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Biomimetic approaches to the design of smart textiles for protection

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Abstract: Biomimetics is a hybrid discipline that enables the transfer of technology from biological systems into the man-made world. Nature is regarded as a source of inspiration for solutions to problems encountered in various areas of engineering. Biomimetic technologies have already found commercial applications in the textile sector that reduce the environmental costs of production. This chapter discusses relevant aspects of biomimetic design and explores ideas that could enrich the design and development of smart protective textiles.

Key words: smart materials, biomimetic design, protective textiles.

7.1 Introduction: smart material design in nature

Imagine a material or structure that could grow, self-repair, reproduce, sense and respond to its environment by adapting its properties and/or behaviour. From autonomous space suits (Banks, 1993) to *Bio-fabrics* made from genetically modified botanical tissue (Ballard, 2001), science fiction writers describe visions of symbiotic garment systems that extend the natural abilities of the wearer and, to a certain extent, become an additional prosthetic organ. They envisage a huge shift in the functionality of clothing that will ultimately blur the boundaries between wearer and garment. These ideas are no longer simply the realm of science fiction; innovations in material science have permeated sectors such as technical textiles to create new products that challenge our perception of textile functionality (textile scaffolds used for medical implants made from smart polymers and gels; military and surveillance garments with interwoven electronic circuitry to enable remote communication; infant clothing incorporating temperature-sensitive pigments that signal overheating to help prevent cot death). Current technology push is directed towards the synthesis of textiles that behave (to various extents) like living organisms. There are countless examples of adaptive, multifunctional materials and structures in biology that could act as paradigms for the design of smart textiles.

Polymath Otto Schmitt invented a pivotal electronic component known today as the *Schmitt Trigger* as part of his doctoral work in the 1930s. The design of the device was inspired by Schmitt's study of the human nervous system but, unable to identify an existing phrase to describe the translation of ideas from biology to engineering design, he coined the term *biomimetics*. Other popular synonyms used across the world are bionic, biomimicry and biognosis.

Biomimetics has already delivered several commercial technologies to the technical textile sector that offer alternative and arguably improved functions to existing practice. The *Lotus Effect*, for example, is a nano-scale treatment inspired by the surface geometry of the lotus leaf and attributes superhydrophobic, self-cleaning, stain-resistant properties to the textile to which it is applied. The technology was developed by biologists Barthlott and Neinhuis from the University of Bonn in 1975 (Barthlott and Neinhuis, 1997). It offers a low energy, less polluting method to standard coatings made from silicone or organofluorochemicals (Slater, 2003).

Morphotex™ (Teijin Fibre Corporation) is a fibre that demonstrates structural (instead of pigment) colouration; the technology is based on the design of the brilliant blue South American *Morpho* Butterfly wing. The Morphotex fibre is composed of 61 alternating nylon and polyester layers, to produce a colour range of iridescent blue, green and red without the use of pigments. This technology offers an alternative, less hazardous method for introducing colour to textiles. Unfortunately, Morphotex fibres are not commercially available because low market demand prevents the production of sustainable volumes.

There are significant restrictions on available resources for making things in nature; this means that in order to survive, organisms have had to evolve clever ways of optimising the way they use materials. For the purposes of this argument, if we regard evolution in its broadest sense as a form of ‘design development’ (stretched out over millions of years with tiny incremental changes), bearing in mind there is no designer but a process of natural selection, good design survives while bad design does not (Vogel, 2003). We have significantly more types of material to make things with; this allows us to think less about the way we engineer mechanisms and structures. There are many lessons we could learn from the limitations and consequent solutions found in biology.

Intrinsic material properties are at the very core of our cultural evolution. We define history by the landmark material technology of the period, e.g. stone, bronze, iron ages. The invention and consequent mass production of synthetic polymers revolutionised fashion in the 1950s. Cheap, superlightweight stockings (*nylons*) rapidly superseded their exclusive silk counterparts and were available to all. In 1969, as Neil Armstrong took ‘one small step for man, one giant leap for mankind’ and planted a nylon flag on the surface of the moon in a suit made from 30 layers of nylon and aramid fibres, synthetic materials captured the world’s imagination and became the epitome of the *space-age*.

Most engineers, luckily, do not face the same penalties if they get a design wrong; however, our approach to the design and production of new materials is somewhat deterministic. This is inevitable because all designers work to a brief that outlines the product requirements prior to the start of the design process. What is difficult to accommodate with this model is change. What happens when conditions alter and different performance is required, or indeed the item becomes damaged? In the situation where manual adjustments to alter functionality or repair are either impossible (by design) or too 'expensive', the entire product becomes unsuitable and is replaced.

