computed by dividing the number of the actual step (i.e. the number of the inserted fibres) for the total number of steps.

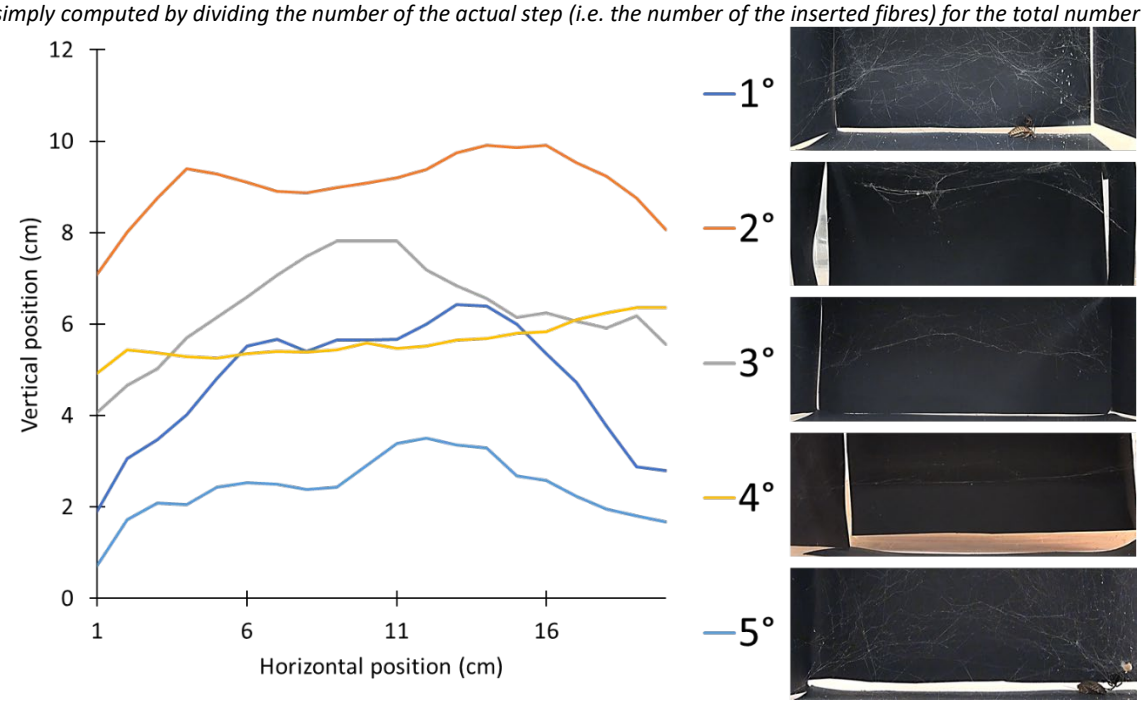

Figure S4: The height profile of the main structure of the tangle webs of the tested spiders.

