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# Active control of spider silk strength: comparison of drag line spun on vertical and horizontal surfaces

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**Abstract**

There is widespread interest in producing high-performance fibers that mimic the behavior of natural silks, especially spider drag line. Given the multiple roles of drag line in nature, it is pertinent to explore whether spiders can tailor the tensile properties of this material to match its intended use. Here we distinguish between the ability of spiders to control the quality (intrinsic stress–strain response) versus the amount (load-bearing cross-section) of drag line. The mechanical characteristics of drag line spun during a vertical climb differ from those of drag line spun when the spider crawls on a horizontal surface. Also, the intrinsic stress–strain response of drag line spun during a vertical climb is significantly more reproducible (i.e. dependable) than when this fiber is produced under other conditions. Implications for biomimetic polymer science are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords*: Fiber; Spider silk; Tensile properties

## 1. Introduction

Spider silks, especially the load-bearing fibers in drag line and web radial threads, exhibit combinations of strength, stiffness and toughness that are unrivalled by synthetic fibers [1–4]. Efforts to produce biomimetic analogs of drag line are helped by insights into the genetic control of spider silk sequence and composition [2,5–7], and by an understanding of the changes in molecular order that accompany the spinning of liquid crystalline silk secretion into insoluble fiber [8,9]. The flow of material through the spinning apparatus is under the active control of the spider [9], suggesting that the spider might be able to tailor the tensile behavior of the silk to match its intended use by varying the fiber diameter and/or microstructure.

To investigate this possibility, we have compared the tensile properties of drag line spun by spiders crawling on vertical and horizontal surfaces. We find that the stress–strain characteristics of drag line produced in an undisturbed vertical climb are more reproducible than the response [10–13] of silks spun under other conditions, and are optimized for dissipating the energy of a falling spider via viscoplastic deformation. A heavier spider uses fiber with a correspondingly thicker cross-section, without altering the intrinsic stress–strain response. Drag line spun by spiders crawling horizontally exhibits a greater variability of intrinsic tensile properties. Although this silk may already have the intrinsic properties appropriate to arresting a fall, the spider spins a thread that is too thin to support it safely and so conserves material if there is no actual danger of a fall occurring.

## 2. Experimental

*Argiope trifasciata* (Argiopidae) spiders were allowed to move unimpeded on wooden surfaces, from where their drag line fibers were harvested. Horizontal surfaces (with the spider on top) and vertical surfaces were used; in the latter case, silk was only collected if the spider had been ascending. The surfaces were black and smooth, to provide a background against which the silk could be seen easily, and to facilitate efforts to lift the fibers with tweezers in a way that did not cause stretching or damage. Typically, intact drag line consists of two filaments spun from the contents of the major ampullate glands and two from the minor ampullate glands; we made no attempt to isolate single filaments. To optimize the reproducibility of results, the silk was only characterized if the spider had been moving freely, i.e. without being disturbed and without encountering any edges or obstacles.

The harvested samples were cut into 30 mm lengths;

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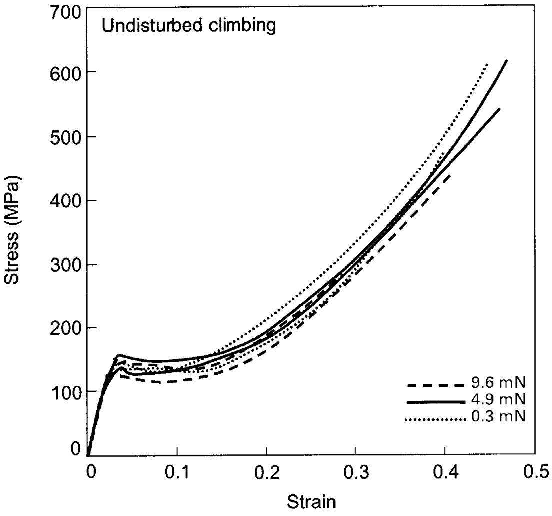

Fig. 1. Stress–strain plots for drag line silk spun by three *A. trifasciata* spiders while crawling upwards on a vertical surface. The weight of the spiders is indicated in each case by the line style coding of the plots.