There is a fundamental difference between the nature of materials in biology and those of the man-made world: we design *with* materials while materials *become* in nature. We rely on the material to deliver properties such as strength, toughness etc. When we need a structure to demonstrate property X and we do not have a material that delivers the specific performance, we synthesize one that does. As a result, there are over 300 man-made polymers currently in use. There are two main polymers that form the basis of all biological materials and structures; protein and polysaccharide (Vincent *et al.*, 2006). Variations in the assembly of these materials deliver the vast range of properties demonstrated in biological materials. Insect cuticle, for instance, is made from protein and chitin, yet can demonstrates a host of mechanical properties: it can be stiff or flexible, opaque or translucent, depending on the way the raw materials are put together (Vincent, 1982).

Materials and structures in nature are responsive: they alter and adapt their properties to accommodate changes in requirements. Penguins live in conditions of extreme cold and dive to depths of 50 m underwater to feed. The secret of their survival is in the dual functionality of their coat and its ability to adapt to changes in functional requirements. On land, their coat provides a highly effective insulation barrier; in the water, the coat transforms to a watertight skin that enables the animal to hunt efficiently in the deep sea. The multifunctional/ adaptive nature of such biological mechanisms presents great opportunity for the design of smart materials.

Biological structures are far more complex than those made by man. If we look at the hierarchy of a single organism, there are nine levels of organised structural elements: atom, molecule, macromolecule, sub-cellular organelles, cells, tissues, organ, organ system and organism. The organisation of raw materials within and across each level is what enables the rich diversity in properties demonstrated by biological structures (Tirrell *et al.*, 1994). We tend to use less complex, non-hierarchical design processes.

Lakes (1993) defined Hierarchy Order by the number of levels within a recognised structure. The Eiffel Tower is a third order design while skyscraper buildings adopting conventional engineering design, such as the World Trade Center (New York), are first-order designs. The effect of differences in structural hierarchy between the two types of building is in the amount of material required to achieve the desired strength and the quality of the raw materials used. Lakes (1993) compared relative density ρ/ρ_o (structural density ρ, mass per unit volume of structure, divided by material density ρ_o, density of material of which it is made) of both buildings and found that the relative density of the Eiffel Tower is 1.2×10^{-3} times that of iron (which is weaker than structural steel) while the World Trade Center was made from structural steel and had a relative density of 5.7×10^{-3}. It is clear that significantly less material was used to construct the higher order structure although the raw material itself had inferior strength. Clever design does not always need to rely on the nature of the raw materials to deliver key properties.

Textiles are multiple hierarchy structures. Key textile properties are introduced to the system through the choice of fibre; for example, tensile strength, conductivity, elasticity, and relationship to moisture. Yarn blend, type and twist can affect aspects such as the texture, strength, and permeability to heat, air and moisture. The construction method (knit, weave, non-woven) influences dimensional stability, durability, permeability, etc. This is a very general description and is by no means exhaustive; however, it indicates that there is opportunity to manage the performance of a textile at every level of the hierarchy. Currently, there is more opportunity at the lower (fibre) stages. The question at hand is: can biology show us how to optimise the performance of textiles through hierarchy design without relying on specific properties of raw materials? Can we design a lightweight ballistic vest from cotton instead of Kevlar?

Biomimetics offers a platform that facilitates the transfer of technology from biology to the man-made world. Initial outcomes, such as the Lotus Effect and Morphotex, deliver useful functionalities that reduce the impact of textile and garment production on the environment, but these represent merely the tip of the iceberg. There is a plethora of paradigms in biology that could present solutions or inspiration for the design of smart textiles; we could also discover ways of improving or optimising existing technology to create textiles that adapt and respond to stimuli without necessarily using materials that are costly to the environment and ultimately the consumer. The next section reviews existing biomimetic developments that focus on smart textiles for protection and discusses relevant biological mechanisms that deal with various aspects of protection.

7.2 Biomimicry of smart protective textiles

The protective textile sector is a dynamic driver in smart textile innovation. Designers call upon 'smart' technologies to engineer solutions they cannot execute efficiently or achieve using conventional technology. Propelled by increasingly demanding and sometimes contradictory specifications (e.g. tougher, harder, lighter), combined with the permeation of new hybrid technologies, the boundaries of functionality and application have been ruptured. Clothing, for example, that enables remote monitoring of body functions, integrated personal computers, mobile phones, etc. would not be possible without the fusion of electronic and textile technology. Wearable electronics is just one of the emerging technologies driving the future of the protective textile industry.

