J Bio Tribo Corros (2016) 2:23
DOI 10.1007/s40735-016-0053-0

Advances in Bio-inspired Tribology for Engineering Applications

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Received: 2 July 2016 / Revised: 6 August 2016 / Accepted: 9 August 2016 / Published online: 17 August 2016

Abstract Bio-inspired tribology is an interdisciplinary field of science where scientists and engineers seek to investigate and incorporate tribological properties encountered in biological beings into engineering applications. In this paper, bio-inspired tribological research that are speculated to have a huge impact on tribological applications have been reviewed. These research involve (1) investigations related to replication of lubricin found in synovial fluids of mammalian joints which have super-low friction values that can be utilized in IC engines, (2) surface replication concerning to superhydrophobic properties of gecko skin which is seen to have anti-wetting and self-cleaning properties, (3) friction-reducing shark skin through specialized nanoparticle coatings that is seen to give a different perspective on surface texturing, (4) new techniques, such as soft lithography to replicate surfaces of lotus leaf and air lubrication phenomenon inspired by emperor penguins that is being applied to propel boats, ships, and torpedoes faster by reducing skin friction underwater. Further, an investigation in self-healing materials inspired from pitcher plant that has led to the innovation of self-healing and slippery liquid-infused porous surfaces has been discussed. These research works reviewed not only provide a deep insight into the current advances in bio-inspired tribology but also helps understand the plausibility of the research applications in the future and the practicality of innovations possible.

Keywords Bio-mimetic tribology · Skin friction · Boundary lubrication · Air lubrication · Superhydrophobicity · Hydrogels

1 Introduction

Over the last decade, Biomimetics, more commonly known as Bio-inspired science, has become a very popular field of interest, inspiring innovation in many engineering applications more so in tribology and material science. Understandably, this research is however still in its infancy, mostly because it is not easy to comprehend and implement the working of many biological ideas into engineering applications. The very essence of nature's way of experimenting and optimizing is the way the world is seen today, through innumerable generations [1]. Although the theory of evolution may not be evident and accepted by many, it is possible to agree on one thing that nature has its own way of learning to make sure there is a sustainable progress of all life forms.

A bio-inspired technology for an engineering application is a challenge for researchers with regard to efficient replication or adoption. Although many of these bio-inspired concepts such as flying (Fig. 1), swimming, camouflage, honeycomb structure, spider web structure, bat's acoustic sensor, fluorescence materials in fireflies, and gecko's dry adhesion have been adopted ingeniously they still are far behind in efficiency with which nature has implemented the same. The attempts made toward this is the essence of biomimetics.

It is only very recently that the concept of learning from nature is being adopted by researchers. Jack Steele of the US Air Force was the first to present the idea of *Bionics* at a meeting in Wright–Patterson Air Force Base in Dayton,

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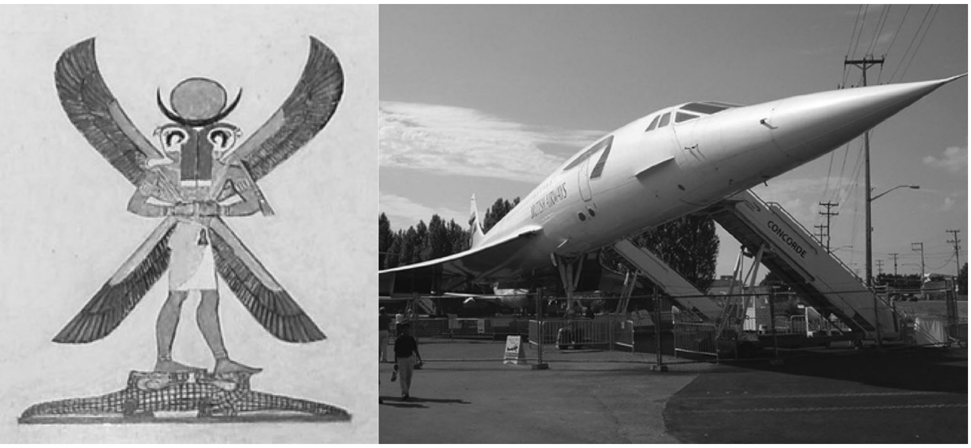

Fig. 1 The image of the Egyptian God Khensu with wings (*left*) illustrates the age-old fantasy of humans of being able to fly [2]

Ohio. He presented it as a study involving copying, imitating, and learning from biology [3]. Later in 1969, Otto.H. Schmitt coined the science and engineering behind this as *Biomimetics* [4]. The term Biomimetics is derived from *bios,* meaning life, and *mimesis,* meaning to imitate. It is literally the science of mimicking nature (biomimicry) to incorporate the mechanisms and capabilities behind a biological phenomenon or be it for an engineering application.

In the current era where crises in resources, energy, and environmental conditions are being seen around the world, tribology is expected to play a major role to strive toward application of eco-friendly technology. There is so much scope for biotribological applications in engineering that deal with the development of functional adhesives inspired from gecko feet; novel mechanical attachment devices inspired by insect attachment pads onto the plants; 3-D micro-electromechanical systems inspired by diatom hinges and their interlocking devices; stain-resistant paints, shoe or windshield coatings inspired by plant surfaces concerning their self-cleaning and anti-wetting properties [5]; bioengineered Synovial Fluids (SF) for low-speed lubrication applications inspired from native SF from SF joints in mammals [6]; are amongst a few. Biomimetic materials are also usually environmentally friendly, since they are a natural part of the ecosystem. For this reason, the biomimetic approach in tribology is particularly promising [7].

The present study discusses latest ongoing researches concerning adaptation of technology from biological beings which serve as an inspiration for tribologists and material scientists to move away from the conventional methods of material design and look for new innovative techniques that yield better results. The applications discussed in this study shows endeavors of researchers to make sense of incomprehensible tribological phenomenon of nature and their attempts to mimic it, keeping in sight its limitations.

While, in most cases, it is not possible to directly borrow solutions from nature and to apply them in engineering, it is often possible to take biological systems as a starting point and a source of inspiration for engineering design.

2 Case Studies

The scope of research in biomimetics tribology has become so vast that there are literally hundreds of experiments currently in progress which are aimed to tap into nature's elegant designs and efficient mechanisms which makes use of materials and resources in the most optimal way possible. Some of the best and most intriguing studies concerning tribology which are expected to have a high impact with their engineering applications are discussed in this section.

2.1 Synovial Joint Lubrication for IC Engines

With preceding seven decades of lubricant technology research, most of the lubricants in use today for engineering applications are oil-based lubricants relying on chemical additives. These lubricants are expected to serve their basic tribological function like protection from wear, maintain required level of friction, remove heat from the system, carry away impurities, and wear debris. The pivotal function that serves these purposes is providing boundary lubrication which is defined by asperity contact of tribo-couples and the tribochemical reactions that occur as a result of this contact.

Another motivation for researchers to look toward nature for efficient lubricants is the drive toward recyclable eco-friendly lubrication, which brings us to biomimetics tribology as the future for effective and efficient tribological systems. One of the more plausible inspiration in this regard has come from synovial joints in mammals which

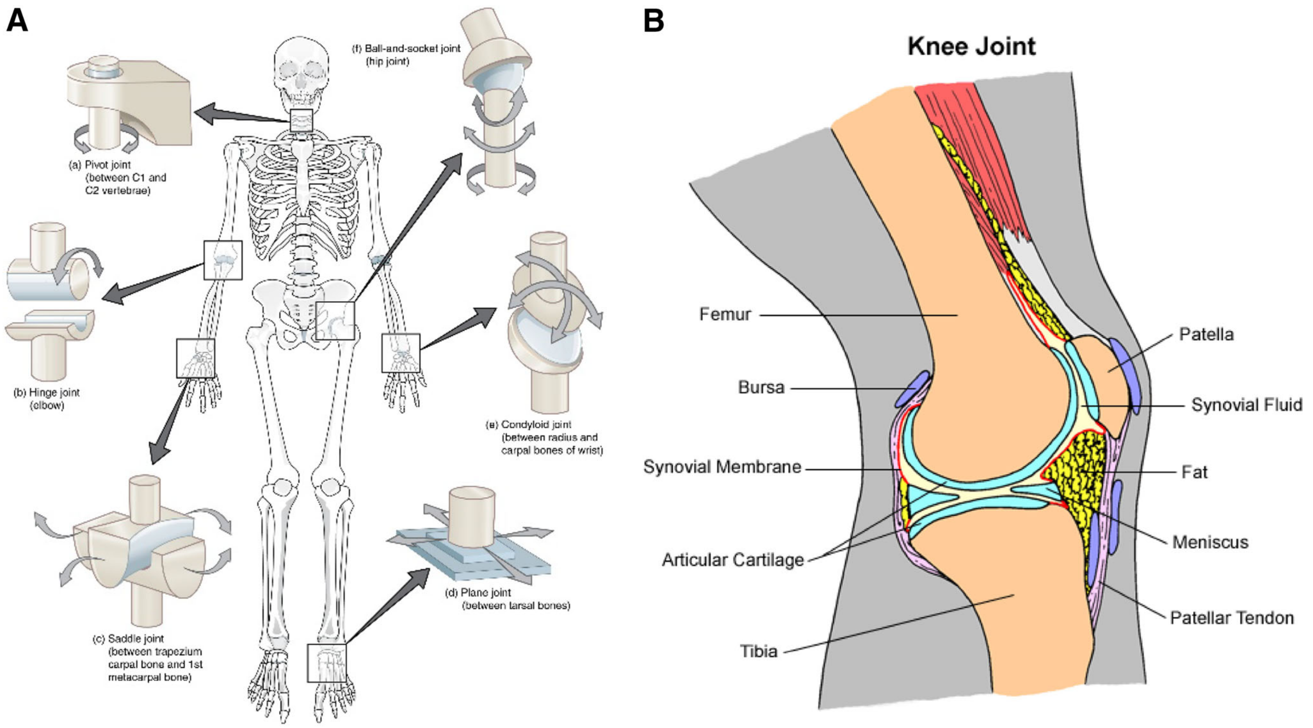

Fig. 2 **a** Types of synovial joints. Clockwise from *top-right*: Ball and socket joint, Condyloid joint, Plane joint, Saddle joint, Hinge joint, and Pivot joint; **b** Structure of synovial joint in the Knee [8]

humans also possess (Fig. 2a). These joints are some of the most common and movable joints in a mammal. As with most other joints, synovial joints achieve movement at the point of contact of the articulating bones with the help of a special lubricant know as Synovial fluid (SF). A typical structure of a synovial joint in humans can be observed in the knee joint of a human as shown in Fig. 2b.