these were mounted across rectangular holes cut in cardboard support frames [12] to define the 20 mm gage length of mechanical test specimens. Droplets of cyanoacrylate adhesive were used to secure the fiber to the card at the edges of the holes. The card supports were fixed in the grips of an Instron 4411 mechanical testing machine and the vertical edges were then cut, so that the force recorded during testing was exerted directly on the fiber. Load was measured with an electronic balance (Precisa 6100 C; resolution ±10 mg) located under the lower grip. The elongation of the fiber was taken as the displacement of the crosshead (resolution ±10 μm), since we estimate that the compliance of the fiber is at least 1000 times greater than that of the experimental hardware. Tensile tests to determine force-displacement curves were performed under ambient conditions (nominally 20 °C and 60% relative humidity) at a nominal strain rate of 0.0002 $s^{-1}$.

After tensile testing, sample diameters were measured by scanning electron microscopy [12,13]. Initial sample cross-sectional areas were calculated from these measurements, assuming that sample volume is conserved during the tensile tests [13]. The cross-sectional areas were needed to re-scale force-displacement plots as engineering stress–strain curves.

## 3. Results and discussion

Fig. 1 shows six representative stress–strain curves corresponding to fibers collected from three different *A. trifasciata* spiders climbing on a vertical surface. The weights of the three spiders were markedly different: 0.3, 4.9 and 9.6 mN. From the similar trajectories of their stress–strain curves, it is evident that the samples exhibit consistent intrinsic tensile properties, as was indeed the case for all 20 samples collected from spiders climbing vertically. Only the extrinsic behavior (the stress and strain at breaking, which are sensitive to the size distribution of internal flaws in the silk [12]) display significant variability. This reproducibility of the intrinsic stress–strain characteristics is a notable improvement on the tensile behavior of spider silk collected by any other technique, including forced reeling directly from spiders [10,11], and harvesting from webs [13].

The ability of the climbing spiders to produce material that has reproducible stress–strain characteristics is independent of their very different weights—and therefore independent of their different ages and relaxed spinneret dimensions. It also does not depend on the speed at which the spiders crawl. Together, these observations imply a sophisticated ability of the spinning process to control the fiber microstructure in a way that compensates for the differences in flow cross-section and rate.

The function of the drag line spun during locomotion on a vertical surface is to arrest the spiders during a fall. We must therefore expect the load-bearing capacity of the silk to increase in tandem with increasing spider weight [14]. Since we have shown that the intrinsic properties of the material do not change significantly, the increase in load-bearing ability has to be achieved by an increase in the cross-section to which the load is applied. Such an increase has also been demonstrated in web silk when the weight of spiders is increased artificially [15]. It is therefore apparent that spiders can exercise active control over their drag line cross-section. In addition, the drag line thickness increases with each molt of the rigid exoskeleton [16,17].

Three of the stress–strain curves from Fig. 1 (one for each spider) are reproduced as force-displacement (*F-d*) curves in Fig. 2. In other words, Fig. 2 shows tensile test data that have not been normalized with respect to the fiber cross-sectional areas. On each *F-d* curve, the weight of the spider is indicated by a horizontal stippled line; it is always located within the initial elastic region, and lies close to the elastic limit. It has been reported [14] that the strength of drag line spun by spiders *while* they are falling is proportional to the weight of the spiders, and that the load corresponding to the elastic limit is approximately twice the weight of the spider. In the present case, however, where the silk is produced in *anticipation* of a possible fall, a lower elastic limit is advantageous to the spiders. If the spider falls and must be arrested by the drag line, the minimum displacement that the silk must sustain without breaking is equal to twice the displacement that would be caused by applying the spider's weight quasi-statically. This limiting situation will arise when the spider is in free-fall for an infinitesimally small distance only [18], in other words just after the spider has attached the drag line to the substrate. A still higher displacement must be sustained if the interval between attachment points allows a longer free-fall. The kinetic energy of the falling spider should be dissipated, by the silk deforming viscoplastically, rather than being stored