The requirements are very specific. By definition, smart protective textiles (SPTs) need to sense a predetermined threat and respond by actuating a defence mechanism that protects the individual(s) or object(s) it covers/encloses. In terms of clothing, types of threat can be real or imaginary, psychological or physical (Augé, 1995; Bolton, 2002). This chapter will explore opportunities for SPTs presented in a small selection of biological examples in the context of real, physical threat. The aim is to give a few examples of how technology can be transferred and begin to create an understanding of how methodologies can be shaped.

7.2.1 Camouflage

Certain species of animal have evolved surface markings and colouration that function as a primary form of defence: they can blend in with their environment (crypsis) or mimic the appearance of others (Batesian or Müllerian) and so avoid detection by predators. Camouflage is an important area of protective textiles, used mainly in military and surveillance operations. It can conceal the wearer or large machinery when observed (eye, photography or wider band of electromagnetic spectrum) from a distance, thus preventing attack. The key limitation with this type of technology is that patterning and colour remain unaltered, making the material suitable only for specific environments. Also, when machinery needs to be concealed for long periods of time, the camouflage system will not adapt to seasonal changes in the surrounding environment. There is opportunity for SPT in adaptive camouflage.

Chameleons are iconic creatures, known for their ability to mimic the colours and patterns of their surroundings, but there are many more species that can adapt their appearance. *Miomantis paykullii* live in grassy landscapes that are predominantly brown during periods of prolonged drought but can turn green from rapid plant growth after a sudden storm. The nymph of *M. paykulli* relies on crypsis to avoid detection and has evolved a clever adaptive colouration mechanism that detects changes in environmental relative humidity and turns the nymph green (Edmunds, 1974).

Cephalopods (octopus are part of this group) undoubtedly display the most remarkable adaptive colouration. They draw upon highly sophisticated skin to create complex visual displays used, not only to prevent detection, but to intimidate predators and communicate with other cephalopods. The adaptive colouration mechanism is controlled by a combination of hormones and the animal's nervous system. The skin contains chromatophores: tiny sacks containing pigment, that can expand and contract to reveal or conceal the pigment. These sit on layers of light-reflective tissue (irridophores) made from tiny sheets of reflective plates. The cephalopod is able to alter the colour reflected by the irridophores by changing the distance between the layers of reflective plate. In 2007, a team led by Professor E. Thomas of Massachusetts Institute of Technology (MIT), developed a smart gel based on the cephalopod's skin structure. The team used a self-assembling block copolymer thin film made from layers of polystyrene and poly-2-vinyl-pyridine. The thickness of the layers controls the refractive indices and thus the colour of the reflected light. The poly-2-vinyl-pyridine layer is designed to alter its thickness in response to stimuli such as pH and salt concentration, thus changing the gel's colour (http://web.mit.edu/newsoffice/2007/techtalk52-6.pdf).

7.2.2 Impact resistance

Textiles of this type are designed to shield the wearer from penetration of high-velocity objects such as bullets, knives, shrapnel, etc. Ballistic protection depends on the textile's ability to absorb energy locally and on efficiency/ speed of transferring absorbed energy of impact to the crossover points of yarns (energy from the impacting object is dissipated by stretching and breaking yarns). Silk was originally used in the construction of protective garments but high-modulus, high-strength aromatic polymer fibres such as Kevlar (DuPont) are now used. These polymers are composed of highly aligned, long molecular chains, held together by strong bonds. Kevlar yarns are densely woven into plain or basket weave structures. Plates made from hard materials such as steel and ceramics are used as inserts to reinforce protection of vital areas of the body (Chen and Chaudry, 2005). Protection from high-velocity impact with a bladed object poses an additional set of requirements. Unlike a bullet, the blade of a knife can be very sharp and can slice through a textile. The main materials used in this case to protect wearers are aramid fibres/yarns and chain-mail (Scott, 2005).

