Spiderman silks – science and fiction

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Seeing Spiderman swing through New York City tingles the spine and exercises the brain. His ease in making and manipulating gossamer filaments for aerial stunts is truly breathtaking and awe inspiring. If only I had these powers, so one thinks. Which, for materials biologists with decades of experience analysing the stuff, is humbling, to say the least, as totally unforeseen and novel capabilities and capacities emerge. As Spiderman squirts, swipes and swings he suspends both himself and belief in a world where manly strands and strings of gossamer silk are used elegantly both in defence and attack.

Let us forget about the ability to sustain body blows that would kill the normal spider, which is quite fragile and, once punctured, loses its mobility as the universal consequence of leakage in a hydraulic system. Whether spiders have a faster reaction time than humans remains to be tested but is most certainly an interesting proposition. Seeing homo arachnoides tumble and swing suggests a good capacity for high g-forces (comparable to that of astronauts and Formula One drivers). Indeed, spiders have such capacity and will build webs in forces up to 14*g* – but then they are much smaller than our hero, and body size does matter in this department. This brief overview of his fabulous capabilities brings us to the silks, which are Spiderman's signature feature, in both name and spirit.

Observations from nature

What, concerning his strands and strings, can we learn from our arachnid hero? Silks are a diverse group of filamentous materials produced by a range of arthropods, which have independently evolved both the material and its various uses starting approximately 400 million years ago. All silks are protein polymers that rely on extrusion spinning to activate the correct chemical processing pathway, which guides the gel-like pre-cursor, dope, to largely self-assemble into the solid fibre we call silk[1]. Thus, unlike other biopolymer protein complexes such as collagen, keratin and cellulose, which are assembled into their tertiary and quaternary conformations during a growth process, typical silks are not grown but spun using flow elongation and shear-force-fields in combination with chemical primers to initiate molecular self-assembly. We say 'typical' because, as always in biology, there are also exceptions in silks, for example, the gluey capture silk of the araneid orb weavers that consists mostly of neurotransmitter compounds[2], as opposed to the usual silk-fibroin molecules, and which stays wet and sticky rather than drying out[3]. Importantly, these systems use clever self-assembling micro-windlass technology that is driven by elasto-capillarity of the watery coat rather than just the elastic properties of the thread alone[4]. As such systems often use electrostatic charges to capture prey[5] we believe that Spiderman will have comparable systems in his armoury (considering the powers of some his more formidable foes), although so far we have found little hard evidence for it.

How to manufacture silk in a hurry

First, let us examine Spiderman's method of generating his threads. In-depth inspection/analysis of an extensive online database of video imagery, as well as background visual literature (commonly called comic strips), confirms that Spiderman seems to shoot filaments from the wrist. This immediately raises a number of questions. Firstly, where are the silk glands situated? As silk dope takes time to synthesize, these glands must be rather bulky to hold sufficient material to allow at least a day's travel – i.e. comparable to a spider who starts its work with a web's worth of material in storage. Moreover, note that a spinnable dope would be an aquamelt[6] with *at least* half of its bulk as water, which would be lost (or recycled) during extrusion. This, of course, means that the glands would indeed be rather massive, probably too large/unwieldy to be situated in the arms, whether lower or upper. Indeed, as the silk spin-extrusion process would entail an internal drawdown associated with the water recovery process, the gland's ducts would have to be rather long. So, all evidence points to the glands

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being located in the thorax of Spiderman; a simple body scan would confirm this hypothesis. In its absence, video analysis of Spiderman's dimensions before and after a day's work should probably show a marked, ideally highly significant, decrease in upper-body volume. Research in progress analyses comic imagery in an attempt to falsify this hypothesis.

How strong is a piece of string?