Research concerning the tribological benefits of synovial fluids have been investigated since more than four decades [9–12], the investigations concerning the replication of the synovial fluid properties are shown in Table 1. Most of these investigations had already found out the friction coefficient at these joints to be in the range 10^{-3}–10^{-2}. There were also questions raised by some researchers about the possibility of such a lubricant layer being generated and maintained at these synovial joints [13, 14]. These initial investigations showed that a locally generated pressure has the ability to smooth the initial rough cartilage surface as they pass through the loaded region. The initial two decades of research provided new and convincing explanations of the mode of lubrication of nature's remarkable bearings.

But now, it is clear that synovial fluid in native joints functions as a biomechanical lubricant, lowering the friction and wear of articulating cartilage in synovial joints. A bioengineered SF recapitulating the properties of native SF has been found to be beneficial in tissue engineering of articular cartilage and synovial joints for the treatment of arthritis. This appropriate lubricating environment may be critical to maintain the low-friction, low-wear properties of articulating cartilage surfaces undergoing joint-like motion in bioreactors.

Jin et al. [15] have conducted brief tribological analysis for various artificial hip joints with different bearing material combinations such as ultra-high molecular weight polyethylene against metal or ceramic, metal-on-metal, and ceramic-on-ceramic. The application of these material combinations revolves around the effectiveness of boundary lubrication that can be achieved at these synovial joints. Oungoulian et al. [16] have further conducted more specific wear and damage analysis of bovine articular cartilage against glass and alloys such as cobalt chromium alloy and stainless steel alloy. It has been suggested that the frictional loading occurs as a result of subsurface fatigue failure that leads to delamination and progressive wear, with surface chemistry and roughness of implant materials influencing these observations. The friction coefficient and wear volume comparisons for various material contact is shown in Fig. 3.

Morrel et al. [17] have conducted in vitro cartilage pressure measurements which give an insight into the pressure conditions at the synovial joints under various conditions. To add to this, Katta et al. [18] developed a model as tools not only help to understand the cartilage

Table 1 Experimental work to replicate the properties of synovial fluid

Type of lubricant	Composition	Tribological studies conducted	Reference no.and year
Natural Synovial Fluid (SF) from knee joint of rats	Hyaluronate (HA), Glycoprotein (lubricin), Glycosaminoglycans such as chondroitin-4-sulfate, chondroitin-6-sulfate, and keratan sulfate in minute quantities.	Schmidt et al. [110] [111] demonstrated the boundary lubrication ability of synovial fluid in an in vitro disk-on-annulus setup. In the study, synovial fluid was shown to provide lower friction levels compared to phosphate buffered saline (PBS) in a cartilage rotating against cartilage model under boundary lubrication conditions. Synovial fluid was shown to have qualities which protected cartilage from wear that were lost when digested with trypsin. It was also shown that an intact articulating surface played an equally important role as the intrinsic mechanical properties of cartilage tissue had an important step in determining its wear resistance [18].	[110], 2007 [111], 2007 [18], 2008
Glycoproteic gel solution	1. 3 g l^{-1} hyaluronic acid (HA), 18 g l^{-1} bovine serum albumin (BSA), 2 g l^{-1} γ-globulin in phosphate buffered solution (PBS) buffer pH 7.4. 2. Gel-in: glycoproteic gel was added over the phospholipids. 3. Gel-out: glycoproteic gel containing lipid vesicles.	Polished borosilicate glass surfaces and Hydroxyethyl methacrylate (HEMA) lenses were used as the tribo-pair for analysis. For the basic glycoproteic gel solution, coefficient of friction was found to be 0.008. Gel-in solution test was conducted for the composition 2 where large accumulation of fluorescent details outside of contact was found because of the expulsion of lipid vesicles, but there is no variation in friction coefficient value (0.008) for lipids. But for the Gel-out solution test of composition 3 friction coefficient was found quite higher (0.11) due to generating velocity accommodation through rolls used in the test.	[112], 2013 [118], 2014
Phosphate Buffered Saline (PBS)	Phosphate buffered saline (abbreviated PBS) is a buffer solution commonly used in biological research. It is a water-based salt solution containing disodium hydrogen phosphate, sodium chloride, and, in some formulations, potassium chloride and potassium dihydrogen phosphate. The osmolarity and ion concentrations of the solutions match those of the human body	Bovine osteochondral explant was used as the specimen material on which Pin-on-disk test was conducted at normal load varied between 0.9 and 24.3 N, sliding speed 0.5 mm s^{-1} and for a sliding distance of 7.85 mm. The friction coefficient was found to decrease with increasing contact pressure and decreasing equilibrium time.	[113], 2011 [118], 2014
Physiological solution	1. Albumin, HA without lipidic vesicles 2. Solution with small lipidic bilayers (2 gl^{-1}) 3. Solution with lipidic bilayers	The Albumin, HA was tested on model of articular cartilage (hydrated hydroxyethyl methacrylate (HEMA) and borosilicate glass), with the other two lubricants being tested on Model of steel joint implant 316 L steel and rigid (HEMA), steel 0.8 mm diameter, glass roughness $Rq = 0.05$ µm. At a contact pressure of 5 MPa, combination of lipids with HA and albumins gave a higher friction coefficient than the lubricants containing only protein like HA and albumin. No beneficial effect of lipid bilayer was observed for implant joints.	[114], 2007
Hank's balanced salt solution (HBSS)	The essential function of a balanced salt solution is to maintain pH and osmotic balance as well as provide your cells with water and essential inorganic ions. Solutions most commonly include sodium, potassium, calcium, magnesium, and chloride.	Friction coefficient ranges from 0.02 to 0.09 µm. It was found that if bovine serum albumin (BSA) is added to other lubricants, then the friction coefficient becomes less in case of metallic surfaces because polymeric film transfer does not occur in metallic surface, but in case of alumina, the polymeric film transfer is much more intense when the BSA is added to solutions. As a result, the coefficient of friction is quite higher on alumina surfaces.	[115], 2006

Table 1 continued

Type of lubricant	Composition	Tribological studies conducted	Reference no.and year
Human serum albumin 8 mg ml^{-1}	Human serum albumin is the version of serum albumin found in human blood. It is the most abundant protein in human blood plasma; it constitutes about half of serum protein. It is produced in the liver.	Pin-on-disk tribometer test was conducted using UHMWPE (Ultra High Molecular Weight Polyethylene) as the pin material on a ceramic disk material. This lubricant renders more hydrophobic surfaces which adsorb denatured proteins and increases friction forces, but thicker, denser films are formed by the adsorption of native proteins on more hydrophilic surfaces, which has the potential to reduce lubricated friction.	[116], 2005
Hyaluronic acid (HA)	Consists of alternating units of glucuronic acid (1-β-3) and N-acetylglucosamine (1-β-4)	HA is a major component of synovial fluid in diarthrodial joints and is believed to be at least partially responsible for the excellent biolubrication of articular cartilage due to its remarkable viscoelastic properties. HA imparts stiffness and resiliency due to the well-known entropic elasticity of polyelectrolytes. A coefficient of 0.27 was typical for this system, which does not indicate the quality of a good boundary lubricant when compared to the low friction of synovial fluid between cartilages ($\mu = 0.002$–0.03) or between latex-glass surfaces ($\mu = 0.019$). Overall, the results show that one can covalently graft HA to a supported membrane surface, but that this does not impart excellent lubrication or sufficient wear properties.	[117], 2004