The requirements of military or security body armour are very similar to those of the reinforced external coverings of heavily armoued creatures, such as armadillos. Predator attacks usually involve scratching and biting. Therefore, protective structures need to prevent penetration from the aggressor's teeth, beak, nails, claws, etc. Pointy spines are used to form barriers that physically injure the attacking animal upon initial impact, thus discouraging further efforts, e.g. sea urchin spines. Hedgehogs and echidnas roll up into a ball to protect their head and ventral parts, and erect dorsal and lateral spines. Animals such as armadillos, pangolins, woodlice and millipedes are protected by tough, horny plates that will resist repeated impact.

The Dinosaur eel, *Polyoterus senegalus*, is a fish that retains an incredibly tough yet ancient form of dermal armour (hence its name). Tough, high penetration-resistance skins were common in prehistoric fish because there were many large, invertebrate predators around. There are much fewer around today so this mechanism was gradually phased out as it became less advantageous. *P. senegalus* is a cannibal and is believed to have maintained its dermal structure because its main threat is its own species (Bruet *et al.*, 2008). Bruet studied the scales of *P. senegalus* and found that they are composed of four layer of materials with very different mechanical properties. Focusing on indentation modulus E and Hardness H, findings revealed that the outer surface of the scale is approximately 10 μm thick and is composed of guanine, a very hard, enamel-like material ($E = \sim62$ GPa, $H = \sim4.5$ GPa). This is followed by 50 μm of dentine ($E = \sim29$ GPa, $H = \sim1.2$ GPa), 40 μm of isopedine and 300 μm of a bone basal plate (both materials $E = \sim19$ GPa, $H = \sim0.7$ GPa). The findings show that the indentation modulus and hardness decrease as they approach the inner surface of the scale. Each layer also has different deformation and energy dissipation mechanisms. The top stiff guanine layer transfers load to the softer dentine layer, which dissipates energy via plasticity. This is lined by isopedine, whose microstructure cracks during deeper penetration in a way that minimizes impact on the structure.

The scaly-foot snail (*Crysomallon squamiferum*) inhabits one of the most hostile environments on Earth; the deep sea volcanic vents of the Central Indian Ridge. The snails have evolved remarkable exoskeletal structures that enable them to live in such extreme conditions and resist attack from crabs, their main predators. The crabs will squeeze the scaly-foot snail in their claws for days if necessary, but the unique shell structure allows the animal to withstand these kinds of pressures (Yao *et al.*, 2010). Yao studied the structure of the shell and found a three-layer system comprising two stiff mineralised layers with a thick organic layer sandwiched between them.

Current military body armour, designed to protect against high velocity bullets, can weigh about 15 kg, while a bomb protection outfit can weigh 30 kg (Scott, 2005). The structural design of *C. squamiferum* and *P. senegalus* could be drawn upon to inspire the creation of lighter weight body armour made from multilayer textiles, using less tough and heavy material to deliver equal if not superior protection, that does not burden the wearer.

7.2.3 Auxetic materials: smart blast protection

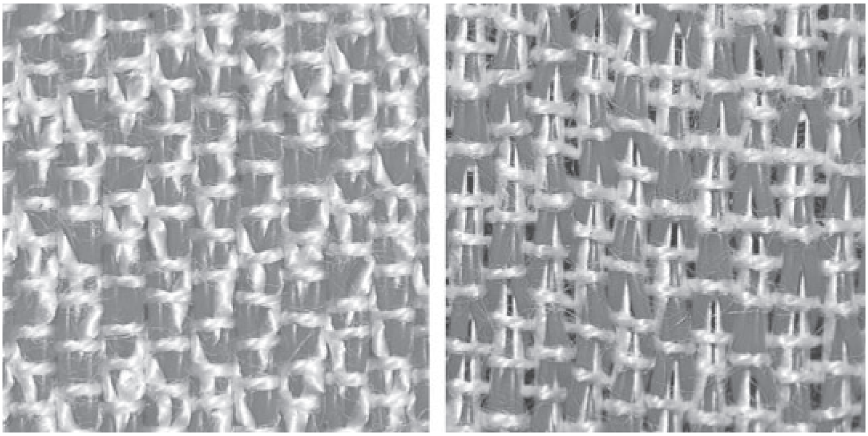
Conventional materials become fatter when compressed and thinner when stretched. The ratio of transverse contraction to longitudinal extension strain in the direction of the stretching force is known as the Poisson ratio (v). Most engineering materials have a $v = 0.3$ (Kevlar 0.35, aluminum 0.32, titanium 0.33): cork has $v = 0$. In practice, this means that when you apply pressure to the top of a cork to squeeze it into a bottle top, it demonstrates no dimensional change. When you try to do the same with a stopper made from synthetic rubber, the bottom expands, thus preventing the stopper from sealing the bottle top; you need to twist the rubber stopper in order to get it into place.