The hypothesis of a significant amount of stored aquamelt pre-silk dope hinges on the mean material properties of the silk Spiderman manages to produce. Obviously, much depends on the tensile and vibratory qualities of his threads, which are tuned as they are spun[7,8] and able to gain superhuman strength with decreasing (viz!) diameter[9]. In the film footage (and the older illustrated literature) available to this reviewer the threads appeared rather bulky, with apparent diameters in the range of centimetres rather than millimetres. While Spiderman is a rather slim male of average height, with a bodyweight of approximately 75kg (12 stone) he does, from time to time, transport a prey or companion. In addition, he seems to swing with great panache, which would generate g-forces doubling or tripling his own weight. Adding companionship and additional swing-*g* to the ultimate safety factor, his thread (within solid safety margins) would have to accommodate weights of up to one ton. Given an average tensile strength of a dragline-type spidery thread of ultimate strength around 1.5 GPa with an E modulus of around 15 GPa, Spiderman's personalized silk would indeed be less gossamer and more cable, confirming our visual analysis of footage and literature where it shows up rather obvious. We note, however, that the range of spider silks is breathtaking in functional and structural properties, in chemical composition, and, of course, also in mechanical properties with engineering strengths (i.e. stress/strain properties compensated for fibre dimension. Arachnid silks range in modulus from1 kPa modulus for a highly hydrated 'gel' filament to about 20 GPa for the stiffest dragline silk, and display strengths from almost zero values of yield stress to about 1.6 GPa, respectively. (1) In comparison, a decent commercial silk fibre (as used in textiles) would have a modulus and strength of, respectively, about 10 GPa and 400 MPa.

But Spiderman not only swings, he also captures, and the act of his capturing a train in full swing has been elegantly analysed by Bryan et al.[10] showing that this behaviour, too, is not (necessarily) a figment of anyone's imagination but supported by the detail that Spiderman produces superior spider silk , which he then pushes its use to the very limits of wisdom. But then, judging from his appearance and behaviour, he is an adolescent male with ample testosterone, and hence likely to be neither cautious nor careful.

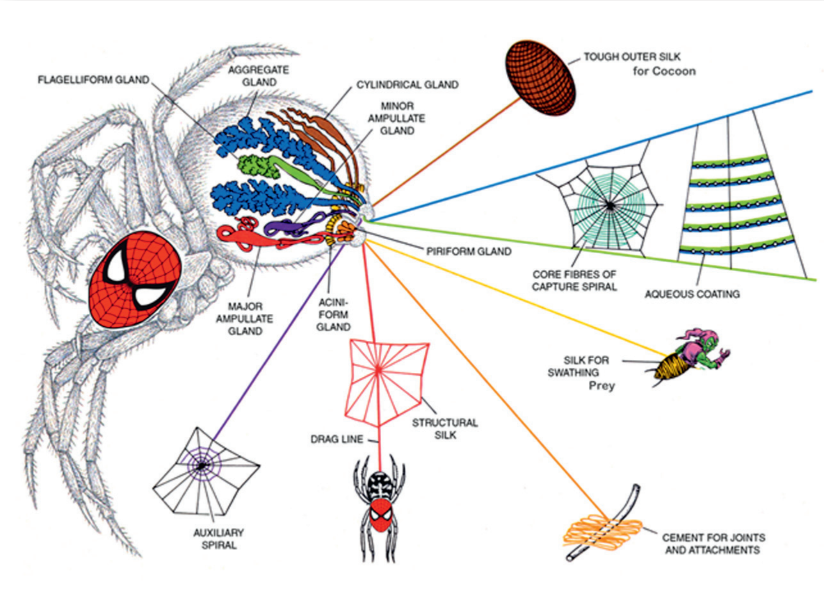

Figure 1. The Garden Cross spider *Araneus diadematus* dressed up for Halloween and showing her substantial armoury of silk glands and threads with their various functions (after Vollrath 1992)[12].

The origin of Silk

Silks have independently evolved many times, including 23 times within the insects, once within the spiders and at least once within the crustaceans[13–15]. Whereas insects will produce one type of silk at one particular life stage, spiders produce multiple types of silk throughout their life. These silks have evolved similar protein sequences and processing conditions, but they differ in the origin of the silk-storing gland(s)[15–17]. This diversity of structure and properties reveals both remarkable adaptations as well as considerable constraints on the protein composition and processing of silk, indicating that there are a limited number of ways to make a silk fibre. Importantly, the diversity seen in silks concerning both natural functions and material properties originates from a combination of spinning feedstock diversity and complex spinning and processing of these silk precursors. Thus, a constrained number of protein motifs can lead to many different materials

For example, the spider's Major Ampullate, or dragline silks, have similar gene sequences across the Araneomorphae, including glycine-alanine (GA) and repeats of alanine (polyA), with some novel repeats[18]. Dragline silks are made up of two proteins: MaSp1 and MaSp2[19]. In contrast, the basal silks contain some unique repetitive sequences in their silk genes involving amino acids such as serine and threonine[18,20]. However, all spider silk genes share polyA repeats, suggesting that these sequences have been maintained over 240 million years[18].