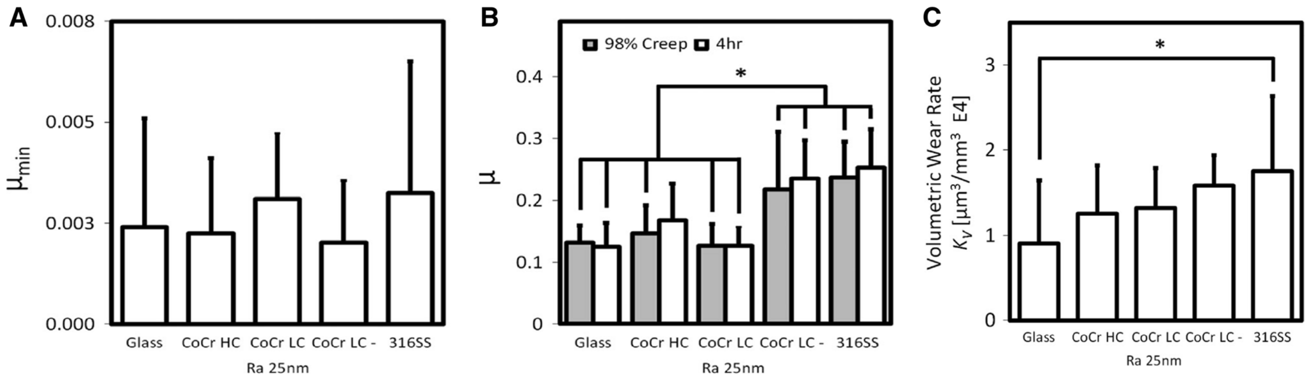

Fig. 3 Frictional properties of cartilage against different counterface materials. **a** Minimum friction coefficient (μ_{min}, no differences across counterface materials, *p value ≥ 0.72). **b** Comparison of friction coefficient at time of 98 % creep displacement and final time at 4 h (*p value ≤ 0.01). **c** Volumetric wear rate (*p value ≤ 0.043) [16]

tribological characteristics but also to evaluate current and future cartilage substitutions and treatment therapies.

For biotribological applications, the most common area of interest for researchers, is the impact of engineered synovial fluid lubricants as applied for engineering applications which can be enormous. Hill [19] has shown that the effective lubrication of SF in these joints is expressed by a low friction in the range of 0.002–0.006. Even in the same working conditions as the synovial joints, this kind of low friction values cannot be achieved with all the advancements made in boundary lubrication technology.

Synovial joints are hydrodynamic-based lubricants, and hence show lower viscosity when compared with most of the oil-based lubricants in use today. If this synovial joint mechanism is successfully mimicked in an IC engine, the benefits with regard to fuel economy and emission reduction would be many [20]. Firstly, there would be a drastic reduction in friction as has been shown by Hill [19], a

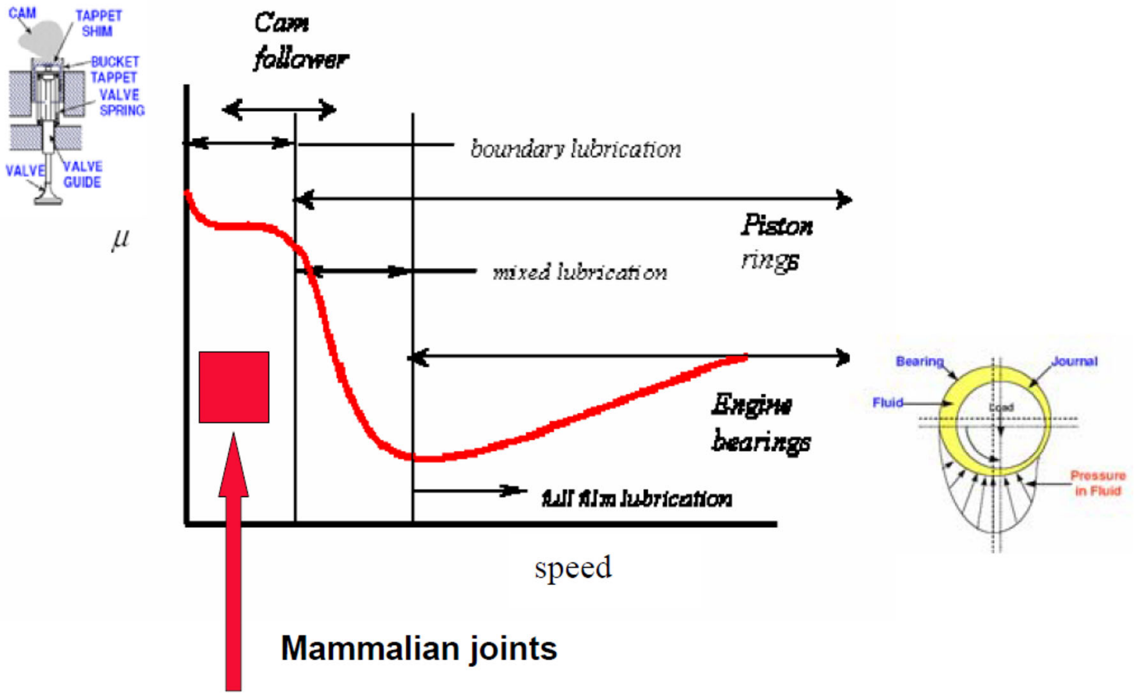

Fig. 4 Lubricity Chart comparing mammalian joint friction against friction obtained in IC engine tribological system [19]

lubricity chart (Fig. 4) comparing the friction in synovial joint and various working parts inside an IC engine. Since these friction losses are inextricably linked to fuel economy, a huge improvement in this regard can be expected.

Secondly, the most important bit is the durability aspect of lubricants, mammals do not go around getting their synovial joint fluids replaced from time to time! It is estimated that these joints can operate efficiently for over 75 years exhibiting low friction and wear. This equates to nearly 1 million loading cycles per year and more than 75 million loading cycles over a lifetime. Whereas a good IC engine lubricant for passenger car needs to be replaced every 100,000 miles with a total loading cycle of 220 million. There are more biological systems that exhibit even greater durability cycles than that of synovial joints like the heart valve leaflets which can operate efficiently for up to 5 billion cycles [21].

But now, the question arises what function of synovial joints can actually be mimicked? It is not possible to ignore the fact that the tribological conditions in terms of load, temperature, speed, and other environmental conditions vastly vary in the synovial joints when compared to IC engines or any other application for that matter. It is important to note that, it is the functionality that there is some degree of similarity and a potential for biomimicry exists.

Many tribologists and researchers are working toward better understanding of this functionality. Gregory et al. [22] focus to understand the biology of lubricin that is secreted in the synovial joints. It has been observed that it is this lubricin in the synovial fluid that provides boundary lubrication and helps avoid the cell and protein adhesion to achieve a near frictionless joint motion. Investigations into lubricin are also being made by Alexandra et al. [23] to synthesize and characterize a libricin mimic which will be able to behave similar to lubricin in synovial fluids and be able to reduce friction and adhesion on articular cartilage surface. Recently, many such research concerning role of lubricin and boundary layer lubrication have been analyzed with respect to the lubrication and wear mechanisms observed in synovial joints and articular joints in general [24–31]. These researches are aimed to help better understand the technology behind one of nature's most effective lubrication mechanism.

Guoqiang et al. [32] have been investigating potential microgel-based lubricants to mimic similar tribological properties as synovial joints and have very recently reported [33] their success in fabrication of a new microgel-based artificial synovial fluid which is not only useful for arthritis treatment but also for biomimetic aqueous lubrication applications. They were able to achieve the similar ultra-low coefficient of friction as in synovial joints under soft friction pairs (Fig. 5).

The road ahead in this regard is in no way easy to achieve through present available armory of materials and lubricants. This in a way is a motivation than demoralizing for tribologists to explore such an application that can revolutionize the use and implications of eco-friendly and efficient lubricants.

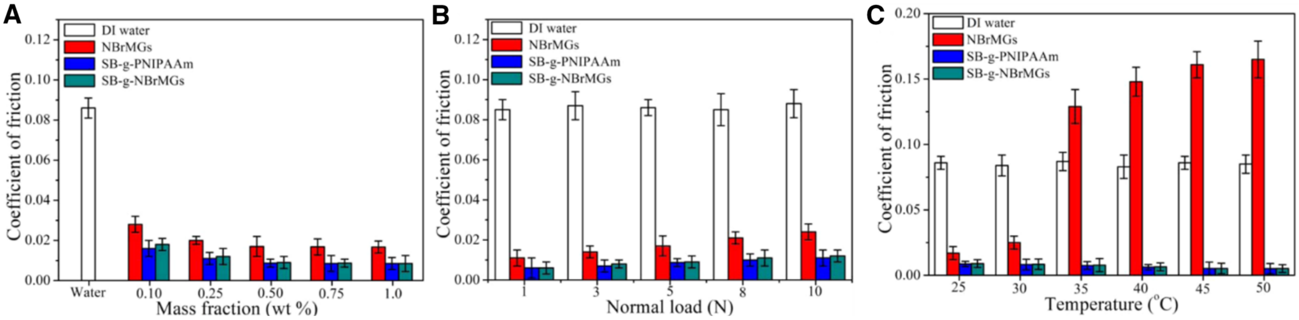

Fig. 5 **a** COFs with microgels NBrMGs, SB-g-PNIPAAm, and SB-g-NBrMGs suspensions with different concentrations under the normal load of 5 N at 25 °C. **b** COFs with NBrMGs, SB-g-PNIPAAm, and SB-g-NBrMGs suspensions (0.5 wt%) under different normal loads. **c** COFs with NBrMGs, SB-g-PNIPAAm, and SB-g-NBrMGs suspensions (0.5 wt%) under the normal load of 5 N at different temperature [33]

2.2 Gecko: It is not About their Feet Anymore!

For over nearly a decade now, gecko's feet exhibiting remarkable adhesion properties has been a significant attraction and inspiration to many tribologists [34–37]. But this overwhelming interest toward their feet had led to ignorance of other fascinating regions of a lizard's body. This is somewhat surprising as the outer skin of a lizard had been speculated to exhibit a range of functions including ecdysis, coping with varying temperatures, pheromone capture, retention, and dispersal, especially tribological functions such as reduction of friction and wear protection and also reflection of radiation [38].