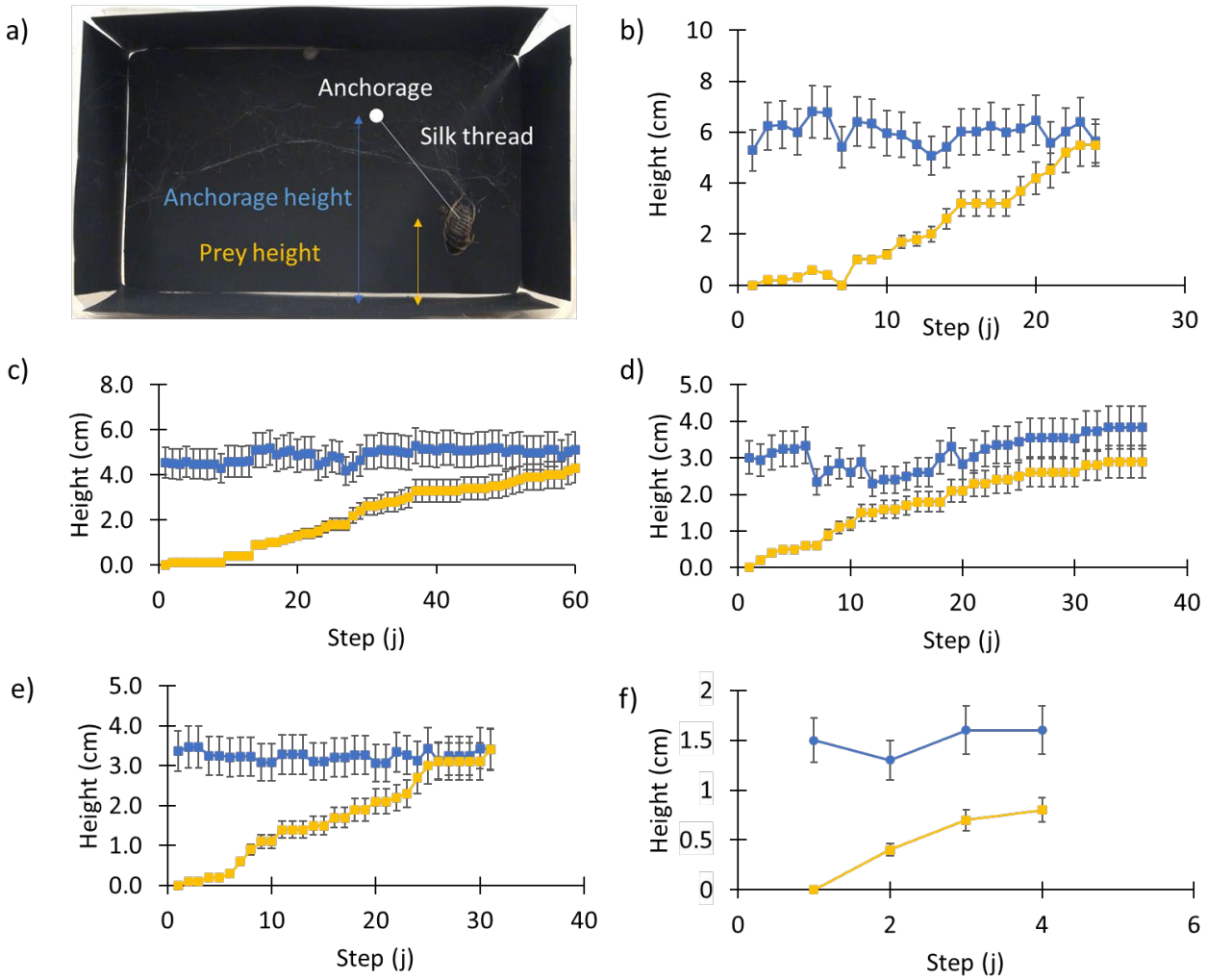

Figure S5: a) Comparison between the height of the prey and the height of the anchorages during the process. Notice the almost constant height of the anchorages during the predation of the analysed spiders: b) Steatoda triangulosa 1°, c) Steatoda triangulosa 2°, d) Steatoda triangulosa 3°, e) Steatoda triangulosa 4° and f) Steatoda paykulliana.

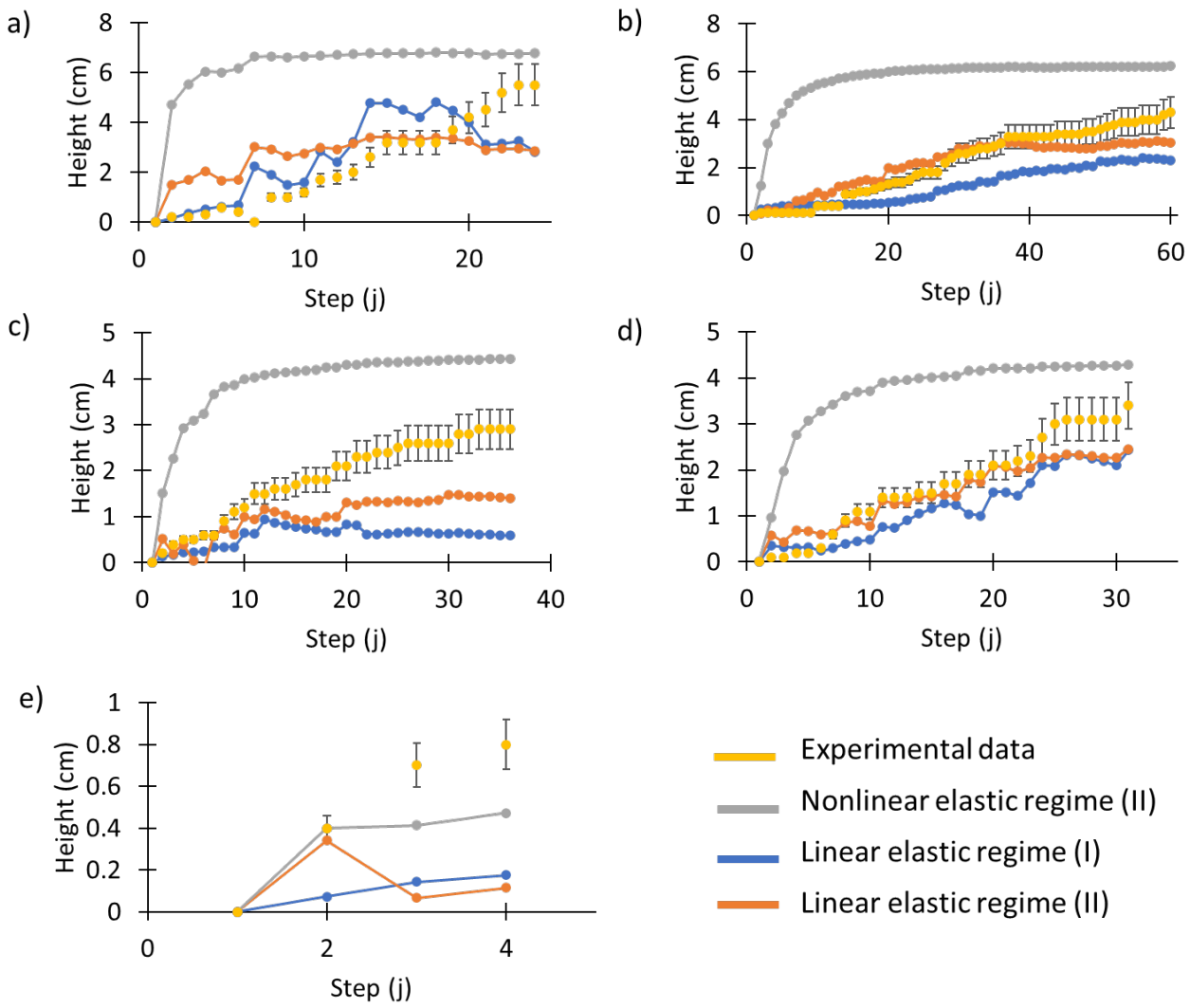

Figure S6: Comparison among the theoretical model and the experimental data of the lifting of Steatoda triangulosa 1° (a), 2° (b), 3° (c), 4° (d). e) Comparison among the mix-model and the experimental data of the lifting of Steatoda paykulliana. Grey lines = nonlinear elastic regime (II strategy); blue lines = linear elastic regime (I strategy); orange line = linear elastic regime (II strategy); yellow points = experimental data.