Traditional and Modern Biomaterials Science Uses of Spider Webs (Arachnida: Araneae)[1]

Brynne M. Godfrey[2]

Abstract: Spiders and their webs are generally despised, yet many cultures, including traditional ones, have held these arachnids and their silky products in high-esteem. Spider webs have been used to stop bleeding; uses in painting, textile-making, and fishing are also known. Limited scientific evidence seems to support the usefulness of spider webs to stop bleeding from small cuts. In modern biomaterials science, spider webs are considered model systems due to their strength and flexibility. Consequently, intense efforts are underway to understand the functional molecular structure of the proteinaceous silk threads, to synthesize the proteins in the laboratory without the spiders, and to understand what uses spider webs have, particularly in medicine. Promising results using in vitro models suggest that bioengineered spider web fibers could have a place in future reconstructive surgery.

Key Words: Spider webs, folk medicine, medicine, painting, textiles, fishing, biomaterials, biotechnology, protein engineering, recombinant spider silk, materiomics, Arachnida, Araneae

Spiders and their webs have negative connotations in many modern societies. Yet, this has not always been the case both in traditional and modern societies as well as among biomaterial scientists, those who create art with paints and textiles, as well as fishermen/women. Below, I summarize some uses of spider webs in medicine and in other human endeavors. Within each major activity category, I have structured the narrative in approximated chronological and then geographical order. Emphasis is placed on the literature post Newmann and Newmann (1995) seminal paper on medicinal uses of spider silk. Thereafter, I summarize the uses of spider webs in modern biomaterials research.

Traditional uses of spider webs in medicine[3]

Antiquity. Spider webs have been used fairly commonly in medical settings for millenia. According to Ballal and Varghese (2015), the Greeks applied cobwebs directly to wounds. The Roman, Gaius Plinius Secundus (25 - 79CE), also known as Pliny The Elder, said that a web placed on an open wound would promote its healing (Newman and Newman 1995). A medical writer and fellow

[1] Submitted on November 11, 2015. Accepted on December 11, 2015. Last revisions received on January 26, 2016. Scientific names of spiders have been updated using the *World Spider Catalog* (2015).
[2] The Pennsylvania State University. York, Pennsylvania, USA. E-mail: bmgodfrey3@gmail.com
[3] As this paper headed to press, I became aware of a forthcoming book entitled, *Gossamer Days: Spiders, Humans and Their Threads* (2016) by Eleanor Morgan. Full reference in Literature Cited.

DOI: 10.9784/LEB3(4)Godfrey.01
Electronically available on January 31, 2016. Mailed on January 31, 2016.

Roman from Burdigala (modern day Bordeux, France), Marcellus Empiricus (4th – 5th century BC), believed that using spider webs was good for impetigo, a highly contagious skin rash primarily caused by *Staphylococcus aureus* Rosenbach, 1884 and sometimes by *Streptococcus pyogenes* Rosenbach, 1884. He also thought that the ashes of spider webs mixed with boiled cornmeal, known as polenta, were useful for joint wounds. Spider webs were used by the Romans to heal a variety of medical cases such as joint wounds, warts, ringworms, and leprosy. According to Newman and Newman (1995), the most famous and prolific physician of Roman times, the Greek, Galen of Pergamon (129 - circa 215 CE)[4], proposed placing a spider cocoon inside a painful, decayed tooth. It was also not uncommon for Roman surgeons to remove a wart by placing a spider web around it and setting it on fire before removing it. This practice is still used in western China (Zhao, personal communication to Jorge Santiago-Blay, December 2015). Also, there were neuropsychiatric uses for spider webs, according to Newman and Newman (1995). In ancient China, it was common knowledge that a cobweb placed secretly beneath the collar on the 7th day of the 7th month would dull mental conditions and cure forgetfulness. Nevertheless, the most common traditional use of spider webs was, and has remained, as a styptic, to stop bleeding of external wounds.

Medieval Age. On Episode 8 of the South Korean historical drama, *Shine or Go Crazy*, Wang So, who would become King Gwangjong (925 - 975CE), is wounded in a battle. As he is treated inside a cave, his bleeding arm is wrapped with spider webs from the walls of the cave. Similarly, French troops carried packets of webs to be used to stop hemorrhage in the Battle of Crécy (part of the so-called Hundred Years' War between the kingdoms of England and France) in 1346 (Newman and Newman 1995).

In England, John of Mirfield (1407) echoed a similar point of view: "Or if a simple wound in the flesh be fresh… a spider's web cleansed of dust may be put on, it cures the wound because it cleanses and consolidates, but take care that neither the foot nor any part of the spider stays in it which could easily infect the whole body. Or for a simple wound in the flesh or in the head or elsewhere in the body, apply spider's web soaked in common oil and vinegar. And it should not be removed until it is cured."

Spiders and their webs are still viewed as a source of life in the creation narratives of Hopi and other native southwestern USA peoples (Figure 1) as well as objects to (allegedly) trap evil (Figure 2).

[4] Additional information on the life of Galen of Pergamon can be found in this link, http://www.bbc.co.uk/programmes/b03c4dys (British Broadcasting Corporation 2013). Although the word, "galen", is not commonly used to refer to doctors in the USA, the Spanish word, "galeno", is fairly commonly used in Latin America. Western medicine relied on "the Great Galen", as sometimes he was referred to many centuries after his death (e.g. by Sir William Harvey, Wright 2013) and in some cases up to the 19th century.

Figures 1-2. Kokyanwhti, or Spider Woman, of the Hopi native people of southwestern United States creation story. Her creative powers are expressed through her web. (Reproduced from http://www.jacksbromeliads.com/myanhopiprophecy.htm, with permission.) 2. Dreamcatcher, the best known artifact representing spider webs in Native North American cultures. Invented many generations ago by the Ojibwe of what is known today as Ontario (southcentral Canada) and the northcentral USA states of Michigan, Wisconsin, North Dakota and Minnesota, the one herein shown was crafted by artists of the Piscataway Indian Nation (Maryland, USA).

Rennaissance and beyond. This subsection is organized geographically, beginning with Europe and Africa, then Asia, and ending in the western hemisphere.

Europe. The use of spider webs to stop bleeding is mentioned in Shakespeare's *Midsummer Night's Dream* (circa 1590 - 1597), "I shall desire you of more acquaintance, good master cobweb … If I cut my finger, I shall make bold of you.". Edward Topsell's *The History of Four-Footed beasts, Serpents, and Insects*, a collection of stories published in 1658, advocates using spider webs to stop bleeding and to provide therapy for skin lesions.

According to Hulden (2011), the first Finnish malariologist, Johan Haartman (1725 - 1788) discussed many remedies Europeans tried to cure the disease with, including eating spider webs with peppers, embedded figs, or plums. An older method consisted of mixing spider web with mustard or garlic and putting it on the arteries.

Africa. A prescription from the Siwa Oasis (Egypt) people, mostly Berbers, calls for healing wounds by grinding a dry mixture of spider's web and palm dates *Phoenix dactylifera* L., 1753 (Arecaceae) and then applying the powder onto the wound with "kohl" [a cosmetic commonly used in northern Africa made out of a sulfide mineral (Sb_2S_3), called stibnite, or antimonite], and sugar or salt (El-Hennawy 2012).

