

Matter of Opinion

Beyond bioinspiration with bionicomposites

Nicola M. Pugno^{1,2,*}

This Opinion discusses the future of bioinspiration, going beyond it and thus the very inspiration from nature, considering the relevant example of bionicomposites, and, in particular, the potentially superior silk spun by spiders fed with nanomaterials.

The past

The Italian artist, inventor, and scientist Leonardo da Vinci (1452–1519) can probably be considered the father of bio-inspired design, as illustrated, for example, by his artificial wings and flying machines based on bird observation and dissection. Five centuries on from his death, bioinspiration is attracting widespread attention worldwide, both in industry and academia, especially in the mechanics community. Indeed, mechanics—writes da Vinci—is the paradise of mathematical sciences because that is where they bear fruit.¹

Many organisms have adapted to their living environments by producing extremely efficient materials and structures, e.g., by exhibiting impressive mechanical, thermal, and optical properties that, in the past, we were unable to observe and that current technology is only becoming partially able to observe, e.g., via atomic force or tunneling or scanning electron microscopies, and reproduce, e.g., via 3D nanoprinting, nanolithography, and laser texturing. These properties are often achieved using hierarchical structures spanning scales from nano to macro.

The present

Thus far, bioinspired approaches have been successful in identifying so-called bioinspired materials, structures, and devices in terms of quasi-static mechanical properties, such as extreme strength (e.g., limpet teeth, sea shells), toughness

(e.g., spider silk, bone), and high or low adhesion (e.g., gecko feet or lotus leaves, respectively), but comparatively little work has been done as far as dynamic ones are concerned (e.g., vibration damping, noise insulation, sound amplification). In particular, currently existing knowledge of how hierarchical architectures can play a role in the optimization of natural structures (although concurrent length scales no doubt allow multiple frequency ranges to be addressed) is relatively limited. We have recently reviewed the main work that has been done to analyze structural optimization for dynamic mechanical properties, highlighting some common traits and strategies in different biological systems and related bioinspired metamaterials.²

The future

While new fields such as bioinspired metamaterials will further emerge, new concepts beyond bioinspiration will also appear in the future. Here, we consider the relevant example of bionicomposites, which we have defined as³: “a new class of composites produced by living organisms after assimilating synthetic nanomaterials from the surrounding environment.” Considering the difficulty in achieving good mixing between the different material phases—the current limiting factor for achieving very high performance composites—bionicomposites, where this problem is directly solved by specialized living organisms, present superior performances, and thus, their design

and production will probably become an interesting area of exploration for both science and technology. As an example, here, we consider the great challenge of mixing the, ideally, strongest artificial material, i.e., carbon nanotubes/graphene, with the toughest natural material known today, i.e., spider silk, using spiders fed with such nanomaterials to obtain the direct spinning of a nano-reinforced bionic silk.^{4,5}

One spider can produce up to seven types of silks for different purposes with excellent properties, e.g., greater strength than steel and greater toughness than Kevlar. Spider silks are composed of an amorphous matrix (of oligopeptide chains) and pseudo-crystalline regions (made up mainly of polyalanine β sheets) with dimensions between nearly 1 and 10 nm, mostly oriented in the fiber direction. Basically, it is a composite made up of a soft matrix and stiff nanoscopic reinforcing inclusions that are nevertheless long enough to be able to transfer load and reinforce the matrix itself, as well as facilitate energy dissipation by imposing longer crack paths and/or sliding at the interfaces, for example. The result is a material with high strength, especially astonishing toughness properties, and stiffness that tends to increase with applied tension, and it is made at room temperature and thus at low energy cost. It is also so environmentally friendly that it is edible.