It has also come to light that the gecko's skin exhibits a very notable interfacial property with regard to solid and aqueous interactions due to an interesting microstructure on the dorsal and ventral regions comprising spinules (hairs) as seen in Fig. 6.

These spinules range between several hundred nanometers and several microns in length. These complex special surface textures on their skin make them superhydrophobic and inhibiting gecko's skin with anti-wetting properties and ability to self-clean through rolling of nanometer-sized water droplets at low velocities.

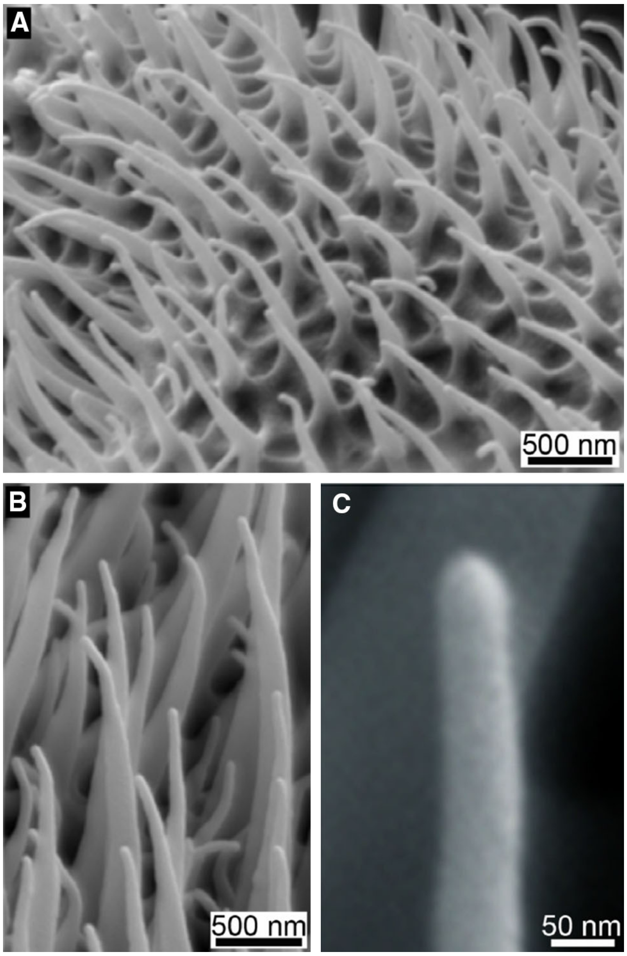

Fig. 6 SEM images of the microstructure on the gecko dorsal scale showing a micro/nanostructure consisting of spinules (hairs) with a sub-micron spacing (A & B) and a radius of curvature of less than 20 nm (C) [38]

Their skin referred to as superhydrophobic is shown to have a static contact angle of a liquid in the range of 151–155° [38]. In the same research, this feature has proved to be true under varying conditions of liquid and its orientation. The anti-wetting nature of water as shown in Fig. 7a, b, suggests that other liquids with sufficiently high surface tension should demonstrate similar wetting behavior as the liquid/solid, solid/gas, and liquid/gas interfacial tension all contribute to the wetting behavior. A range of such liquids shown in Fig. 7c exhibits sufficiently high contact angles with the skin that they were easily removed from the surface by tilting the surface less than two degrees. This anti-wetting property exhibited by the gecko's skin is already being considered for many tribological applications with regard to corrosion-resistant coating, which in a better sense is immune to moisture making the surface immune to corrosion [39–43]. To get a better perspective of what happens when a gecko skin is impacted upon by a water droplet, a time evolution picture

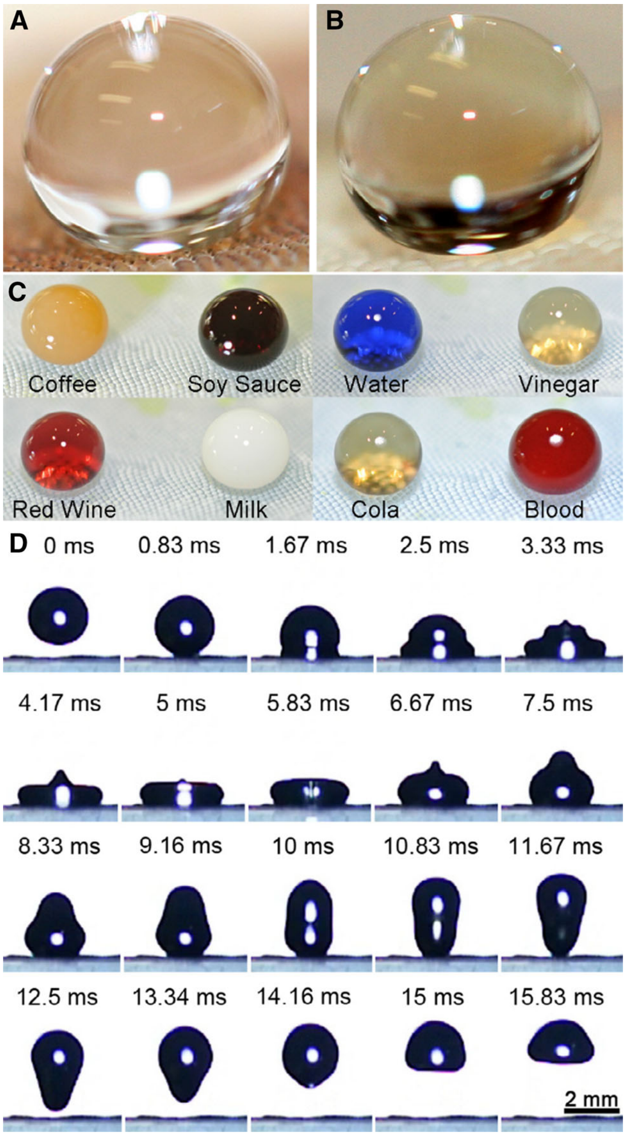

Fig. 7 Images of liquid droplets interacting with the gecko skin. **a** Small droplets of water ($\sim 5\ \mu l$) on the dorsal and abdominal region **b** of the gecko *Lucasium steindachneri*. The droplets maintain a near spherical shape and contact angle (above 150°). **c** Droplets of common liquids on the gecko skin. **d** Time evolution of an impacting droplet of 2.2 mm in diameter on the gecko skin [38]

was taken as shown in Fig. 7d which clearly shows the anti-wetting nature of the gecko skin.

Lee et al. [44] successfully replicated gecko-like self-cleaning using high aspect ratio of polypropylene microfibrillar adhesives for contact applications. This process in comparison to the conventional pressure-sensitive adhesive was able to record 25–33 % of the original shear adhesion force even after multiple contacts simulating a good dry self-cleaning. This research started in 2008 has reached a new level of advancement in 2016, where Frost et al. [45] reviewed its advancements related to laser-activated adhesives and nanostructured adhesive devices. This new technology should soon be able to eliminate the use of staples for wound closure overcoming the challenges experienced in moist environment of surgical settings.

The development of water-repelling, self-cleaning, antibacterial, and biocompatible coatings in terrestrial and aquatic environments is of great interest from practical, commercial, and scientific perspectives worldwide. The gecko skin provides a unique topographical template for multifunctional man-made designs which may potentially aid in areas as diverse as self-cleaning of outdoor and indoor surfaces environments (e.g., hospital surfaces, habitat structures) [46–48] and a variety of other applications such as artificial micro-channels and circulatory channels (e.g., syringes, central line ports, next-generation animal capillaries), [49] dental implants, contact lenses, wound-healing architectures, marine structures, and membranes used in industrial applications (e.g., potable water filters) [38, 50–54].

2.3 Spider Silk Fibers: A Leap in Materials Tribology

Kevlar is one of the strongest man-made fibers, but nature has always been way ahead of us. It is seen that spider silk fibers can absorb nearly three times more energy than Kevlar before breaking, this is due to its unique combination of strength and toughness [55]. This apparently has been evident to some of our ancestors like the Australian aborigines and New Guinean natives who utilized spider silk as fishing lines, nets, head gear, and bags. They were also extensively used during World War II as crosshairs in optical devises due to its small diameter which is almost 1/40th of a human hair.

Natural silk webs are usually obtained from either silkworm or spiders but it is found that unlike silkworm silk, the spider silk has evolved in its mechanical performance in webs and has become the toughest biological material known to us. Spider silk has become a highly desirable material for application not only in biomaterials but also for high-performance industrial fibers. Despite its clear potential, it is extremely difficult to obtain silk from spiders [56], and substantial research effort has been spent to produce spider-like silk at commercial scales using biomimetic approaches. While the properties of spider silk have not yet matched, the use of scalable techniques, advances in understanding of the structure and natural spinning of native silks and improvements in protein expression, have been driving the field closer to its goals [57–60].

