IS THE SPIDER A WEAVING MASTER OR A PRINTING EXPERT?

by

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This paper shows that a spider is a spinning master and a printing expert as well. Firstly, a spider can produce different types of silks by controlling the spinning process, which is correlated with silk properties. Understanding the natural spinning process can greatly help for the improvement of artificial spinning processes to control the products' quality. Here we show the periodic motion of muscles connected to the spinnerets plays an important role in controlling the spinning process and the silk properties, which leads to a zero resistance of the viscous flow in the gland duct and ordered macromolecules in the silk. We anticipate this finding can promote a sophisticated study of other animals' spinning properties and bio-inspired design of artificial spinning processes. Secondly, the spider web is not weaved, but it is printed, the process is similar to the modern 3-D printing technology. Finally, a spider-inspired 4-D printing technology is suggested.

Key words: *spider spinning, Bernoulli equation, Pascal principle, periodic motion, 3-D printing technology*

Introduction

Everybody might have seen a spider weaving its web, fig. 1, but scientifically, the web is not weaved but printed just like the modern 3-D printing technology [1-9].

The spider is a spinning master and a printing master as well. The former is well-known, but the latter was never discussed in the open literature. This paper will discuss the spider's spinning and printing abilities.

Figure 1. The spider web printed by the spider

Spider's spinning ability

Spider's dragline silk is famous for its strength and elasticity. Different spiders produce different types of silk by suitable controlling the spinning process, which is strongly correlated with silk properties [10]. The highest mechanical strength was explained in [11], and

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nature inspired artificial fibers have been a hot topic [12, 13], and the spider-inspired bubble electrospinning has now been widely used to fabricate nanofibers [13-18].

The spinneret's geometry and boundary conditions play an essential role in the spinning process [19]. Yang, *et al.* [19] showed that the cross-section of a fiber during the spinning process can be controlled by nozzle's shape, and the mechanism can be well explained by the geometric potential theory [20-24]. The animal can adjust the spinneret's geometry to control the silk's morphology. It was reported that during the spinning process, the anterior lateral spinnerets move very fast, 8.5-13 times per second [25], and the motion of the muscle connected to the spinnerets were also reported [26, 27], but their roles in the spinning process are not clear and there is no a theory to explain the mechanism of these phenomena. This paper gives a complete physical insight into the spinning process.

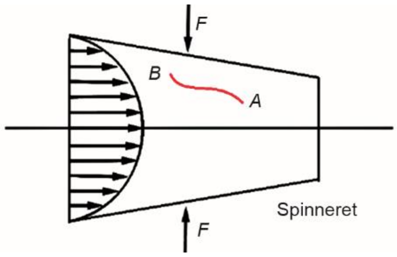

Figure 2. The velocity distribution in the gland duct

It was proved that macromolecules and nanoparticles orientation and distribution during the spinning process can be controlled by a long tube [28, 29]. Spider has a long gland duct leading the silk gland to the spinneret, the velocity distribution across the duct section is given in fig. 2, the center has the maximal velocity while the boundary has zero velocity.

$$u(r) = u_0\left[1-\left(\frac{r}{R}\right)^2\right] \tag{1}$$

where u_0 is the maximal velocity at center and R is the radius of the tube.

According to the Bernoulli equation:

$$\frac{1}{2}u^2 + \frac{P}{\rho} = B \tag{2}$$

where u is the velocity, P – the pressure, ρ – the density, B – the Bernoulli constant, the boundary of the duct has the maximal pressure, and the center sees the minimal pressure. This pressure difference is extremely useful for the protein molecules to be pushed into the center gradually. As shown in fig. 2, where the segment AB presents a molecule chain, it is obvious that $u_A > u_B$ and $P_A < P_B$. The pressure difference pushes gradually the point B into the center, and the velocity difference makes the entangled molecules disentangled, and makes the disentangled molecules ordered.

The protein solution in the duct has a high viscosity, and according to Newton's law, its viscous force can be expressed:

$$\tau = \mu\frac{\mathrm{d}u}{\mathrm{d}r} \tag{3}$$

where μ is the viscous coefficient.

It seems that the viscous force can be avoided entirely when the velocity distribution is uniform across the duct section. According to eq. (2), we have:

$$\rho u\frac{\mathrm{d}u}{\mathrm{d}r} + \frac{\mathrm{d}P}{\mathrm{d}r} = 0 \tag{4}$$

In case the pressure is independent of r, we can obtain du/dr = 0, as a result, a zero resistance is obtained.

In order to obtain the zero resistance in the spinning process, the animal has evolved to have a special ability. As reported that the two anterior lateral spinnerets vibrate fast with a frequency of 8.5-13 per second [25], which means the pressure can be expressed:

$$P = P_0 \sin \omega t \tag{5}$$

where ω is the frequency of the vibration. According to the Pascal law, the pressure is time-predominance, which means:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = 0 \tag{6}$$

We, therefore, obtain du/dr = 0, and finally τ = 0. So the periodic motion caused by the muscles connected to the spinnerets or the glad duct plays an important role in controlling the spinning process.

Spider's printing ability

The spider's web is printed just as the modern 3-D printing technology. The spider first prints the radial one from the point 1 to 2 as illustrated in fig. 3, then it returns to the center, O, and then from the point O to 3, and from 3 to 4. The process continues until all radial lines are formed, the spider comes back the center, and prints axial lines 9-11, until the total web is printed. The modern 3-D printing technology, as illustrated in fig. 4, can be exactly controlled the printing sequence of the web.

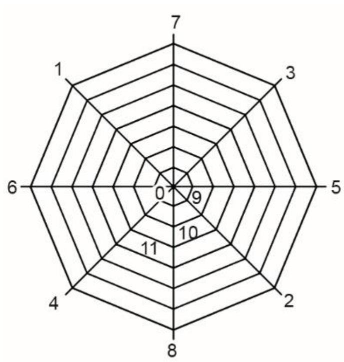

Figure 3. The printing sequence of a spider web

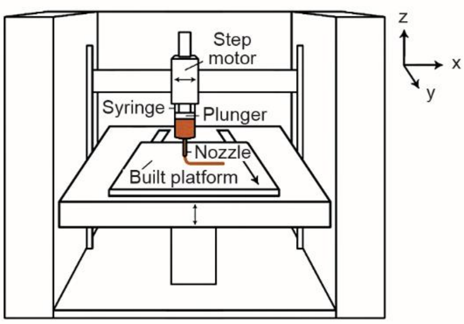

Figure 4. The 3-D printing technology

Conclusions

The spider has been evolved to have the very ability to control the spinning and printing processes optimally. This paper unveils the secret of the spider's spinning and printing abilities. When the spinnerets begin to spinning, a sudden muscle motion is strongly needed to push the macromolecules into the duct center, otherwise, the viscous force is high enough to prevent it from spinning.

This paper explains an intriguing phenomenon in the spider's spinning process. The finding can be used for the design of various spinnerets for controlling the quality of the spun products. The spider's printing ability can arouse a spider-inspired 4-D printing technology in the near future.

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