Asia. As recently as 1999 - 2000, one out of 49 patients studied was treated with spider web as a complementary/alternative medicine along with conventional treatments for cancer in Ankara, Turkey (Karadeniz 2007).

In some regions of China, the old tradition of setting warts on fire is still used. Spider webs are collected and tightened into a ball larger than the wart, then on fire as needed. (H. Zhao, personal communication to Jorge Santiago-Blay, November 2015). In India, Kumari et al. (2013) report that spider webs are used in and around to city of Bokaro (State of Jharkhand) to stop bleeding on small cuts, similar to the use of adhesive bandages. Rubbed directly onto the skin, the ointment was used at 2.5% and 5% w/w concentrations and was used on excision and incision wounds in rats to test its wound healing activity. Compared to normal healing and ointments, it was found that spider web significantly reduced the area of excision wound. This particular spider web ointment showed a 30.65% increase in the tensile strength compared to normal healing in the incision wound. It was also revealed that spider web ointment lowers scores of scabs, ulci or local defects caused by necrosis or inflammation, and polymorphonuclear white blood cells and had high scores of re-epithelialization and neovascularization compared to normal treatments. Spider cocoons are still being used in remote Indian villages to stop bleeding in wounds (Ballal and Varghese 2015). In the states of Arunachal Pradesh and Sikkim (northern India), an indigenous traditional practice to stop bleeding from a leech bite site consists of applying spider webs directly onto the wound. Spider webs, locally called *Borongbu*, are typically used on children when the bleeding continues for a long time (Bam et al. 2015).

Although the practice is not as common today, in Sri Lanka, a broken cattle horn was fixed by using two parts spider web mixed with a lime to make a paste that was applied to the wound (Ediriweera et al. 2011). This paste was applied after the ashes of *Shorea oblongifolia* Thwaites, 1858 (Dipterocarpaceae) resin (Lambert et al. 2013) were mixed with coconut oil and tied around the horn with broken hair.

Western Hemisphere. Catherine Morrah, a former general medical practitioner in the island of Trinidad (West Indies) from 1936-1959, treated infantile tetanus by placing a spider web on the umbilical cord stump (Hayward 2000).

In the USA, Ritter (1992) noted that colonial inhabitants of what would become the United States believed that rolling a spider web into a ball and swallowing it whole would cure asthma. Also, cobweb from a cypress tree

(Cupressaceae) was said to be the best type of treatment for *podagra* (gout, or arthritis of the foot). In the epic poem *Evangeline* (1847), written by Henry W. Longfellow (USA, 1807-1882), Father Leblanc says that fever was cured by a spider shut up (or encased) in a nutshell.

Köhler and Hellstrom (2011) report the use of spider webs as well as other types of dressings to reduce bleeding in "uncomplicated" penile prosthesis (but see Hellstrom 2011). Spider webs were reported as used to stop bleeding in an unconfirmed case of an alligator bite in Florida, USA (Heatherly, no date).

In summary, throughout the world, spider webs have been, and are still, used to stop bleeding. However, limited scientific evidence seems to support their usefulness to stop bleeding from small cuts.

Other traditional uses of spider webs

As canvas for paintings

Amazingly, spider webs have been used as canvases for miniature paintings. Webs of the funnel web spiders (Agelinidae), *Agelena labyrinthica* (Clerck, 1757) and *Tegenaria domestica* (Clerck, 1757) were used as surfaces for painting. However, the canvases of most of the fewer than 100 surviving miniature paintings use silk from caterpillars. This style of miniature painting, using water color or Chinese ink on silk, was begun by monks in mid 18th century in the Pustertal (or Pusterhal) region in the Tyrolean Alps, currently located in northwestern Italy, close to Austria. Not surprisingly, religious themes abound in those earlier paintings; landscapes, folk costumes, and military feats themes appear later on (Cassirer 1956, Maggen 2000, Toldt 1949, Vigoreux 2015). "These works were destined for tourists and art merchants and were exported in great number to Germany, and especially to England and North America." (Vigoureux 2015). The Burritt on the Mountain open-air museum complex, located in Huntsville, Alabama, USA, houses examples of Anne Bradshaw Clopton's paintings using this unique style (1878 – 1956, Burritt on the Mountain 2015). In France, Jean-Jacques Vigoureux practices this technique and his web site contains detailed explanations of the science, art, history, and his techniques.

As textiles for garments or bed hangings

Spider webs have been used to produce garments of extraordinary beauty (Morgan 2015). Although efforts to harvest spider webs had been considered for a long time, Paul Camboué (1849 – 1929), a French Jesuit priest that worked in Madagascar towards the end of the 19th century, was the first to be successful harvesting significant amounts of silk. *Nephila* spiders and their golden webs were abundant in the field and "used by the natives for fastening flowers on sunshades and for other purposes" (Morgan 2015). Camboué implemented the more systematic extraction of silk from the spiders. Eventually a mechanical device was manufactured by Camboué and later improved by other workers in

Madagascar, including M. Jolly and M. Nogué. These improvements resulted in two large golden bed hangings that were exhibited at the Paris (France) *Exposition Universelle* in 1900 (Anonymous 1900, last name misspelled Camboné; Anonymous 2012). Thereafter, others have followed with magnificent works of art, including golden capes (Leggett 2009; Peers and Godley, no date a and b).

According to Ha (2014), "[p]eople in Madagascar work to collect over one million golden orb spiders and extract silk from them to make a textile with golden tint. It was also used to make leather garment interwoven with spider silk to protect the soldiers from enemy arrows. This protection could be due to the high content of aluminium in the silk."

Spider silk has also been used as part of the rituals in the Republic of Vanuatu (formerly part of was used to be known as New Hebrides), located in the southwestern Pacific. According to Taylor (2009), "[i]n the Melanesian New Hebrides a special conical cap made of spiders' webs was used for smothering widows – the task being performed by the widow's son." More recently, however, Morgan (2015) concluded that "[r]ather than being a 'smothering hood', this object is a type of spider web headdress ["from webs spun by *Nephila plumipes*" (Latreille, 1804) "spiders and the smaller *Nephila pilipes*" (Fabricius, 1793)] predominantly used in specific initiation ceremonies, to be bought and worn by the candidate as he enters a higher social grade." Figure 6 in Morgan (2015, also on the cover of the forthcoming book, *Gossamer Days: Spiders, Humans and Their Threads*, Morgan 2016) shows a "Malakulan man in spider web 'tunic'; and on p. 12 '… the man who reaches this level is said "to be dead." This means that even though he is still alive, he has in some sense attained the condition of the ancestor.'

Fishing

Spider webs are also valued by "fishermen in the Indo-Pacific Ocean [as they] use the web of [species of] *Nephila* to catch small fish." (Ha 2014).

Some Aspects of the Biology of Spider Webs

In modern biomaterials science, spider webs are considered model systems due to their strength and flexibility (Brooks 2013, Kluge et al. 2008). Consequently, intense efforts have been put into: 1) unraveling the molecular biology of the silk threads, 2) investigating whether silk can be synthesized *in vitro*, without the spiders, and 3) modern medicinal and biomaterials uses.