Unlike silkworms' silk, the methodology to harvest spider silk is a tedious and complex process. This is mainly due to the territorial and cannibalistic behavior of the spiders due to which spiders cannot be kept in close proximity. Even then attempts have been made to harvest this silk naturally from golden orb-weaving spider *Nephila madagascariensis* for producing a single spider silk cape as shown in Fig. 8. With each spider producing around 40 m of silk, it took 100 people 3 years to produce this cape requiring nearly 1.2 million spiders. Therefore it is not commercially feasible to collect spider silk in this manner and it has become critical for adopting a synthetic method of producing this silk material [61].

The most significant research on the synthesis of spider fibers has emerged in the field of microfluidics [63]. This research gives a tunable fabrication process which allows the fibers to be customized. Researchers have simplified the geometry of a silkworm spinning duct to an exponential function, wherein by dry spinning method, they were able to produce silks tougher than degummed silk [64]. The same is yet to be applied for a spider spinning duct, and very likely to provide improvements in performance. There has also been use of a range of experimental and computational approaches to understand the relationship between structure and function in recombinant silk-like block copolymers that were spun with a tunable microfluidic approach, yet the effects of spinning conditions were not reported [65]. It has been reported that a combined investigation of processing, design, structure, and function will substantially advance the field. Focusing on the extrusion of the silk protein solution will be a key for the next generation of engineered fibers, as it could be that the properties of the end product are more sensitive to the processing and extrusion of the dope solution compared to the protein sequence [66].

Spider silk surpasses the strength of some of the strongest types of fibers known to modern technology—including nylon, wool, Kevlar, and carbon. For its size, spider silk is stronger by weight than high-grade steel, but also is incredibly flexible and light. It even surpasses the elasticity of rubber. If commercialized, synthetic spider silk could be a real game changer when it comes to strengthening materials for bulletproof vests, biodegradable water bottles, flexible bridge suspension ropes, vehicle air bags, and protective cases and covers for electronics. And that list is just the tip of the iceberg. The researchers at Bolt Threads are not the only ones pioneering the spider silk revolution [63].

2.4 Capillarity-Directed Soft Lithography Technique to Mimic Surface of a Lotus Leaf

The lotus leaf (*Nelumbo nucifera*) has a special surface texture that causes the water droplets to bead and pick up contaminants on its surface while rolling off it (Fig. 9). This phenomenon is popularly known as "The Lotus Effect" and referred technically as "super-hydrophobicity."

There have been many investigations which have been working on chemically treating metals and plastics to achieve this effect on the surface [67, 68]. These are already commercially available as Lexan, which are being used to make CD's, iPod covers, windshields of aircrafts, and even car headlamps making them water repellent. About 6 years ago in 2008, General Electric Inc. came up with methods to treat metals in the same way and make the metal surfaces water repellent. Since GE researchers at GE's Global Research Center have not yet published their work, it is still unclear as to how they were able to treat metallic surfaces. Limited information is available about their work in progress which involves changing the surface texture and chemical coating, inspired from lotus-plant leaves. Further, a detailed review on the current materials processing methods has been provided by Roach et al. [69].

Surface tension plays a major role in defining the interface characteristics and tension between any state of matter concerning solid, liquid, and vapor. In the current

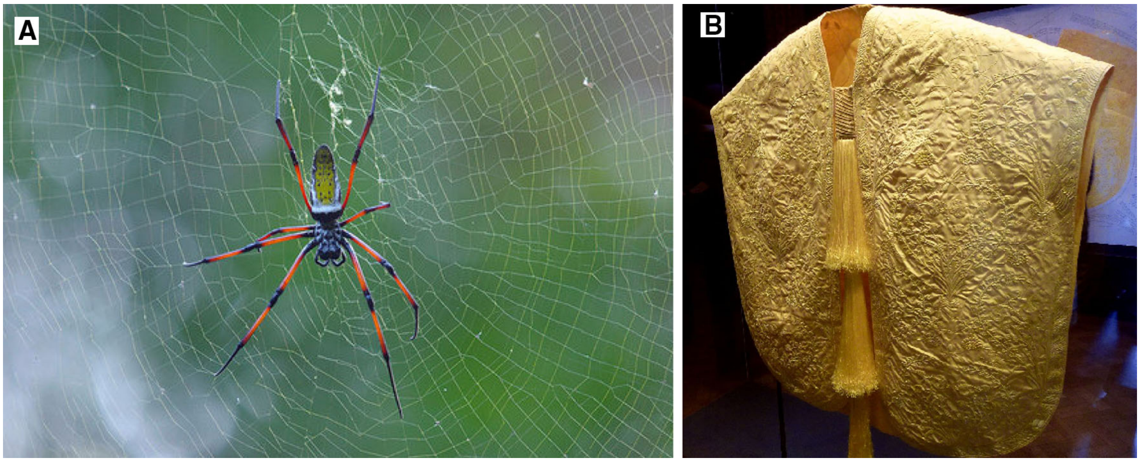

Fig. 8 **a** *Nephila madagascariensis* **b** A cape made from Madagascar Golden Orb spider silk exhibited at London's Victoria and Albert Museum in June 2012 [62]

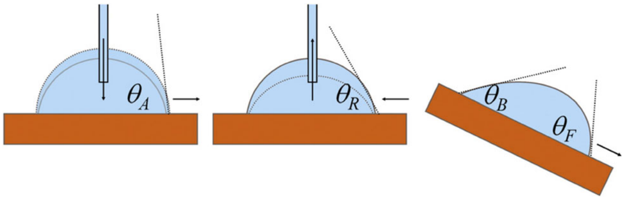

Fig. 9 Process of measuring advancing, receding, and sliding angles as a test for superhydrophobicity [70]

scenario, solid–liquid interfacial tension is of concern though the liquid–vapor interactions may also exist in most cases. The balance between the interfacial forces experienced will determine whether a droplet resting on a solid surface will be pulled out into a film or remains as a droplet and if so, what could be the extent of its footprint on the solid surface [70]. The condition where a thin layer of liquid forms a film on a smooth and flat surface is considered to have its energy lowered [71, 72], given by

$$S = \gamma_{SL} + \gamma_{LV} - \gamma_{SV} > 0, \tag{1}$$

where S is the spreading power, γ_{SL} the solid–liquid interfacial tension, γ_{LV} is the liquid–vapor interface tension, and γ_{SV} is the energy per unit area for dry surface which is smooth and flat. There is a frequent misconception that contact angle (θ_e) of a droplet and the droplet size are somehow related where infact they are not and is described by the Young equation [73]:

$$\cos\theta_e = \frac{(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}}. \tag{2}$$

Over the past two decades, there has been extensive research on methods for producing superhydrophobic surfaces which involved textiles and fibers, lithography, particles, templating, phase separation, etching, crystal growth, and diffusion-limited growth [70]. Of all these, the most commonly used is the lithography process which can be of two methods—photolithography, where layers are illuminated through a patterned mask to activate soft areas; and soft lithography, which is a simplified version of contact printing. Although relatively higher cost is involved in soft lithography it can produce a well-defined surface with excellent repeatability [74–79].

Yoon et al. [80] analyzed the tribological behavior of nanopatterned poly-methyl-methacrylate (PMMA) polymeric surfaces using AFM and custom-built micro-friction testers. A simple capillarity-directed soft lithography technique has been used to direct thin polymer layers into void spaces of elastomeric molds in contact above the glass transition temperature of the polymer [81]. Using this technique, they were able to fabricate various nanopatterns of high aspect ratios in a simple cost-effective manner.

Singh et al. [82] also used this technique to replicate the lotus leaf surface in its fresh condition. The application of this technique in biomimetic tribology utilizes the competition between the capillary and hydrodynamic forces during the pattern formation. The procedure for this method of surface replication has been reported in detail by Suh et al. [81]. The schematic of the procedure to replicate the surface texture is shown in Fig. 10. Through this procedure, they have been able to fabricate nanoscale polymeric asperities which mimic the protuberances of a lotus leaf.

This method if perfected can enhance tribological properties on a micro or even nanoscales as indicated by their results of micro-friction tests shown in Fig. 11. The histogram compares different synthetically prepared surfaces like Silicon wafer and PMMA against bio-mimicked surfaces of lotus leaf and Colocasia leaf (in dry and fresh condition). It is clear that replicated surface of lotus leaf has the least coefficient of friction (0.1). It is a well-known fact that friction force is directly proportional to real area of contact (Friction force = (shear strength) × (real area of contact)) and research speculates that the low friction values of replicated surfaces are due to the reduced real area of contact.

Now through the above-reviewed research works, it is clear that nature-inspired artificial surfaces exhibit superior tribological qualities and have a lot of potential for application in small scale. Some of the significant future application of these bio-mimicked lotus leaf surface on metals are de-icing of aircrafts where ice builds up on engines due to condensation; gas and steam turbines where the buildup of moisture and contaminants on the turbines can be avoided thereby requiring fewer shutdowns for maintenance. Further, research based on unique functions of a lotus leaf for cardiovascular applications in biomedical field are being carried out by Maani et al. [83] where they employ CFD modeling technique to investigate the effect of surface pattern to control blood flow adhesion. The non-wettable character has been claimed in biomedical applications ranging from blood vessel replacement to wound management [84].

Wang et al. [85] reports a highly hard but flexible and superhydrophobic DLC films with bio-mimicked texture fabrication which is based on nanocasting, electroplating, and physical vapor deposition, using biological samples as templates as can be observed in Fig. 12. These have been indicated to have widespread applications such as in bio-robot, biomedical devices and top layer of different biomedical implants.