Materials with negative Poisson ratio (auxetic) are counterintuitive; they become narrower when compressed and thicker when stretched. By a clever design principle, auxetic structures can be made from simple materials such as paper. As materials approach $v = -1$, they become highly compressible but difficult to sheer; they are tougher and more resistant to tearing (Lakes, 1993).

Auxetix Limited is an award winning UK company that owns exclusive rights and IP to a helical-auxetic yarn system. Textiles using this technology (branded *Zetix*) offer enhanced performance in many applications, ranging from aerospace to smart textile sensors. Zetix woven textiles can be engineered to provide blast protection: the structure's ability to deform without failure and dissipate energy over a large area involving many fibres (like a spider's web that remains intact when a flying creature impacts it), enables effective shrapnel capture. The thousands of pores that open up over the surface during impact, 'vent' the blast waves, while the elastic core of the helical-auxetic yarns are resilient – they do not fracture like conventional ballistic resistant textiles (R. Hook, Director of Auxetix Ltd, personal communication, 2011). Figure 7.1 demonstrates the functionality of the fabric under unstretched and stretched conditions. Auxetix Ltd is currently collaborating with the University of Exeter and three other partners on a project funded by the Engineering and Physical Sciences Research Council (EPSRC), applying this technology to the design of a blast-resistant curtain that can capture debris such as glass, protecting individuals working or living in buildings within conflict areas, (http://www.epsrc.ac.uk/newsevents/news/2010/Pages/blastproofcurtain.aspx).

7.2.4 Protection from heat and cold

Predators are one of many threats encountered in the natural world. Sudden changes in environmental conditions (e.g. current global warming) can prove catastrophic. Although organisms can adapt to slow changes, predictions suggest that a 2°C increase of global temperature over the next 90



(a) (b)

7.1 Auxtetic textile: (a) unstretched, (b) stretched. Source: Dr P. Hook, Auxtetix Ltd.

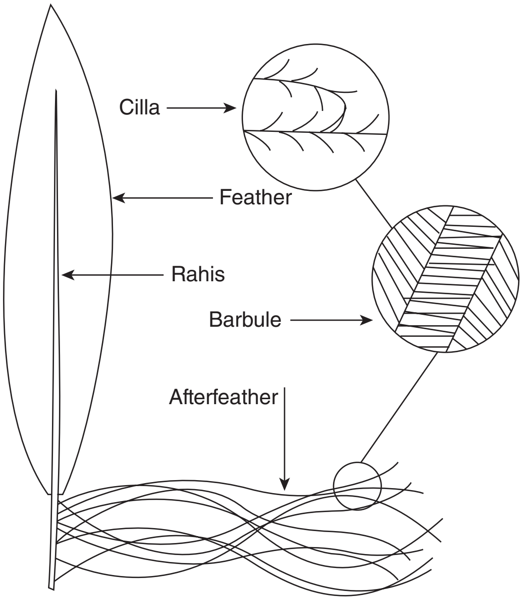
years would put 20–30% of species at high risk of extinction (Schneider *et al.*, 2007).

Animals that inhabit extremely cold environments have evolved ingenious coats of fur or feathers that prevent precious body heat from escaping. Grojean (1980) studied the brilliant white coat of the polar bear and found that the pelt itself consists of a dense, insulating layer of fur, about 1 cm long, with fine fibres (25–75 μm diameter) and thick hairs approximately 100–150 μm in diameter and 6–7 cm in length. These are attached to a thin layer of black skin, approximately 1 mm thick. The longer hairs are hollow in structure along their length and taper to a solid edge at their tip. Although they have a smooth external surface, the core is very rough, while the hairs themselves contain no pigmentation. The air pockets created in the hair's core offer additional insulation (Grojean *et al.*, 1980). Similar cross-sections are used to create insulating hollow fibres from man-made polymers, introducing additional air pockets into a textile system. The advantage of using man-made fibres, especially in textiles used in clothing or products that will be carried around (i.e. sleeping bags), is that they are lighter than wool or any other insulating natural fibre.