Unraveling the molecular biology of the spider web silk threads. One of the most characteristic features of spiders is their use of thready, mostly proteinaceous, fibers, called silk. The silk fibers are produced by several glands (Vollrath and Knight 2001) located ventrally in the spider's posterior body part, the opisthosoma and extruded through the spigots, located on modified appendages, called spineretts (Figure 3). Although the oldest true spiders are dated *circa* 315 Ma (Carboniferous of Russia and Ukraine), the oldest evidence of spinnerets has been found in *Arthrolycosa antiqua* Harger, 1874 (Arthrolycosidae), another Carboniferous fossil spider, dated approximately 305 Ma (Mason Creek *Lagerstätte* located near the city of Norris, Grundy County, northern Illinois, USA, Selden et al. 2014, see also Selden et al. 2008 for possible silk from a Devonian arachnid). Ancient evidence of spider web was also reported by Brassier et al. (2009) for the Early Cretaceous (circa 140 Ma) of England.

Spiders can produce different types of fibers (Tokareva et al. 2014, Vollrath and Knight 2001) and can spin more than one type of silk thread simultaneously. Once exposed to air, the silk threads harden (May, no date; Melina 2010; Vollrath and Knight 2001) although, at least in the laboratory, recombinant spider silk protein can be resolubilized (Jones 2015). These fibers have different mechanical properties (Rising et al. 2005). The fibers form a web used for prey capture - and modifiable depending on the size of the prey item (Boutry 2011) - and as a mating site (Foelix 2011). Other arthropods often inhabit spider webs contributing to forming a complex web of biological interactions on the spider web (Mercado and Santiago-Blay 2015). Recent videos (British Boadcasting Corporation 2015, National Public Radio 2014) and pedagogical activities (Palmquist 2015) describe additional details of spider webs and spider locomotion, respectively.

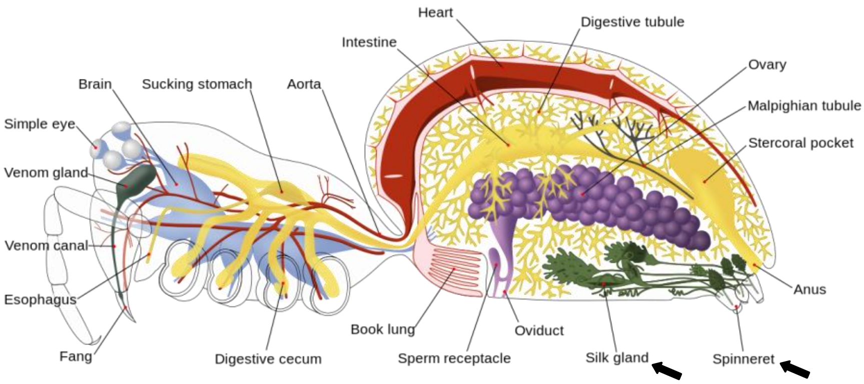
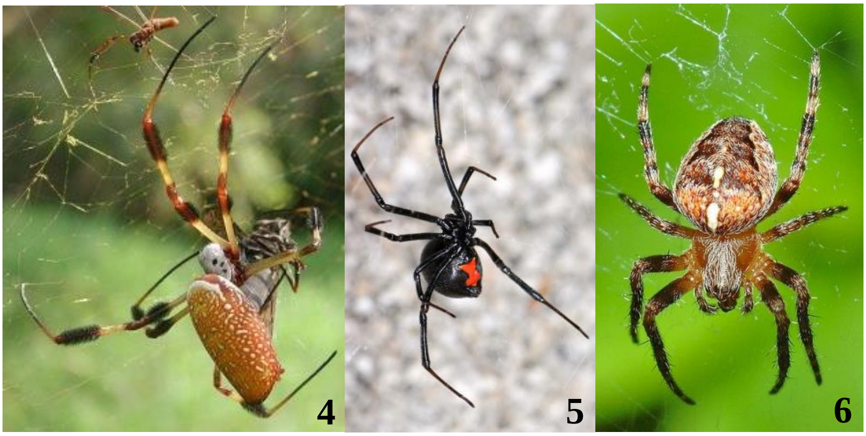


Figure 3. Spider anatomy. Spinnerets and silk glands are located posteroventrally. Source: https://upload.wikimedia.org/wikipedia/commons/thumb/2/22/Spider_internal_anatomy-en.svg/1280px-Spider_internal_anatomy-en.svg.png . http: //creativecommons.org/licenses/by/3.0/

Investigating whether silk can be synthesized in vitro, without the spiders. *Protein Components*. Spider silk contains proteins made mostly from non-essential amino acids (Rising et al. 2005). The spiders *Nephila clavipes* (Linnaeus, 1767) (Nephilidae, Figure 4), an orb weaver, and *Latrodectus hesperus* Chamberlin and Ivie, 1935 (Theridiidae, Figure 5), a cob weaver black widow, are considered model spiders to garner genetic data about the silk

(Vierra et al. 2011). Dragline silk is mostly composed of two proteins, each called spidroin. The partial DNA-sequence for these dragline silk proteins, called Major Ampullate Spidroin 1 (MaSp1) and Major Ampullate Spidroin 2 (MaSp2), contain repetitive sequences with polyalanine regions, varying between four to ten alanine residues in between glycine-rich sequences. The ratio of these two proteins has been found to differ between species, some differences being linked to diet and the environment. The major ampulla stores the liquid mixture of major ampullate spidroins. During extrusion, this liquid mixture is converted to insoluble fibers through chemical and mechanical events, such as a decrease in pH to 6.3 (Vierra et al. 2011), change in salt concentration, and elongational flow. The result of these events is a semicrystalline material with beta-sheet nanocrystals formed from short polyalanine segments.

Transmission electron and atomic force micrographs of cross-sectioned dragline silk fibers from the spider *N. clavipes* revealed that the fibers consist of several concentric regions. The largest unit is the multilayered proteinaceous core (circa 1300-2000 nm) made out of spidroins. An intermediate relatively thin ring (circa 50-100 nm) is composed of glycoproteins. The outermost ring is composed of a thin layer of lipids (only 10-20 nm). As the layers moved outward, they are increasingly resistant to chemicals and presumed protective (Sponner et al. 2007).



Figures 4-6. Spiders of used in biomaterials research mentioned in this paper. 4. *Nephila clavipes*. 5. *Latrodectus hesperus*. 6. *Araneus diadematus*. Sources listed in order used. https://commons.wikimedia.org/wiki/File:Golden_silk_spider_-_*Nephila_clavipes*.jpg , https://commons.wikimedia.org/wiki/File:Latrodectus_hesperus_(F_Theridiidae).jpg , and https://commons.wikimedia.org/wiki/File:*Araneus_diadematus*_(aka).jpg . Authors: 4. Stephen Friedt, 5. Marshal Hedin, and 6. André Karwath.