2.5 Friction-Reducing Sharkskin

Over the last few years' research toward making efficient use of energy, especially with fossil fuels being consumed has been a priority. And yet again, the solution to harness

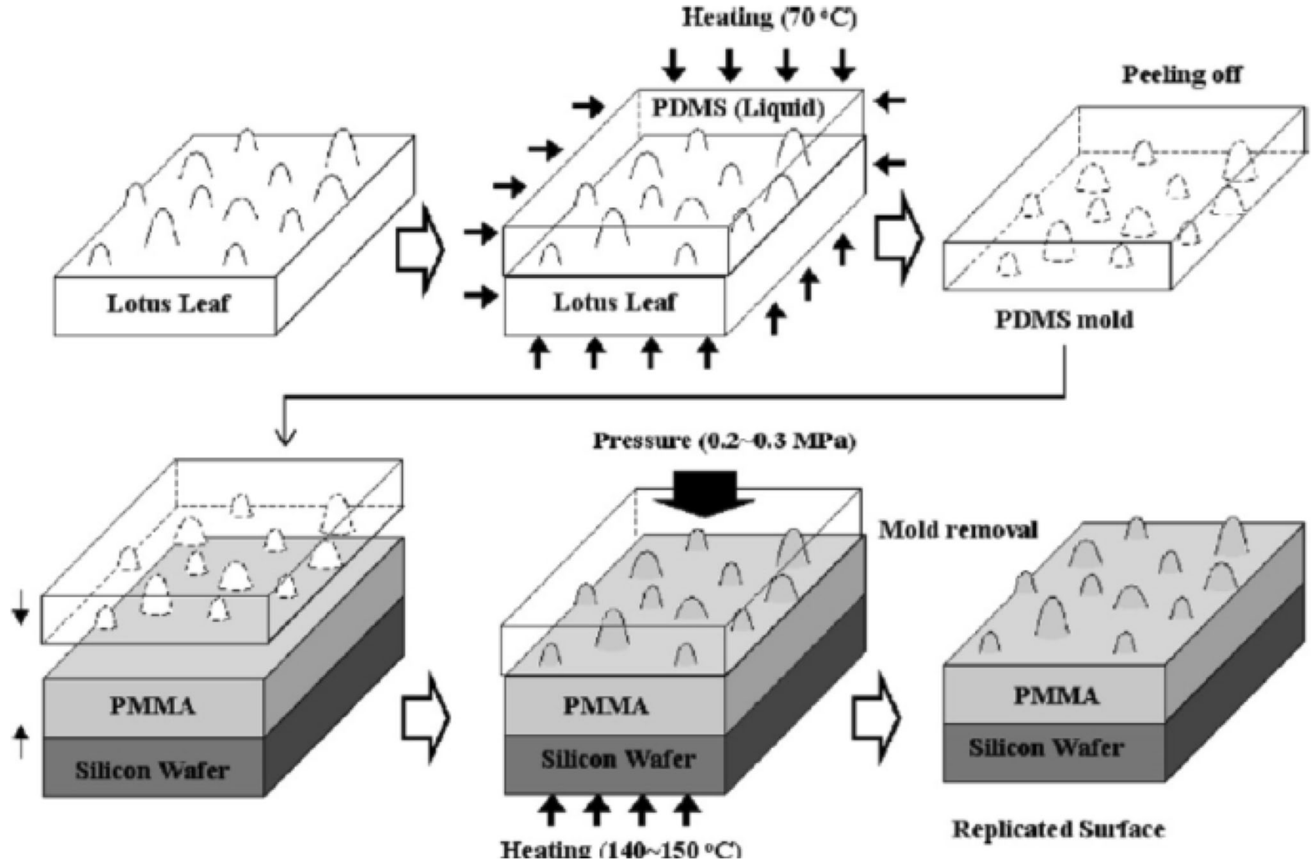

Fig. 10 Sequence of replicating surface texture of Lotus Leaf using capillarity-directed soft lithography technique [82]

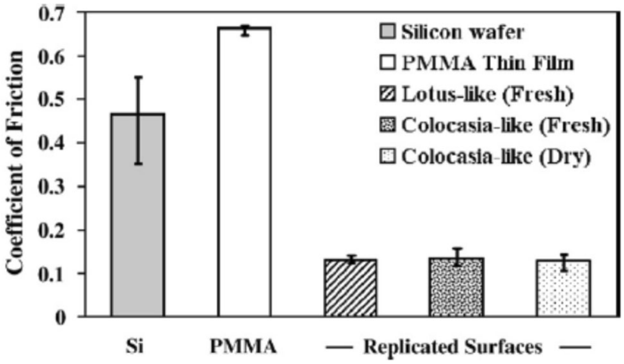

Fig. 11 Comparative *histogram* for friction of test materials indicating the best friction values for lotus leaf mimicked surface [82]

energy more efficiently lies with nature, researchers are looking into the evolved ability of shark's skin to reduce drag by manipulating the flow around the boundary layers. This has led researchers to develop similar coatings for ship's hulls, submarines, aircraft fuselage, and even swim wear for humans. These coatings are able to reduce friction between a solid surface and a fluid flowing over it, which sounds simple but is a complex tribological phenomenon. It is speculated that the speedo's Fastskin FSII swimsuits who made their appearance at Beijing Olympics mimicked this ability of shark in their product used by Michael Phelps and may be helped him to the record eight gold medals in that competition. But one important effect of the denticles is to enhance thrust, and not simply to reduce drag. It was later proved by Oeffner et al. [86] that the mimicked shark denticles on the suit as seen in Fig. 13 had no beneficial loco-motor effect which should have helped propel the body, but in this case, it can only reduce the skin friction to a certain extent.

The notion that aerodynamics is related to sleekness of the body is not completely true as the shark skin texture has shown that the right kind of roughness on a surface to suit the environmental conditions is actually better. Investigations have been made to understand the boundary layer flow over the surface of shark skin and to explain how and why they are able to swim at over 60 mph. At first look at the shark skin, it may not be apparent of the complicated science behind its skin, but on closer look they have jagged scales covered with longitudinal ridges as shown in Fig. 14 which enable them to slice through water so swiftly [87].

The Fraunhofer-Gesellschaft organization concerned with applied research in Europe reported in their editorial research news special edition (05-2010) on the application of sharkskin paint for airplanes, ships, and wind energy

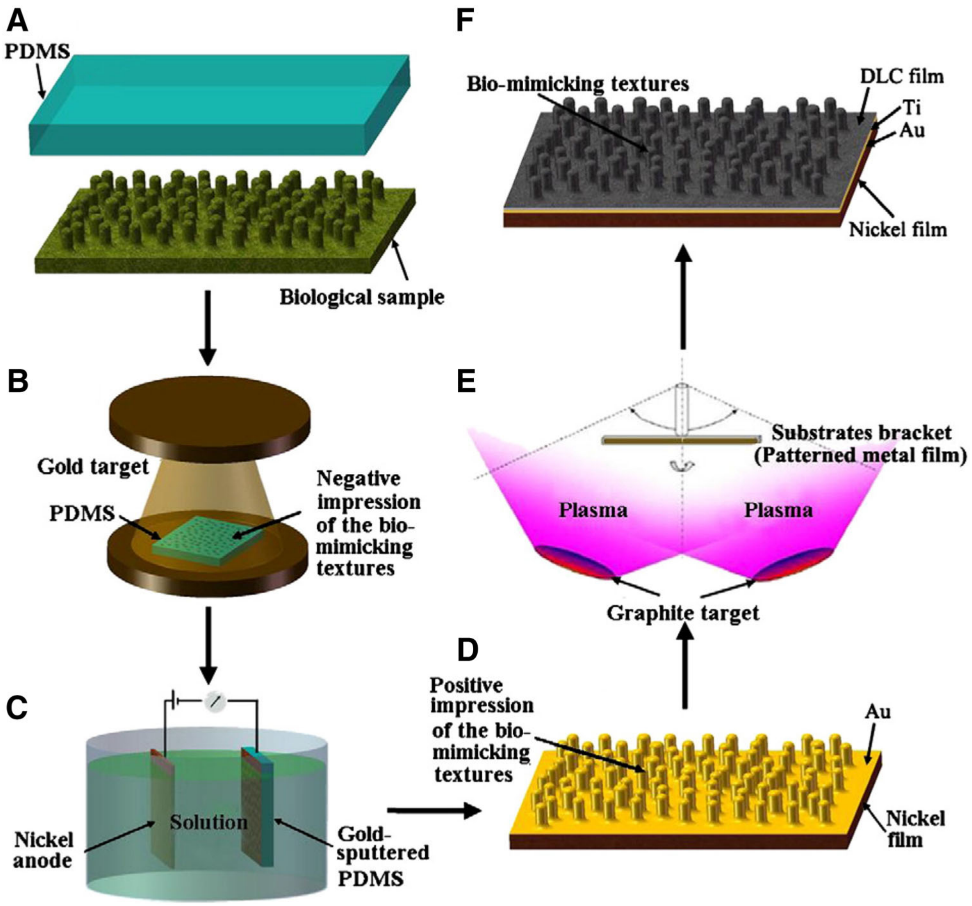

Fig. 12 The schematic diagram of creating DLC film with bio-mimicking textures. **a** A PDMS film is used to replicate the surface microtextures of the biological sample, **b** a thin layer of gold is sputtered on the textured PDMS film to provide a conductive surface, **c** a metallic layer is electrodeposited on the top of the PDMS film, **d** the PDMS film is peeled off to obtain a metallic layer with positive impression of the bio-mimicking textures, **e** a thin hard DLC film was deposited on the top of the metallic layer, **f** DLC film with the bio-mimicking textures [85]