The stiffening of silk under tension is common to most natural materials, in

¹Laboratory for Bioinspired, Bionic, Nano, Meta Materials & Mechanics, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy

²School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK

*Correspondence: nicola.pugno@unitn.it
<https://doi.org/10.1016/j.matt.2023.06.034>



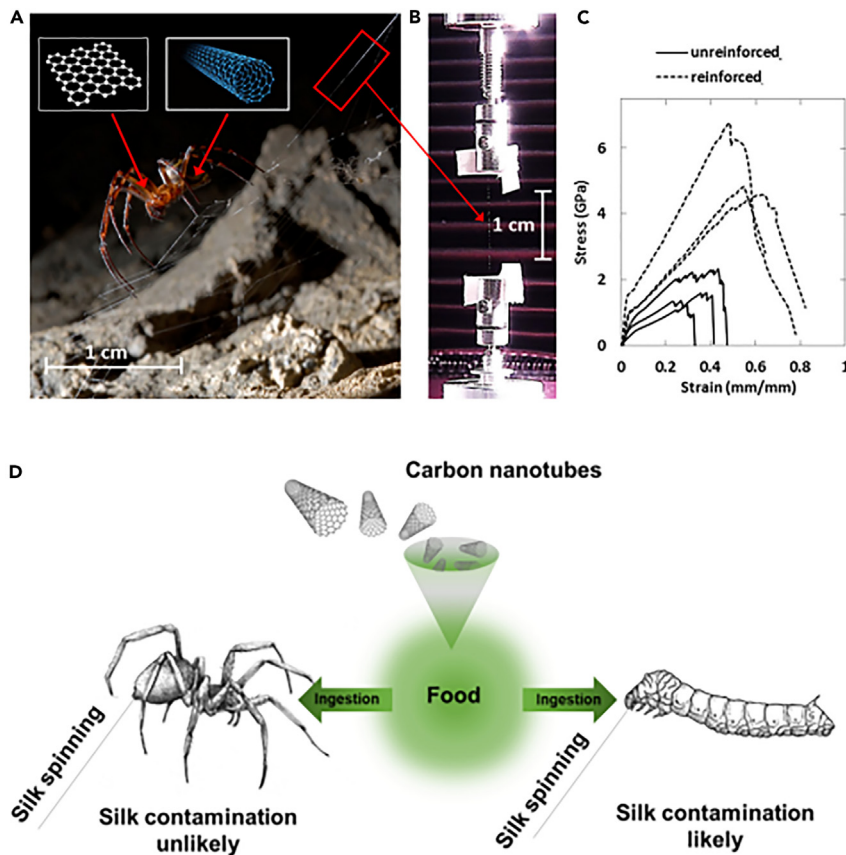


Figure 1. Bioncomposites

(A–D) Spiders fed with carbon nanotubes, graphene, and/or other nanomaterials (A) produced bionic silks that, under tensile testing (B), may in some cases be stronger and/or tougher than their natural counterparts (C).⁴ The challenge in the production of bioncomposites with spiders is greater than with silkworms because of the different biological mechanisms (D) of the two living systems and superior mechanical properties of spider silks that are thus more difficult to further reinforce.⁵

contrast to most man-made ones. For example, the most human-used material is concrete, which is elasto-softening. However, it is the stiffening of silk that makes the web robust. Tomorrow’s man-made stiffening materials could allow us to explore new scenarios, such as buildings made more resistant to aircraft impacts and even earthquakes, for which, moreover, metamaterials have already been shown to work as seismic shields.

The production of materials at ambient temperatures, such as high-strength fibers, related textiles, and composites, would also lead to significant energy savings, and thus significantly lower costs, in

the future. The cost of energy is currently soaring, not entirely justifiably from a technological or economic point of view, but it is also related to the dramatic conflicts that our world is also experiencing today, which are always absurd by definition. Moreover, we have seen a steady increase in the ratio of civilian to military deaths, rising from 1:9 in World War I, to 2:8 in the Cold War, to more than 9:1 in the War of the former Yugoslavia, adding absurdity to absurdity: in nature the struggle for survival does not go that far.

But the heart of the matter regarding nanocomposites today remains our difficulty in properly mixing nanomaterials with a matrix to achieve significant rein-

forcement, especially at their high concentrations. On this we have so far shown that we are, in essence, unable to hit the mark. Nanomaterials tend to agglomerate and thus lose their ideal characteristics, which are related to their high surface-area-to-volume ratio and intrinsic nanoscale properties. So why not start asking living organisms to try to improve the materials they themselves have specialized in producing through the availability of additional artificial ingredients, which have to be nanoscopic in order to overcome their biological barriers?