Non-proteins components. Using atomic absorption spectrophotometry, Ha (2014) found that minerals (99322 µg/g web dry weight) and metals (80655 µg/g web dry weight) make up a tiny fraction of *Araneus diadematus* Clerck, 1757 (Araneidae, Figure 6) silk. Calcium was the most abundant mineral and aluminum as well as iron were the most abundant metals, possibly strengthening the threads. Because the web-silk of the *A. diadematus* is rich in minerals and metals, it is considered beneficial for human antisepsis and wound healing as the silk contains minerals and Vitamin K, both useful in coagulation. The bacteriostatic and fungistatic properties of spider silk prevents microbial destruction of strands of the spider web (Ha 2014).

A simplified depiction of spider silk threads is shown in Figure 7. Repeating units, or modules, represented by boxes, are flanked by non-repeating units. Some modules (in gold) give the thread strength; others (in violet) confer flexibility.

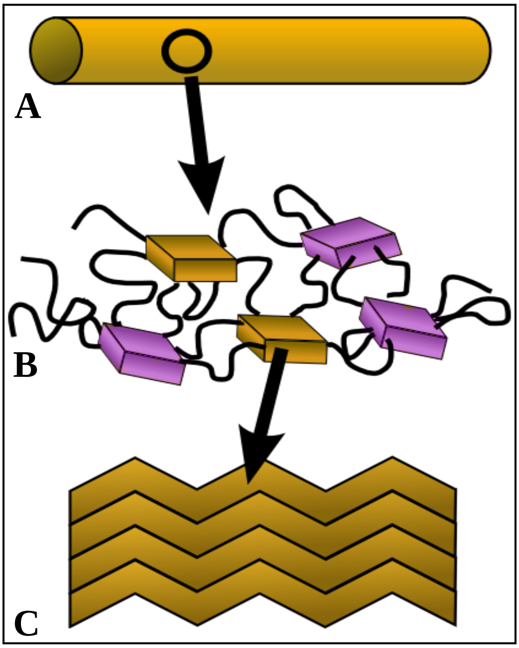


Figure 7. A spider web thread at different magnifications, emphasis on proteins. A. Single thread (1 – 50 micrometers in diameter; typical human hair is approximately 100 micrometers in diameter). B. Small blocks represent repeated modules some (made out of multiple Alanine amino acids, or polyA, in gold) giving toughness to the thread, and others (made out of the amino acids, Glycine, Proline, and Glutamine, in violet) giving elasticity to the thread. They are interspersed by non-repetitive units (black curvy lines). C. Beta-sheet local structure of the protein formed at the very small scale (circa 7 nanometers tall). Sources: Hagn and Kessler (2009). Author, "Kebes at en.wikipedia", slightly modified.

Recent studies have examined structure-function relationships throughout different lengths of the spider silk thread (Tarakanova and Buehler 2012). These studies demonstrate that the web is highly adapted, and that the material as well as hierarchical structure is important for its functional properties, regardless of its length. Spider silk has a hierarchical structure that contains weak hydrogen bonds at its core and uses multiple scales to regulate the material behavior. Materiomics bridges building block components to mechanical behaviors to characterize material systems on multiple length scales. This could lead to many possibilities, such as using artificially spun spider silk to produce high-performance fibers, multifunctional materials, and platforms for tissue engineering or structural applications in the aerospace or defense industry. Silk's superior properties come from the balance of strength and extensibility at the molecular scale.

Modern Medical and Biomaterials Uses of Spider Webs

Biomedical Uses. For the last two decades, there has considerable progress in the pursuit of medical applications of spider silk because this biomaterial contains a unique combination of high tensile strength, high breaking strain, and ultra low weight (Vierra et al. 2011, Dams-Kozlowska et al. 2013, Kundu et al. 2014, Kuwana et al. 2014, Tokareva et al. 2013). Spider silk has been considered as surgical thread, bandages, ropes, etc. (May, no date). Silk threads can assemble into many shapes, which could be used for bidimensional or tridimensional scaffolds for tissue engineering and repair. The wide availability of biotechnology tools has motivated researchers to find cheaper and reliable ways to control the manufacturing of spider silk without the spiders, in the laboratory, *ad libitum* (Hare 2013). Herein, I have organized some of the finds using the functional (as contrasted to developmental) classification of tissue types.

Connective and epithelial tissues. Several research groups have used different methods to purify and assemble spider silk. One of those methods includes the use of recombinant spider silk, called 4RepCT (Fredriksson et al. 2009). The spider silk produced is located in an aqueous solution and thereafter it self-assembles into macroscopic fibers. Fibroblast-like cells, which are common in animal connective tissues, are important in wound healing and are responsible for the secretion of the extracellular matrix, as well as new capillaries (epithelial tissue) that were found in the center of the 4RepCT bundles after just one week. This suggests that 4RepCT implants support and promote the migration of fibroblasts and angioblasts, primordial cells that form the vessels of the blood circulatory system. The 4RepCT fibers support the formation of new tissue and are eventually replaced as they are biodegradable. Also, several laboratories are exploring using the spider silk protein fibers, fibroin, as scaffolds to guide chondrocyte, common cells in cartilaginous tissues, growth (Aoki et al. 2003, Kachi et al. 2010, Kambe et al. 2010, Tanada 2005).

Nervous. Silk from spider webs has been used in the regeneration of peripheral nerves (Allmeling et al. 2008, Fredriksson et al. 2009, Rising 2014). Peripheral nerve injury is usually treated with autologous, or from the same individual, nerve grafts, but they are limited and associated with a loss of sensation at the donor site. Allmeling et al. (2008) used spider silk to evaluate its suitability as scaffolding or guiding material for nerve generation. Nerve grafts were constructed from veins filled with spider silk fibers, either in a cell-free environment or with isogenic cells, or cells with the same or similar genotypes Schwann cells. These nerve grafts were used to bridge a 20-mm gap in the sciatic nerve (the largest nerve in humans) of rats. As it has been done since the late 19th century (Anonymous1900, Leggett 2009), the spider silk was mechanically pulled out of adult female *Nephila* sp. with a spider silk winding machine (c.f. *Harvesting silk from a spider*, Anonymous 2013). The spiders were first refrigerated for a few minutes and then further refrigerated with a compress. Then, the major ampullate gland was stimulated before silk harvesting, with an average of 150 meters of silk collected per hour. The inferior cava vein of rats was dissected and replaced with spider silk, and rats were treated with a gelatinous protein mixture, called Matrigel, with growth medium or left untreated. Indeed, *N. clavipes* silk fibers promoted the migration of Schwann cells along spider silk fiber. Axonal regeneration was examined and bundles of neurites had equally distributed healthy motor and sensory neurons. Fully regenerated neural processes were visible and spider silk fibers could not be detected. In sum, Allmeling et al. (2008) found that spider silk fibers are suitable for peripheral nerve conduits in tissue engineered only from veins and spider silk. This resulted in a good immunological tolerance and minimal cell morbidity at the donor site.