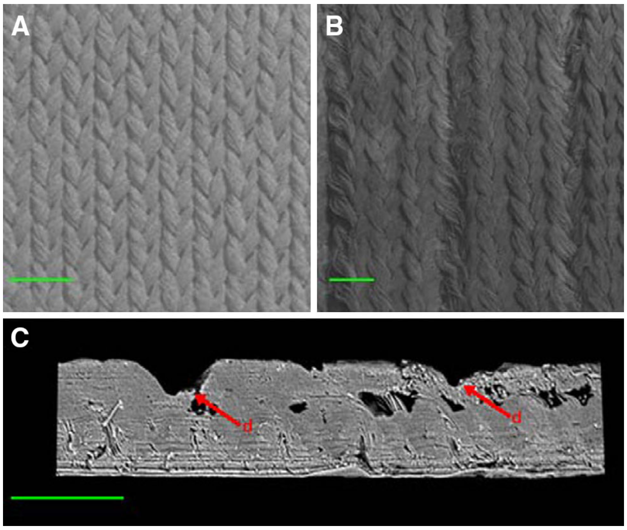

Fig. 13 SEM images of Fastskin FSII Speedo® fabric. **a** Surface image of the underside (non-biomimetic) surface of the fabric. **b** Surface image of the outside (biomimetic surface) of the Speedo® fabric at the position of V-shaped printing. **c** Image of a cross-section of the Speedo® fabric, showing the dents on the biomimetic side (*red arrows*, ‘d’) in the fabric that generate the ‘ribbed’ surface. *Scale bars*, 500 µm [86]

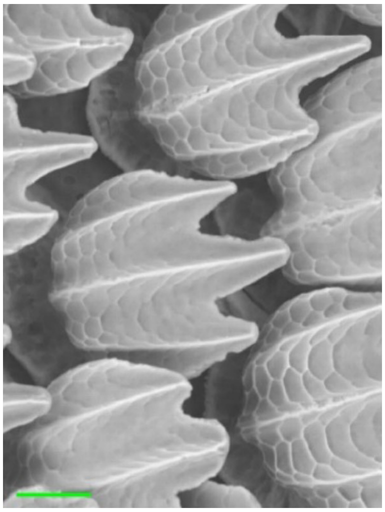

Fig. 14 Close-view ESEM image of denticles from the surface of the mid-body region in a bonnethead shark (Sphyrna tiburo) to show details of typical denticle structure with the three surface ridges and three posteriorly pointing prongs. Such denticle structure is common on the body, fins, and tail, although denticles of this species on the head have a different morphology. *Scale bar*, 50 µm [86]

plants. Wilke et al. [88] in their attempt to diminish drag and resistance to flow of currents for these applications were inspired from the evolved scales of fast-swimming sharks. To impart these tribological properties to a paint they had to overcome the environmental working conditions like temperatures that range from −55 to +70 degree Celsius, intense UV radiations, high speeds, and withstand mechanical loads on a regular basis.

They came up with a sophisticated formulation of paint that made use of nanoparticles which gave the structure surfaces sharkskin-like coating that had the required tribological properties. The paint coat could reduce wall friction by more than five percent for a ship construction test facility. Wilke et al. [88] extrapolated this result over 1 year to show that if this coating is applied to every airplane around the world it could save nearly 4.48 million tons of fuel every year. For a large container ship, this would mean savings of 2000 tons of fuel annually. This innovative surface paint can also be applied to wind energy farms where the drag and friction can be reduced between the rotor blades and air.

With all good things, there is a downside to this application of paint to ship hulls, algae, and muscles get accumulated on them complicating things further. Currently, researchers are working on solving this in two ways, one simply using biofouling methods where by these organisms cannot get a good grasp on the ship hull and get washed away at high speeds; the other way is using a fouling method that acts as a repellent for natural organisms.

This kind of research is a proof that nature has solutions to almost every complicated engineering problem, the biggest hurdle is knowing where to look for.

2.6 Bio-Mimicked Lubrication Inspired by Catfish Skin Mucus Using Hydrogels

It is a well-known fact that some fishes secrete mucus from their skin which not only acts as a defense mechanism from predators but it also enables them to swim through water easily by acting as a lubricant. Wu et al. [89] has shown this mucus to have ultra-low coefficient of friction ranging between 0.005 and 0.007 in distilled water and in buffer solution at 40 degree Celsius (see Fig. 16a). A synthetically formulated liquid known as a hydrogel, exhibits similar or even better lubricating properties. Like the mucus seen on the fish skin, hydrogels are also capable of trapping large amount of water on the gel surface which acts as a lubricating film.

Hydrogel products are a group of polymeric material which have hydrophilic structure that is responsible for their ability to hold large amounts of water in three-dimensional network. A detailed method of its preparation, characterization, and application has been reviewed by Ahmed [90]. A hydrogel can be stimulated by various methods as shown in Fig. 15 to absorb water, whereby its tribological behaviors as a lubricant can be controlled.

These Hydrogels have been designed to mimic the tribological properties exhibited by the mucus on the fish skin. In this regard, extensive research has been carried out by Gong et al. [91] on artificial hydrogels to achieve coefficient of friction of the order 10^{-4} which is lesser than natural fish skin. In their research, investigation has been carried out on rich and complex behaviors of various kinds of hydrogels with regard to friction and their tribological features. It has been reported that the friction force and its dependence on load are completely different from those observed in solids. These tribological properties are seen to differ with chemical structure of the gels, surface properties of opposing substrate, and also the measurement conditions. Also the gel friction during lubrication is found to be due to the hydrated layer of polymer chains when these are non-adherent or repulsive from the substrate and the friction due to elastic deformation is shown to be caused by absorbed polymer chain when it is adherent to the substrate [92].

Various types of hydrogels were analyzed by Kaneko et al. [93] and a hydrogel named DN-L gel was shown to not only have a coefficient of friction in the range of 10^{-5} under extremely high pressures but also a fracture strength of 9 MPa.

Wu et al. [89] have also formulated a pH-thermal-sensitive hybrid hydrogel with multiple responsive characteristics whereby controlling the pH and temperature stimuli the friction coefficient was shown to be controlled accordingly. This has been depicted graphically in Fig. 16b.

The researches discussed above are the rare situations of surpassing nature by bio-mimicking the tribological aspect of lubrication seen in a catfish skin. But still, these artificial lubricants are yet be used efficiently for an engineering application as its use is limited to lubricating layer of few microns and low load conditions. Hence, most of its application are currently limited to medical field as reported by Ahmed [90].

2.7 Air Lubrication of Emperor Penguins to Propel Boats, Ships, and Torpedoes Faster

It is a well-known fact that penguins cannot fly but still this does not stop them from getting in big air times when they have to jump out of water onto sea ice or even sometimes evade predators. This evolution of penguins is quite understandable considering their physical squat body structure with stubby legs which make it difficult for them to climb ashore especially onto rocky shorelines and

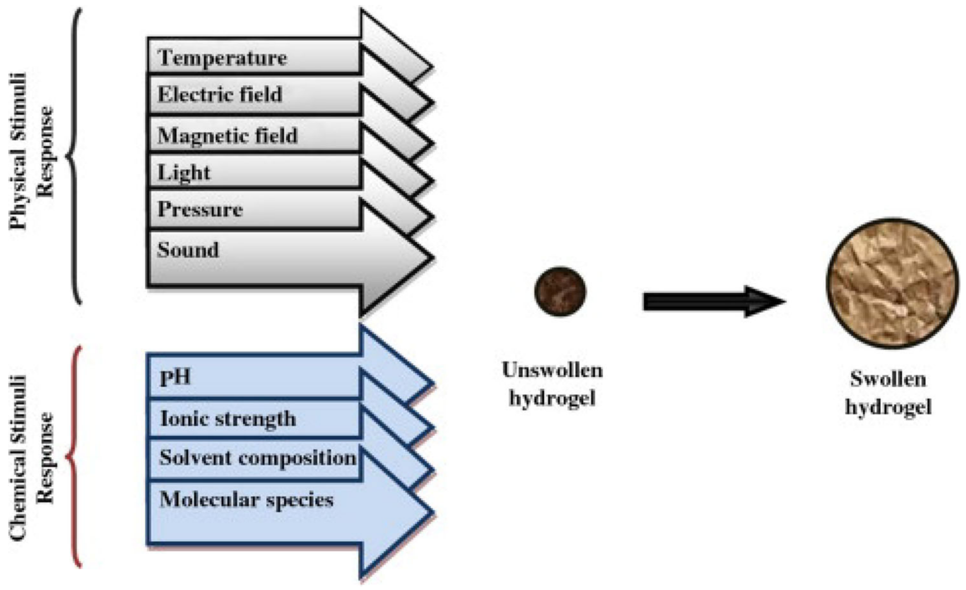

Fig. 15 Various stimulis' to make a hydrogel swell (absorb water) [90]