An animal's coat needs to insulate the animal from cold, yet allow heat generated from activity to escape when necessary. There are numerous examples in biology. However, most coated animals do not experience sudden changes in environmental conditions and therefore do not need to alter the functionality of their fur or feathers; we do! Our built environment is laced with interconnected yet individual spaces; each defined by unique thermal and moisture conditions; transition from one to the other can be as instant as walking through a door. Can we design SPT systems that will sense and react to changes in environmental conditions by adapting the garment properties to manage microclimate conditions in a way that will protect the wearer's thermal regulation?

A remarkable example of adaptive behaviour is in the design of the penguin coat. As mentioned earlier, penguins must withstand extreme cold for up to 120 days without food and then be able to dive up to 50 m into freezing waters in order to feed. When necessary, the penguin coat provides highly efficient insulation that minimises heat loss through radiation and convection, with structural properties that function as an excellent wind barrier, eliminating heat loss though convection. Yet when the animal needs to dive for food, the coat transforms into a smooth and waterproof skin, eliminating any trapped air. This switch in functionality is achieved by a muscle attached to the shaft of the feather; when the muscle is locked down, the coat becomes a water-tight barrier, and when released, the coat transforms itself into a thick, air-filled, windproof layer. The feathers also have numerous large hooks that bind neighbouring feathers into a coherent membrane.

The feathers in a penguin's coat are packed evenly over the animal's body, averaging 30–40 per cm^2. Figure 7.2 illustrates the structure of a typical penguin feather. Dawson *et al.* (1999) and Wan *et al.* (2009) identified that the mechanism responsible for the insulation properties is found in the afterfeather (Fig. 7.2). The diameter of the afterfeather fibres (barbs) is



7.2 Structure of penguin feather. Source: Dawson, 1999.

approximately 5.5 (± 0.9) μm (Wan *et al*. 2009) and consists of approximately 50 barbs averaging 24 mm in length (Dawson *et al*., 1999). Each barb is covered with around 1250 barbules that are about 335 μm in length. This structure creates airspaces of around 50 μm in diameter, which provide an enormous volume for trapped air, thus creating a structure capable of providing such high levels of insulation (Dawson *et al*., 1999). Wan (2009) found that higher resistance to radiative heat transfer is closely related to the fineness of the fibre at the same fibre volume fraction. They compared radiative heat transmission properties of fibres with different diameters: Duck and penguin fibre down exhibit similar diameters 4(± 0.6) μm and 5.5 (± 0.9) μm respectively, polyester 17.6 (± 0.2) μm and wool 26.6 (± 6.1) μm.

A key factor in the success of the adaptive mechanism is the ability to recreate a uniform division of air space every time the coat's functionality switches from waterproof to high insulation. The mechanism that enables this is found on the surface of the barbules – Dawson *et al*. (1999) noticed that tiny hairs known as cilia covered the barbules that function as a stick–slip mechanism to keep the barbules entangled and maintain the movement in directions relative to one another to ensure uniformity in the creation of air pockets during the coat's function change.

So, the insulation properties of the penguin's coat adapt by varying the volume of air trapped within the system by drawing the feather towards the skin when the waterproof functionality is required, and releasing it when the penguin needs to be kept warm. Attempts to interpret this mechanism into garments have led to the creation of an experimental textile system referred to as *Variable Geometry*. The structure is made of two layers of fabric, which are joined together by strips of textile at a right angle to the plane of the two fabrics. By skewing the two parallel layers, the volume of air between them reduces, and this results in a reduction of thermal resistance. The idea has been used in the design of military uniform systems that can be adapted to function in both extreme cold and hot conditions. This was commercialised in 2002 by Gore & Associates, who created an ePTFE membrane and polyester structure (76%PE: 24%PTFE), to be used as a garment insert, under the brand name *Airvantage*. The product allows the user to inflate/deflate the jacket, thus adjusting the garment's insulation properties.

7.3 Conclusion and future trends

The functional profile of textiles in their wider context is changing. Fuelled by innovations in materials science, textile structures are becoming *soft machines*, able to heat, sense, actuate, protect, etc., and eventually become symbiotic structures integrated into many aspects of our lives. Biomimetics is a platform that facilitates transfer of technology from nature to the man-made world. Initial outcomes have been innovations, such as the Lotus Effect and Morphotex, which offer useful functionalities, able to reduce the impact of textile and garment production on the environment. Biological materials and structures are 'smart' by nature; they need to enable a multitude of mechanisms necessary to support life; they also need to protect, repair, maintain and adapt to changes in the environment. This chapter has begun to illustrate the huge potential for biomimetic design that could inform, even inspire, the development of smart protective textiles.

7.4 Acknowledgements

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