Novel Biomaterials. In the context of use in humans, these novel materials made, in part, with spider-derived silk, should be safe (e.g. "non-immunogenicity, biocompatibility, slow and/or controllable biodegradability, non-toxicity, and structural integrity"; Kundu et al. 2014, see also Dams-Kozlowska 2012, Tokareva et al. 2014). Recently, Dams-Kozlowska 2012, tested whether "two bioengineered spider silk proteins composed of different numbers of repetitive motifs of the consensus repeats from spidroin-1 from *Nephila clavipes* (15X and 6X) were cloned and expressed in *Escherichia coli*. … The soluble spider silk proteins were not cytotoxic and did not activate macrophages over a wide range of concentrations, except when present at the highest concentration. Films made of the different silk variants supported the growth of the cells. Based on these data, and as the biodegradation rate of silk is very slow, the bioengineered spider silks are presumed safe biomaterials for biomedical applications." Kundu et al. (2014), mostly using insect-derived silks, have recently reviewed the substantial variety of structural designs that bioengineered silk can have addressing similar safety concerns.

The success of biomaterial-derived biodevices tends to be based on the biomimetic architecture of the materials. Spider silk has been used to reduce the diameter of synthetic fibers. For instance, Zhang et al. (2011) used silk from the tarantula, *Ornithoctonus huwenus* (Wang, Peng, and Xie, 1993), currently placed in the genus *Haplopelma*, as *H. schmidti* von Wirth, 1991, Theraphosidae, to produce thinner and mechanically enhanced electrospun polylactic acid (PLLA), or polylactide, a biodegradable polyester fiber. The mechanical and hydrophilic properties of PLLA fibers were improved by adding the spun spider silk fibroins, giving excellent biocompatibility to the composite fibers. Electrospun polylactic acid fibers are thought to have many applications in tissue engineering, scaffold material, wound dressing, and more that is similar to the possible applications of spider web. Promising results using *in vitro* models suggest that bioengineered spider web fibers could have a place in future reconstructive surgery.

Challenges and Future Directions

Challenges. Economic production of spider silk in vivo and in vitro. There have been difficulties in producing silk for human-related uses as many spiders are hard to farm. Spiders tend to be cannibalistic, hence keeping them in separate containers causes a space problem. Also, most spiders tend to produce relatively small amounts of silk to make it economically feasible (Rising 2014). Thus, the production of spider silk using non-spider, or heterogous, systems has been explored. Additionally, Jones (2015) noted that "[t]wo major hurdles face the production of recombinant spider silk protein (rSSp) based materials. First, the production of sufficient quantities of rSSp has proven difficult due to their highly repetitive nature and protein size (>250kDa). Secondly, rSSp and native silks are practically insoluble in water based solutions, necessitating the use of harsh organic solvents that can remain in the material after production."

Standard modern molecular techniques allowed Vendrely et al. (2008) to produce spider silk recombinant DNA in *Escherichia coli* (Migula 1895) Castellani and Chalmers 1919, a bacterial host. The final result was spider silk in the form of a film, which can scaffold cell growh (Dams-Kozlowska et al. 2012), not a thread. *Escherichia coli* expression systems are generally preferred to enrich heterologous proteins because of its high expression levels which facilitate commercially-scalable purification methods. Yet, according to Vendrely et al. (2007), it is difficult to obtain recombinant spider-silk proteins because the silk genes are large and have repetitive sequences. Using bacterial hosts, such as *E. coli,* to produce silk may be difficult because of the large gene size and the fact that bacteria have a different codon use than spiders and bacteria often remove repetitive sequences.

Hauptmann et al. (2013) discuss the possibility of producing spider silk from plants. Plants have cost, safety, and scalability advantages as compared to conventional eukaryotic and prokaryotic cell systems. They reported that different recombinant spider silk proteins have been produced in tobacco *Nicotiana tabacum* L., 1753; potato, *Solanum tuberosum* L., 1753 (both Solanaceae) leaves, tubers, and others (Vendrely et al. 2007). Plant-based expression systems for producing recombinant spider silk proteins form stably transformed transgenic plants suitable for protein expression. It was found that seed-specific expression combined with retention of the proteins in the endoplasmic reticulum provided the most spider silk proteins in transgenic seeds. The most promising spider silk protein production seems to be the enrichment of heterologous spider silk proteins in protein-rich legume seeds, but this has not been fully demonstrated yet.

According to Sponner et al. (2007), attempts are being made to mass produce silk, but the properties of spider-produced silk have not been matched yet. This could be because no full length spider silk sequences have been expressed, since N- and C-termini may contribute to fiber formation. Also, the major ampullate silk's properties vary depending on the spinning speed. The dragline silk needs to be produced at a fast speed and acidified (Melina 2010; Vollrath and Knight 2001), resulting in a stiff fiber that can support the spider's body weight. A solution to these problems could be to use engineered, double-stranded DNA oligonucleotides that have an adjusted bacterial codon usage, to form silk genes that are expressible in bacteria. Another potential solution is to use eukaryotic hosts, instead of bacteria, to express the spider's cDNA. Eukaryotic cells are thought to make good hosts because their codon usage is similar to that of spiders. Nexia Biotechnologies (Vaudreuil-Dorion, Quebec, Canada) developed a method to produce spider silk in the milk of transgenic goats, *Capra aegagrus hircus* (Linnaeus, 1758). Unfortunately, the goats produced little silk protein in their milk.

A baculovirus expression system in cells of the domesticated silk moth (Bombycidae), *Bombyx mori* (Linnaeus, 1758), for silk gene expression has been developed (Miao et al. 2005). The use of transgenic silkworms to produce silk fibers have developed much further. For instance, Kuwana et al. (2014) demonstrated the commercial feasibility for machine reeling, weaving, and sewing of transgenic silkworm/spider silk [dragline from the orb weaver spider, *Araneus ventricosus* (L. Koch, 1878)], including the weaving of a vest and scarf.

Future Directions. Tokareva et al. (2014) suggests that a greater variety of silk fibers should be explored, particularly as molecular bioengineering techniques have improved so much. In combination with polylactide fibers, ever more purified bioengineered spider threads seem to hold promise as scaffolding materials in reconstructive surgery (e.g. neurons, Allmeling et al. 2008) and the circulatory system (e.g. vessels, Fredriksson et al. 2009). As materials to stop bleeding from small cuts, I can see native spider webs surviving as part of traditional medicine. However, spider webs are no match for human-made materials, such as *QuickClot*® (Anonymous 2008), *VetiGel* (Bloomberg 2014), or a "trauma foam" (Columbia Broadcasting System 2014) in rapidly and safely halting internal haemorhages.

Acknowledgements

Dr. Jason Dunlop (Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany) and Dr. Paul A. Selden (Department of Geology, University of Kansas, Lawrence, Kansas, USA) provided paleobiological references. Mr. Jack Lewis (Florida, USA) gave permission to reproduce Figure 1. Mr. Mark Tayac and his colleagues (Piscataway Indian Nation) brought numerous artifacts and provided a spectacular demonstration of Native American culture. Ms. Barbara Dennis (The Pennsylvania State University, York, Pennsylvania, USA) photogaphed a dreamcatcher (Figure 2). Mr. Hainhan Zhao (Penn State University, York) communicated information traditional uses of spider webs in China. Ms. Suzanne Shaffer (Penn State University, York), a connoisseur of Korean drama, provided the original idea to pursue this project. Two anonymous reviewers and the Guest Editor offered numerous constructive comments that greatly improved the typescript.