Given the diversity in silk properties and natural applications, silks are a superb resource to inspire novel biopolymers[18]. Nature has evolved these materials over hundreds of millions of years of trial and error and this is now providing intellectual stimuli for industrial materials research and development[21].

Two threads are better than one

In this respect (i.e. judicious use of the material) it is important to note that Spidermanshares bilateral body symmetry with spiders, and, in consequence, also has the ability to produce a double thread. However, unlike spiders, which *always* produce a double thread (each with the ability to singly hold the animal's weight, as an extra safety feature) Spiderman more often than not shoots only from *one* wrist. This behaviour, to me, appears to be highly cavalier – if there were no extra safety features integrated into the thread. For, what would happen if, for example, a point impurity would very locally weaken the intra- and inter-molecular interaction between the silk proteins? As is well known in fracture mechanics, the weakest link in a chain determines its overall strength; the same paradigm of course holds true for silk protein–chain mechanics. Hence we must assume some quality control (probably through split-second sensory feedback loops) during spinning. Spiderman-inspired (S'man-mimetic) efforts are now underway to investigate whether spiders, too, might have such feedback systems. In any case, Spiderman has survived despite this apparent lack of concern for safety margins, so we have to assume some highly sophisticated quality control system by or near the wrist-nozzle or the duct linking nozzle and silk gland.

Benefits of cross-species hybridization

Now, such a system would have to be highly derived starting from the arachnid ancestry of our Spiderman. Because, unlike all spiders, Spiderman has mutated (or evolved in the relatively short time span of one generation) a spinning system unlike any other found in his spidery lineage. All known spiders spin by pull-trusion, as indeed seem to do all other animals that also spin silks e.g. moth silkworms, pseudo-scorpions and mites, as well as bee and flee larva, to name a few. Spiderman, on the other hand, seems to use push-trusion. This is intriguing, as it seems to fly in the face of traditional silk production. Perhaps Spiderman has discovered (or to be scientifically precise: the set of mutations that led to the genetic merger of man and arachnid have led to) a way of silk spinning which is novel to Nature as we know it? This could be important since – whatever it is – Spiderman's way seems most energy efficient, probably even more so than natural silk spinning which, in itself, is already 1000 times more efficient than man's spinning of high-density polyethylene (HDPE)[6]. Moreover, being able to use push-trusion without molecular log-jam could be another important lesson to transfer to the UK polymer industry[11]. Although with the entrepreneurial hero being a New York American I suspect that this truly remarkable and always well-briefed homo-arachnid chimera has already patented the process (as well as the product, to give the IP extra protection).

Continuing the quest

There are, obviously, many other features to be studied once we have secured a specimen (or, rather, THE specimen, as there is no evidence for more than one Spiderman) for *in vivo* and *in vitro* studies. Unfortunately, with an N=1 and n=1 it is unlikely that any serious journal would accept our publication of the findings. In consequence, I don't think that my group shall attempt to secure the funding to collect the specimen for study, and instead we will have to continue to rely for our research on second and third hand reports and films, which (of course) might, by all intents and purposes, have been 'doctored'. ■

Professor, Senior Research Fellow, Department of Zoology, University of Oxford, Pembroke College Education, training and main positions in Germany, Panama, Oxford, Basel and Aarhus. Fieldwork in Central and South America, Australia, Papua/Micronesia, Asia and Africa. Main research interests cover silks and silk-structures as well as animal decision-making. To fully appreciate 'silk' one needs to understand both its evolution and its uses for the animals that make it be they spider, moth or bee. Apart from their fascinating ecology, silks are interesting and important model systems for probing into the details of protein folding. On a practical side, fundamental research has led to a number of spin-out companies, mostly focussing on the use of silk in regenerative medicine. Other interests cover the evolution of the spider's web, the role of emergent properties in animal behaviour and the behavioural economics of elephant conservation. Email: fritz.vollrath@zoo.ox.ac.uk

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