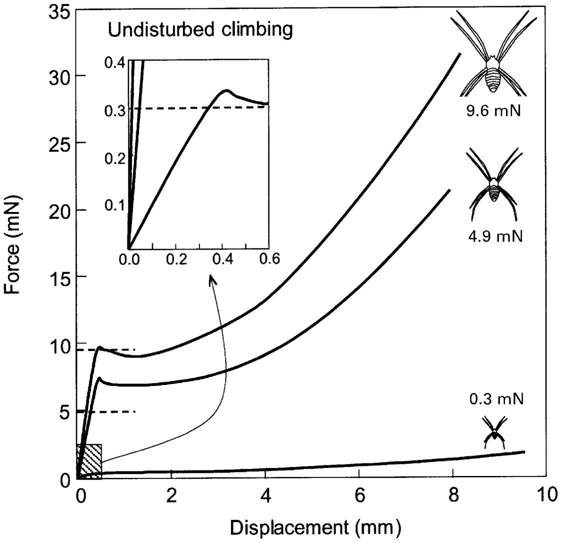

Fig. 2. Force-displacement plots corresponding to three of the stress–strain plots in Fig. 1—one for each spider. A magnified version of the plot for silk spun by the lightest spider is shown in the inset. Stippled horizontal lines indicate the weight of the spider that produced each silk sample.

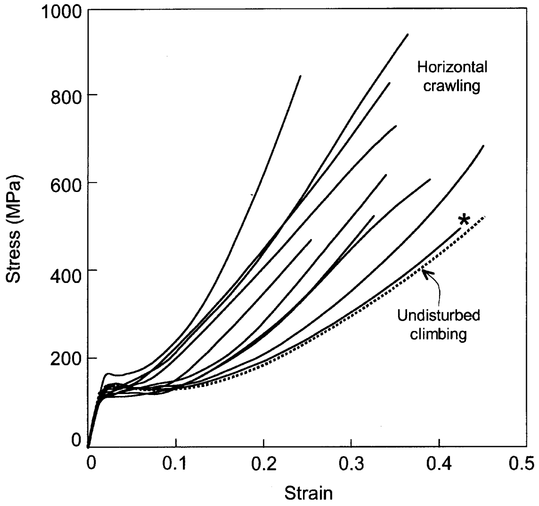

Fig. 3. Stress–strain plots for *A. trifasciata* drag line silk spun on a horizontal surface (solid lines). The plot marked with an asterisk is re-scaled as a force-displacement plot in Fig. 4. Also shown (broken line) is a plot from Fig. 1, for silk spun by the 9.6 mN spider climbing on a vertical surface.

up in elastic deformation of the silk and then transferred back to the spider.

In contrast to the drag line spun while climbing, the fiber laid down by spiders crawling on a horizontal surface exhibits a large scatter in its intrinsic mechanical properties, similar to that of frame silk harvested from webs [13]. The corresponding stress–strain curves in Fig. 3 demonstrate this variability. Fig. 3 also repeats one of the stress–strain curves shown in Fig. 1 for drag line spun by a climbing spider; the resistance to deformation exhibited by drag line spun on a horizontal surface or used in web frames, although variable, is always the same as or higher than this. We must not, however, regard the silk spun by climbing spiders as being intrinsically inferior, despite its comparative deformability. We have already noted that this material is reproducibly optimized to endure the dynamic loads and displacements associated with a falling spider while at the same time dissipating kinetic energy into viscoplastic deformation. The reproducibility of intrinsic tensile properties maintained during vertical climbing but relinquished during horizontal crawling suggests that microstructural control makes greater demands than diameter control on the spider's metabolic resources.