Literature Cited

Allmeling, C., A. Jokuszies, K. Reimers, S. Kall, C. Y. Choi, G. Brandes, C. Kasper, T. Scheper, M. Guggenheim, and P. M. Vogt. 2008. Spider silk fibres in artificial nerve constructs promote peripheral nerve regeneration. *Cell Proliferation* 41: 408–420. http://dx.doi.org/10.1111/j.1365-2184.2008.00534.x

Allmeling, C., C. Radtke, and P. M. Vogt. 2013. Technical and biomedical uses of nature's strongest fiber: spider silk. pp. 475-490. In, Nentwig, W. (Editor). Spider Ecophysiology. Springer-Verlag. Berlin, Germany. 529 pp. http://dx.doi.org/10.1007/978-3-642-33989-9

Anonymous. 1900. A rival of the silkworm. *The Literary Digest* XXI(23):697. http://www.archive.org/stream/literarydigest21newy#page/694/mode/2up).

Anonymous. 2008. *Field eXpedients: Quik-Clot Life Saving Powder-and Now Gauze*. 2'27", https://www.youtube.com/watch?v=e9xvIbKBJn4

Anonymous. 2012. Golden cape made with silk from a million spiders - in pictures. *The Guardian* (23 January 2012). http://www.theguardian.com/artanddesign/gallery/2012/jan/23/golden-silk-cape-spiders-in-pictures

Anonymous. 2013. Harvesting silk from a spider – video. *The Guardian* (12 January 2013). http://www.theguardian.com/science/video/2013/jan/12/fritz-vollrath-spider-silk-video

Aoki, H., N. Tomita, Y. Morita, K. Hattori, Y. Harada, M. Sonobe, S. Wakitani, and Y. Tamada. 2003. Culture of chondrocytes in fibroin-hydrogel sponge. *Bio-medical Materials and Engineering* 13:309–316.

Ballal, V. and J. Varghese. 2015. Web yourself to cease bleeding. *Dentistry* 5(2):e115. http://dx.doi.org/10.4172/2161-1122.1000e115

Bam, J., S. Rai, D. Bhattacharya, S. Maiti, S. Islam, P. Pathak, A. K. Bera, and S. M. Deb. 2015. Indigenous curative and prophylactic traditional practices used against haematophagous leeches in Arunachal Pradesh and Sikkim. *Indian Journal of Traditional Knowledge* 14(3):493-497. http://nopr.niscair.res.in/bitstream/123456789/32108/1/IJTK%2014(3)%20493-497.pdf

Bennett, B. C. 2007. Doctrine of Signatures: an explanation of medicinal pant discovery or dissemination of knowledge? *Economic Botany* 61(3):246-255. http://dx.doi.org/10.1663/0013-0001(2007)61[246:DOSAEO]2.0.CO;2

Bloomberg. 2014. *VetiGel: The Band-Aid of the Future Stops Bleeding Instantly*. https://www.youtube.com/watch?v=dJLxRcU9No4 3'59". Note, there are several spellings for VetiGel, including Vetigel and Veti-gel.

Bogush, V. G., K. V. Sidoruk, L. I. Davydova, I. A. Zalunin, D. G. Kozlov, M. M. Moisenovich I. I. Agapov, M. P. Kirpichnikov, and V. G.Debabov. 2011. Recombinant analogue of spidroin 2 for biomedical materials. *Biochemistry, Biophysics and Molecular Biology. Doklady Biochemistry and Biophysics* 441(1):276-279. http://dx.doi.org/10.1134/S1607672911060093

Boutry, C. 2011. A biological and evolutionary approach to the study of spider silk material properties. PhD. Dissertation. Department of Biology. The University of Akron. Akron, Ohio, USA. 131 pp. https://etd.ohiolink.edu/!etd.send_file?accession=akron1301684925&disposition=inline

Brasier, M., L. Cotton, and I. Yenney. 2009. First report of amber with spider webs and microbial inclusions from the earliest Cretaceous (c. 140 Ma) of Hastings, Sussex. *Journal of the Geological Society* 166:989–997. http://dx.doi.org/10.1144/0016-76492008-158

British Broadcasting Corporation (BBC). 2013. Galen. *In Our Time*. BBC Radio. http://www.bbc.co.uk/programmes/b03c4dys 43'. Additional references on Galen are provided in the reading list of this article.

British Broadcasting Corporation (BBC) 2015. The Real Spider-Woman. *BBC One*. https://www.facebook.com/BBCOne/videos/1030694156951002/ 3'14".

Brooks, C. 2013. Tangled webs: Why scientists want to recreate spider silk. British Broadcasting Coorporation (BBC). http://www.bbc.co.uk/science/0/21685308

Burritt on the Mountain. 2015. http://www.burrittonthemountain.com/. Brief statement of Mrs. Anne Bradshaw Clopton's paintings on spider web canvas can be found here: http://www.burrittonthemountain.com/burritt-site-and-facility/burritt-mansion/burritt-museum/114-roatating-exhibits.

Cassirer, I. 1956. Paintings on cobwebs. *Natural History Magazine* 65:202–207/219–220.

Columbia Broadcasting System (CBS) Boston, WBZ 4. 2014. *MGH Surgeon Developing Life-Saving Trauma Foam*. https://www.youtube.com/watch?v=O_C6R6aRfhY . 2'12"

Dams-Kozlowska, H., A. Majer, P. Tomasiewicz, J. Lozinska, D. L. Kaplan, and A. Mackiewicz. 2012. Purification and cytotoxicity of tag-free bioengineered spider silk proteins. *Journal of Biomedical Materials Research Part A* 101(2):456-564. http://dx.doi.org/10.1002/jbm.a.34353 (Published first online in 2012, printed in 2013.)

Ediriweera, E. R. H. S. S., N. G. A. A. S. Nanayakkara, O. T. M. R. K. S. B. Kalawana, and Y. K. S. S. L. Sugathadasa. 2011. A review on traditional veterinary medical practices in Sri Lanka with special reference to cattle diseases. *Tropical Agriculture Research & Extension* 13(3): 55-62. https://www.mysciencework.com/publication/read/8297611/a-review-on-traditional-veterinary-medical-practices-in-sri-lanka-with-special-reference-to-cattle-diseases#page-null

El-Hennawy, H. K. 2012. Spiders in Africa. pp. 1-34. *Animal Resources and Diversity in Africa*. In, Ghabbour, S. I. (Editor). *Encyclopedia of Life Support Systems* (EOLSS). Developed under the auspices of the UNESCO. EOLSS Publishers. Paris, France. Full pagination unavailable. http://www.eolss.net (Note to readers: Apparently, access to this paper needs login and password.)

Foelix, R. F. 2011. *Biology of Spiders*. Third Edition. Oxford University Press. New York, NY, USA. 419 pp.