Consider the case of a spider fed with properly prepared nanomaterials. We cannot rule out the possibility that nanomaterials will reach the silk and further strengthen and toughen it. Direct evidence that this happens is difficult to observe (such as following the nanomaterial on its journey inside the spider), but partial indirect evidence results from observing the statistically enhanced mechanical properties of the silk spun by the spider in the days following contamination. This is, in essence, what we initially observed in spiders (Figures 1A, 1B, and 1C),^{4,5} and it has been observed⁶ and confirmed in silkworms.^{7–9} In the latter, integration of nanomaterials into silk is expected to be much more likely because of their spinning system. The digestive system of spiders is very complex and not directly connected with the silk glands; on the other hand, the silkworms spin silk from their mouths, to which the silk gland is directly connected, making it easier to contaminate with nanomaterials (Figure 1D). Unfortunately, silkworms produce less durable silk to begin with, though they allow for greater scalability because of our knowledge of the processes involved in extracting their silk. Someday, spider silk factories capable of overcoming the spiders’ natural tendency to cannibalism and possibly capable of further improving their silk through nanomaterials could represent a revolution in

fiber, fabric, and composite production to date unfeasible in terms of performance and energy savings. However, artificial silk is also being worked on today, and interesting results have recently been obtained in terms of production, toughness, and scalability.¹⁰

The concept of bionicomposites, broader than the specific case considered here—although extreme and therefore very relevant—involves, in general, all materials produced by living organisms, from the animal and plant world and from other organisms, like yeasts, which we have already successfully employed for the production of bionicomposites.

Looking beyond bioinspiration, we could thus see the advent of a new material era, after those of stone, bronze, iron, and current materials, that we hope will be useful for finding new solu-

tions for more peaceful and healthy lives on our planet.

DECLARATION OF INTERESTS

N.M.P. is a member of Matter's advisory board.

REFERENCES

1. Pugno, N.M. (2019). The commemoration of Leonardo da Vinci. *Meccanica* 54, 2317–2324.
2. Bosia, F., Dal Poggetto, V.F., Gliozzi, A.S., Greco, G., Lott, M., Miniaci, M., Ongaro, F., Onorato, M., Seyyedizadeh, S.F., Tortello, M., and Pugno, N.M. (2022). Optimized structures for vibration attenuation and sound control in nature: A review. *Matter* 5, 3311–3340.
3. Pugno, N.M., and Valentini, L. (2019). Bionicomposites. *Nanoscale* 11, 3102–3111.
4. Lepore, E., Bosia, F., Bonaccorso, F., Bruna, M., Taioli, S., Garberoglio, G., Ferrari, A.C., and Pugno, N.M. (2017). Spider silk reinforced by graphene or carbon nanotubes. *2D Mater.* 4, 031013. (available online since april 2015 at. <https://arxiv.org/abs/1504.06751>).
5. Greco, G., Valentini, L., and Pugno, N.M. (2022). Advances in the use of spiders for direct spinning of nanomaterials-reinforced bionic silk. *Apl. Mater.* 10, 101111.
6. Wang, J.-T., Li, L.L., Zhang, M.Y., Liu, S.L., Jiang, L.H., and Shen, Q. (2014). Directly obtaining high strength silk fiber from silkworm by feeding carbon nanotubes. *Mater. Sci. Eng. C* 34, 417–421.
7. Wang, Q., Wang, C., Zhang, M., Jian, M., and Zhang, Y. (2016). Feeding single-walled carbon nanotubes or graphene to silkworms for reinforced silk fibers. *Nano Lett.* 16, 6695–6700.
8. Xu, H., Yi, W., Li, D., Zhang, P., Yoo, S., Bai, L., Hou, J., and Hou, X. (2019). Obtaining high mechanical performance silk fibers by feeding purified carbon nanotube/lignosulfonate composite to silkworms. *RSC Adv.* 9, 3558–3569.
9. Ramos, N., Miranda, M.S., Franco, A.R., Silva, S.S., Azevedo, J., Dias, I.R., Reis, R.L., Viegas, C., and Gomes, M.E. (2020). Toward spinning greener advanced silk fibers by feeding silkworms with nanomaterials. *ACS Sustainable Chem. Eng.* 8, 011872–011887.
10. Rising, A., and Johansson, J. (2015). Toward spinning artificial spider silk. *Nat. Chem. Biol.* 11, 309–315.