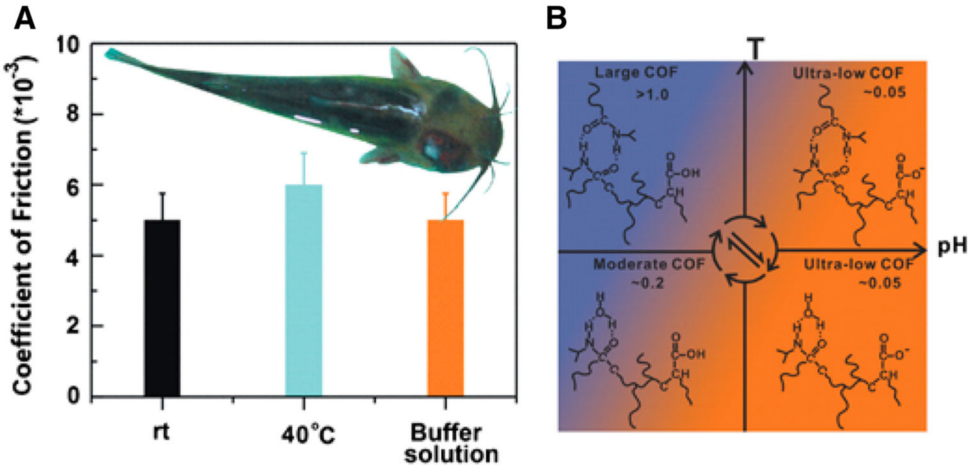

Fig. 16 **a** COF of catfish skin under varying environment conditions; b. Change in COF seen when pH and temperature stimuli conditions are varied [89]

mostly impossible for it to climb onto sea ice. Some species like the emperor penguins have been seen to fly as high as 9 feet in the air at nearly 17 feet per second and land on ice safely.

Fascinating new observations have been made by Davenport et al. [94] to uncover the secret behind the sudden bursts in speed achieved by emperor penguins. In their research, it has been convincingly hypothesized that this ability of emperor penguins can be attributed to 'Air Lubrication.' Air lubrication is the method of injecting air into the boundary layers which is also a technique that has been used to propel ships and torpedoes at high speeds through sea water. This kind of lubrication in penguins has only recently been uncovered even though the emperor penguins have been a subject of study to many scientists for decades.

In one of the studies by Sato et al. [95] they recorded detailed physical movements of penguins including their speed and distances before (underwater) and after a burst of speed (underwater and in air) by emperor penguin to jump onto sea ice. They found that the velocities required to overcome the effect of gravity correlated with the exit speeds achieved by the penguins and interpreted the stopping of flipper action some distance below the jump reason for better buoyancy. Although this was true in an earlier research with a different species of penguin [96], it has been shown to not be the same in case of emperor penguins.

Davenport et al. [94] made use of these footages of the documentary Blue Plant from BBC Natural History Unit (see Fig. 17), using which they have analyzed air lubrication phenomenon which aid the emperor penguins to achieve high bursts of speed. They measured the upward underwater ascent speeds of these penguins to be nearly 5.3 ms^{-1} which is estimated as the maximum speed they can achieve. This high speed during ascent is attributed to

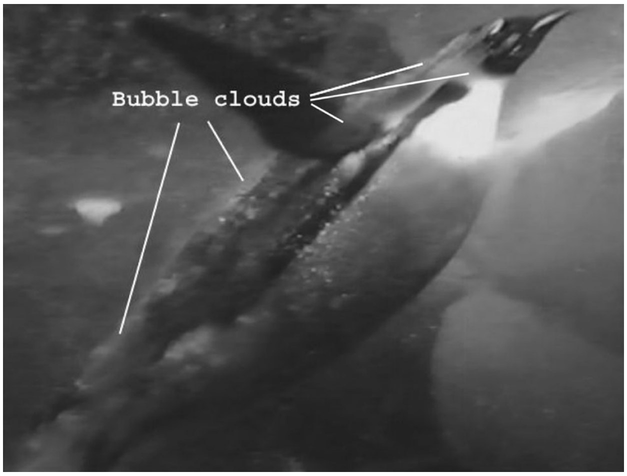

Fig. 17 An emperor penguin ascending to break the surface of water with notable air bubble clouds emerging from various regions on a penguin body [97]

the penguins emitting air bubble clouds into the turbulent boundary layer over most of their body surface. This emission of air bubbles unlike the misconception does not reduce their speed but increases it as they approach the water surface. The air bubble cloud performs a drag-reducing function whereby it reduces the friction between the solid skin surface of penguin and the water around it.

The investigations reviewed in this case study show that some aspects of biomimetics tribology are already in use for engineering application, here it has been for marine vehicle applications [97]. It has also been reported that penguins far exceed drag/friction reduction than those achieved in the marine engineering applications [98]. This is attributed to the plumage of penguins which is water repellent due to peen oil being present on them unlike in marine applications where it is still a difficult task to maintain sufficient bubble coverage within the turbulent boundary layer.

2.8 Efficient Slippery and Self-Healing Coating From Pitcher Plant

The technological implications of a surface that is able to repel various liquids is enormous, especially in the field of biomedical devices, automobiles, and even architecture. As discussed in the earlier section where lotus leaf presents similar implications with its microtextured surface being mimicked efficiently to act as a non-wetting structure [99–101]. Even with over a decade's worth of research into this, there are still major problems like high contact angle hysteresis with limited olephobicity [101], failure under pressure, and inability to self-heal when physically damaged accompanied by high fabrication costs, restricting their practical applications [102–104]. To overcome these hurdles, researchers have looked for new bio-inspired surface.

The plausible solution has been found by Wong et al. [105] in *Nepenthes* pitcher plants (see Fig. 18) which is found to exhibit surface properties very different from lotus leaf.

Wong et al. [105] present a strategy to create a self-healing and slippery liquid-infused porous surfaces (SLIPS) that will have superior liquid repelling properties. They have made use of a nano/microstructured substrate that can lock in an infused lubricated fluid which will then be able to repel other liquids as depicted in Fig. 19.

This formulated surface is shown to be stable and defect-free and have an inert slippery interface. The surface is also able to exhibit self-healing properties by being able to restore its liquid repellency within 0.1–1 s of a physical damage. To prove the sustainability of this surface, Wong et al. [105] compared its capability against best in the market synthetic liquid-repellent surfaces by testing with simple and complex liquids such as water, hydrocarbons, crude oils, and blood. This bio-mimicked surface was able to outperform its counterparts [107–109] in all scenarios by being able to perform at high pressures, resist ice adhesion, and maintain a low hysteresis angle. It is also shown that geometry of the substrate has minimal effect on the performance of the lubricated layer. With this kind of performance, SLIPS surface will be useful in optical sensing, medicine, self-cleaning, and antifouling materials operating in extreme environments as applied to automobiles, ships, airplanes, medical equipments, and mobiles.

During the study of the above bio-inspired tribological cases, the authors find that biology papers are frequently isolated for engineers, since they are too imaginative and contain concepts and approaches such as taxonomy with its Latin names that are too far from any concepts in engineering. It is found that the omnipresence of tribology in

Fig. 18 *Nepenthes* Pitcher Plant [106]

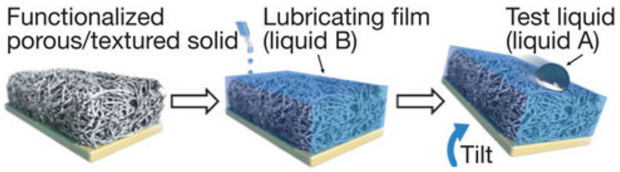

Fig. 19 Fabrication of a SLIPS by infusing a lubricating film [105]

biology is not well communicated mainly due to scientific papers being difficult to analyze in terms of biological concepts.

A new type of presentation of knowledge is needed, perhaps multidisciplinary science, so that researchers from various fields can profit from each other findings. The huge amount of publications in biology would be screened for tribologically interesting contents and needed experiments could be suggested, linking microtribology and biology. This review of bio-inspired tribology has lead the authors to believe that life forms in some aspects are technology in every proper sense, with diversity of designs, materials, engines, and mechanical contrivances of every degree of complexity.

3 Conclusions

It is conclusive from the case studies that reproducing the precise mechanical properties of native biological beings may not necessarily be useful or entirely possible, since most species have evolved to possess their characteristic abilities to survive in a specific environment. This perhaps is the greatest weakness when it comes to biomimetic tribology. The major conclusion of the case studies made above with respect to their practical application and realistic targets are listed below:

- The Synovial fluid fabrication in the form of microgels is found to be the most effective plausible way for replicating its lubricant form for applications in arthritis treatments and biomimetic aqueous lubrication applications. The findings of this fabrication method may be useful for further research applicable in IC engine oils.
- The properties of gecko's skin are already in process adaptations for many water-repelling, self-cleaning, antibacterial, and biocompatible coatings in terrestrial and aquatic environments. So it is fair enough to say that this technology will be commercially incorporated into a wide range of products in due time.
- The process of replicating spider silk, lotus leaf surface, shark skin properties, and catfish skin mucus are still lagging in understanding of their biological functioning and method of fabrication for an engineering application, and hence have huge scope for development.
- One of the most aspiring researches toward a self-healing surface inspired from pitcher plant has to be the most influential technology if fabricated efficiently.

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