Fredriksson C., M. Hedhammar, R. Feinstein, K. Nordling, G. Kratz, J. Johansson, F. Huss, and A. Rising. 2009. Tissue response to subcutaneously implanted recombinant spider silk: An in vivo study. *Materials* 2(4):1908-1922. http://dx.doi.org/10.3390/ma2041908

Hagn, F. and H. Kessler. 2009. Spider silk proteins: Structure and function revealed by NMR spectroscopy. *Laboratory Journal – Business Web for Users in Science and Industry*. http://www.laboratory-journal.com/science/chemistry-physics/spider-silk-proteins-structure-and-function-revealed-nmr-spectroscopy. 6 pp.

Ha, E. M. 2014. Minerals and heavy metals constituents of a spider web made by *Araneus diadematus* (Araneidae). *International Journal of Biology, Pharmacy, and Allied Sciences* 3(1):21-30. http://ijbpas.com/pdf/1388905070MS%20IJBPAS%202013%201664.pdf

Hare, D. 2003. What of animal cloning? *The Canadian Veterinary Journal* 44(4):271-272. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC372227/

Hauptmann, V., N. Weichert, M. Rakhimova, and U. Conrad. 2013. Spider silks from plants – a challenge to create native-sized spidroins. *Biotechnology Journal* 8:1183–1192. http://dx.doi.org/10.1002/biot.201300204

Hayward, C. 2000. Obituaries: Catherine Morrah (née Day). *British Medical Journal* 321(7257):388.

Heatherly, J. A. (posted by) No date. Gator bite victim used spider web to stop bleeding. WEAP NS Media. *Tactical and Survival Magazine* (October). http://weaponsmedia.com/gator-bite-victim-used-spider-web-to-stop-bleeding/ (Accessed on November 15, 2015.)

Hellstrom, W. J. G. 2011. Using wound drains for the uncomplicated penile prosthesis. Con. *The Journal of Urology* 186(4):1188-1189. http://dx.doi.org/10.1016/j.juro.2011.07.042

Hulden, L. 2011. The first Finnish malariologist, Johan Haartman, and the discussion about malaria in 18th century Turku, Finland. *Malaria Journal* 10(1):43. http://dx.doi.org/10.1186/1475-2875-10-43

Jones, J. A. 2015. *Aqueous Solvation Method for Recombinant Spider Silk Proteins*. PhD Dissertation. Department of Biology. Utah State University. Logan, Utah, USA. 159 pp. http://www.intechopen.com/source/html/46460/media/image1.jpeg, http://digitalcommons.usu.edu/etd/4267

Kachi, N. D., A. Otaka, S. Sim, Y. Kuwana, Y. Tamada, J. Sunaga, T. Adachi, and N. Tomita. 2010. Observation of chondrocyte aggregate formation and internal structure on micropatterned fibroin-coated surface. *Bio-medical Materials and Engineering* 20:55–63.

Kambe, Y., K. Yamamoto, K. Kojima, Y. Tamada, and N. Tomita. 2010. Effects of RGDS sequence genetically interfused in the silk fibroin light chain protein on chondrocyte adhesion and cartilage synthesis. *Biomaterials* 31:7503–7511. http://dx.doi.org/10.1016/j.biomaterials.2010.06.045

Karadeniz, C., F. G. Pınarlı, A. Oğuz, T. Gürsel, and B. Canter. 2007. Complementary/alternative medicine use in a pediatric oncology unit in Turkey. *Pediatric Blood & Cancer* 48(5):540-543. http://dx.doi.org/10.1002/pbc.21012

Köhler, T. S. and W. J. Hellstrom. 2011. Using wound drains for the uncomplicated penile prosthesis. Pro. *The Journal of Urology* 186(4):1187-1188. http://dx.doi.org/10.1016/j.juro.2011.07.042

Kluge, J. A., O. Rabotyagova, G. G. Leisk, and D. L. Kaplan. 2008. Spider silks and their applications, *Trends in Biotechnology* 26(5):244-251. http://dx.doi.org/10.1016/j.tibtech.2008.02.006

Kumari, P., M. K. Chahar, G. Spandana, B. S. Thippeswamy, and S. Badami. 2013. Spider web ointment: A traditional based approach in cutaneous wound healing. *Indian Journal of Traditional Knowledge* 12(4):657-663.

Kundu, B. N. E. Kurland, S. Bano, C. Patra, F. B. Engel, V. K. Yadavalli, and S. C. Kundu. 2014. Silk proteins for biomedical applications: Bioengineering perspectives. *Progresss in Polymer Science* 39(2):251-267. http://dx.doi.org/10.1016/j.progpolymsci.2013.09.002

Kuwana, Y., H. Sezutsu, K.-i. Nakajima, Y. Tamada, and K. Kojima. 2014. High-toughness silk produced by a transgenic silkworm expressing spider (*Araneus ventricosus*) dragline silk protein. PLOSOne http://dx.doi.org/10.1371/journal.pone.0105325

Lambert, J. B., E. W. Donnelly, E. A. Heckenbach, C. L. Johnson, M. A. Kozminski, Y. Wu, and J. A. Santiago-Blay. 2013. Molecular classification of the natural exudates of the rosids. *Phytochemistry* 94:171-183. http://dx.doi.org/10.1016/j.phytochem.2013.06.013

Leggett, H. 2009. 1 million spiders make golden silk for rare cloth. *Wired* (Science 09.23.09). http://www.wired.com/2009/09/spider-silk/

Maggen, M. 2000. The conservation of watercolour paintings on spider webs. *In*, Spiderwebs and wallpapers: International applications of the Japanese tradition in paper conservation. *Proceedings of the International Seminar of Japanese Paper Conservation*. 14-20 December 1988. Kyoto, Japan. 197 pp.

Manamela, K. 2003. Traditional beliefs and uses of arachnids in Africa. *Annals of the Transvaal Museum* 40:151-153. http://reference.sabinet.co.za/webx/access/journal_archive/00411752/15.pdf

May, P. No date. *Spider Silk. Applications of Spider Silk*. In, *Molecule of the Month* web site. Chemistry Department at Bristol University. http://www.chm.bris.ac.uk/motm/spider/page4.htm

Melina, R. 2010. How Do Spiders Make Silk? *Live Science* http://www.livescience.com/32582-how-do-spiders-make-silk.html

Mercado, J. E. and J. A. Santiago-Blay. 2015. Multiple model mimicry and feeding behavior of the spider web-inhabiting damsel bug, *Arachnocoris berytoides* Uhler (Hemiptera: Nabidae), from Puerto Rico. *Life: The Excitement of Biology* 3(1):33-56. http://dx.doi.org/10.9784/LEB3(1)Mercado.01

Miao Y,, Y. Zhang, K. Nakagaki, T. Zhao, A. Zhao, Y. Meng, M. Nakagaki, E. Y. Park, and K. Maenaka. 2006 (Epub 2005 September 13, 2005). Expression of spider flagelliform silk protein in *Bombyx mori* cell line by a novel Bac-to-Bac/BmNPV baculovirus expression system. *Applied Microbiology and Biotechnology* 71(2):192-199. http://dx.doi.org/10.1007/s00253-005-0127-2

Mirfeld, J. of. 1407. (translated by Colton, J. B., with an *Introduction* by Berry, F. B. 1969). *Surgery. Translation of his Breviarium Bartholomei.* Part IX. Hafner Publishing Company. New York, NY, USA. 230 pp.