A further difference between the silk spun by a crawling spider on vertical and horizontal surfaces emerges if we consider raw *F-d* data. For silk spun on horizontal surfaces, the weight of the spider no longer lies within the range of loads associated with the initial elastic region of the *F-d* curve. Instead, the weight now consistently lies close to the *breaking* load of the fiber. Fig. 4 illustrates this observation by comparing *F-d* curves of material spun by the 9.6 mN spider crawling both horizontally and vertically. Also, because the *stress–strain* curves (see Fig. 3) and therefore the microstructures for these two samples were fortuitously similar, it is apparent that the spider can adapt the cross-sectional area of its drag line in response to a change in loading conditions. When crawling horizontally, the spider was not subjected to an immediate risk of falling. Although the connectivity of the lifeline was maintained, the thickness of this fiber would not have been sufficient to prevent it from breaking in the event of a fall [18], since the

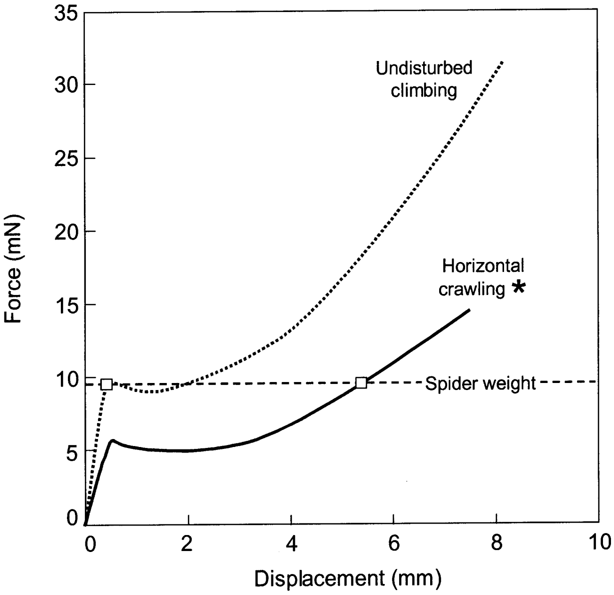

Fig. 4. Force-displacement plots for silk spun by the 9.6 mN spider crawling horizontally and vertically. The plot marked with an asterisk corresponds to the similarly labelled stress–strain curve in Fig. 3 (horizontal crawling). The plot shown as a broken line corresponds to the similarly presented stress–strain curve in Fig. 3 (vertical climbing).

*F-d* coordinates corresponding to the spider's weight are more than half the values of the failure load and displacement, respectively. When climbing vertically, the spider was exposed to an immediate risk of accident, and so the drag line had a larger cross-sectional area that could provide the necessary safety factor to arrest a fall. Thus, although the spider may already be producing silk with the appropriate intrinsic properties for arresting a fall, it maintains drag line continuity but conserves material if there is no immediate danger of a fall actually occurring.

The preceding observations have two immediate implications for silk biomimicry, and hence for polymer science. First, they show how it is possible to acquire spider drag line that exhibits reproducible tensile properties. To date, attempts to characterize microstructure-property relationships for drag line have been constrained by the poor reproducibility [11,13,19] of silk tensile behavior. Both intraspecific variability (referring to variations in the mechanical properties of samples obtained from different individuals that belong to the same species) and intra-individual variability (referring to variations in the mechanical properties of samples obtained from a single individual) contribute to this uncertainty [20], masking any structure-property dependence that might be learned by studying the drag line produced by distinct species from unique habitats. We propose that future studies of drag line microstructure-property correlations could usefully focus on material collected from freely climbing spiders. Second, we see that spiders can control the tensile behavior of their fiber without resorting to a change in polymer composition, spinning rate or processing temperature. This ability must be integral to their capacity to achieve the combination of properties that make silk attractive as an engineering material, and so merits further study.

## 4. Conclusions

1. The stress–strain characteristics of *Argiope trifasciata* drag line produced in an undisturbed vertical climb are more reproducible than the response of silks spun under other conditions, including horizontal crawling.
2. When climbing vertically, a heavier spider uses fiber with a correspondingly thicker cross-section, without altering the intrinsic stress–strain response. The weight of the spider lies in the range of loads associated with the initial elastic region of the force-displacement curve, close to the proportional limit; this optimizes the opportunity for viscoplastic deformation to dissipate the energy of a spider that falls during a climb.
3. When a spider crawls horizontally, it conserves the material and metabolic resources associated with drag line production.
4. The identification of microstructure-property correlations in spider drag line would be facilitated if studies were performed on samples consistently collected from freely climbing spiders.

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