Morgan, E. 2015. Sticky layers and shimmering weaves: a study of two human uses of spider silk. *Journal of Design History* 16 pp. http://dx.doi.org/10.1093/jdh/epv019 First published online.

Morgan, E. 2016. *Gossamer Days: Spiders, Humans and Their Threads*. Strange Attractor. London, England, UK. 184 pp.

Newman, J. and C. Newman. 1995. Oh what a tangled web – The medicinal uses of spider silk. *International Journal of Dermatology* 34(4):290-292. http://dx.doi.org/10.1111/j.1365-4362.1995.tb01600.x

National Public Radio (NPR) 2014. *Spiders Tune in to Web's Music to Size Up Meals and Mates*. http://www.npr.org/2014/06/10/319179807/spiders-tune-in-to-webs-music-to-size-up-meals-and-mates

Palmquist, B. C. 2015. *The Itsy-Bitsy Spider: An Analysis of Spider Locomotion*. National Center for Case Study Teaching in Science. University at Buffalo, State University of New York. Buffalo, New York, USA. http://sciencecases.lib.buffalo.edu/cs/collection/detail.asp?case_id=790&id=790

Peers, S. and N. Godley. No date a. Video: Simon Peers and Nicholas Godley discuss Golden Spider Silk. Victoria and Albert Museum The world's leading museum of art and design. http://www.vam.ac.uk/content/articles/g/golden-spider-silk/

Peers, S. and N. Godley. No date b. Video: Golden Spider Silk: The Process. Victoria and Albert Museum The world's leading museum of art and design. http://www.vam.ac.uk/content/articles/g/golden-spider-silk/

Rising A. 2014. Controlled assembly: a prerequisite for the use of recombinant spider silk in regenerative medicine? *Acta Biomaterialia* 2013:10:1627. http://dx.doi.org/10.1016/j.actbio.2013.09.030

Rising, A., H. Nimmervoll, S. Grip, A. Fernandez-Arias, E. Storckenfeldt, D. P. Knight, F. Vollrath, and W. Engström. 2005. Spider silk proteins-mechanical property and gene sequence. *Zoological Science* 22(3):273-281. http://dx.doi.org/10.2108/zsj.22.273

Ritter, M. R. 1992. Take two spider webs & call me in the morning. Southern folk medicine. *North Carolina Medical Journal* 53(5):244-247. Selden, P. A., D. E. Shcherbakov, J. A. Dunlop, and K. Y. Eskov. 2014. Arachnids from the Carboniferous of Russia and Ukraine,and the Permian of Kazakhstan. *Paläontologische Zeitschrift* 88:297–307. http://dx.doi.org/10.1007/s12542-013-0198-9

Schact, K. and T. Scheibel. 2014. Processing of recombinant spider silk proteins into tailer-made materials for biomaterials applications. *Current Opinion in Biotechnology* 29:62-69. http://dx.doi.org/10.1016/j.copbio.2014.02.015

Selden, P. A., W. A. Shear, and M. D. Sutton. 2008. Fossil evidence for the origin of spider spinnerets, and a proposed arachnid order. *Proceedings of the National Academies of Sciences* of the USA 105 (52):20781–20785. http://dx.doi.org/10.1073/pnas.0809174106

Sponner, A., W. Vater, S. Monajembashi, E. Unger, F. Grosse, and K. Weisshart. 2007. Composition and hierarchical organisation of a spider silk. *PloS One* 2(10):e998-e998. http://dx.doi.org/10.1371/journal.pone.0000998

Tamada. Y. 2005. New process to form a silk fibroin porous 3-D structure. *Biomacromolecules* 6: 3100–3106. http://dx.doi.org/10.1021/bm050431f

Tarakanova, A. and M. J. Buehler. 2012. A materiomics approach to spider silk: protein molecules to webs. *The Journal of The Minerals, Metals & Materials Society* 64(2):214-225. http://dx.doi.org/10.1007/s11837-012-0250-3

Taylor, L. 2009. *Mourning Dress. A Costume and Social History*. Routledge Revivals. Routledge. Taylor & Francis Group. Abingdon, Oxon, England, UK. 324 pp.

Tokareva, O., M. Jacobsen, M. Buehler, J. Wong, and D. L. Kaplan. 2014. Structure–function–property–design interplay in biopolymers: Spider Silk. *Acta Biomaterialia* 10(4):1612-1626. http://dx.doi.org/10.1016/j.actbio.2013.08.020

Tokareva, O., V. A. Michalczechen-Lacerda, E. L. Rech, and D. L Kaplan. 2013. Recombinant DNA production of spider silk proteins. *Microbial Biotechnology* 6(6):651–663. http://dx.doi.org/10.1111/1751-7915.12081

Toldt, K. 1949. Über die Tiroler Spinnweben-bzw. Raupengespinnst-Bilder. *Veröffentlichungen des Museums Ferdinandeum* Band *26*/29. Jahrgänge 1946/49:167–206.

Vendrely, C., C. Ackerschott, L. Römer, and T. Scheibe. 2008. Molecular design of performance proteins with repetitive sequences. *Nanostructure Design* 474: 3-14. http://dx.doi.org/10.1007/978-1-59745-480-3_1

Vendrely, C. and T. Scheibel. 2007. Biotechnological production of spider-silk proteins enables new applications. *Macromolecular Bioscience* 7(4):401-409. http://dx.doi.org/10.1002/mabi.200600255

Vierra, C., Y. Hsia, E. Gnesa, S. Tang, and F. Jeffery. 2011. Spider silk composites and applications. Chapter 15. *In*, *Metal, Ceramic and Polymeric Composites for Various Uses*. (Cuppoletti, J., Editor). InTech (Rijeka, Croatia, European Union). http://dx.doi.org/10.5772/22894

Vigoureux, J.-J. 2015. *Peintures sur toiles d'araignées*. Painting on cobwebs. http://www.auxfilsdelart.com/index.htm.

Vollrath, F. and D. P. Knight. 2001. Liquid crystalline spinning of spider silk. *Nature* 410:541-548. http://dx.doi.org/10.1038/35069000

Wei, K., B.-S. Kim, and I.-S. Kim. 2011. Fabrication and biocompatibility of electrospun silk biocomposites. *Membranes* 1:275-298. http://dx.doi.org/10.3390/membranes1040275

World Spider Catalog. 2015. *World Spider Catalog*. Natural History Museum Bern, Switzerland. Online at http://wsc.nmbe.ch . Version 17.0. (Accessed on January 25, 2016.)

Wright, T. 2013. *William Harvey. A Life of Circulation*. Oxford University Press. Oxford, England, UK. 288 pp.

Zhang, M., T. T. Yi, Y. M. Zhang, L. Zhang, W. Wu, A. L. Zhang, and Z. J. Pan. 2011. *Ornithoctonus huwenna* spider silk protein attenuating diameter and enhancing strength of the electrospun PLLA fiber. *Polymers for Advanced Technologies* 22(1):151-157. http://dx.doi.org/10.1002/pat.1860