Bio-Design and Manufacturing (2020) 3:148–154
https://doi.org/10.1007/s42242-020-00069-5

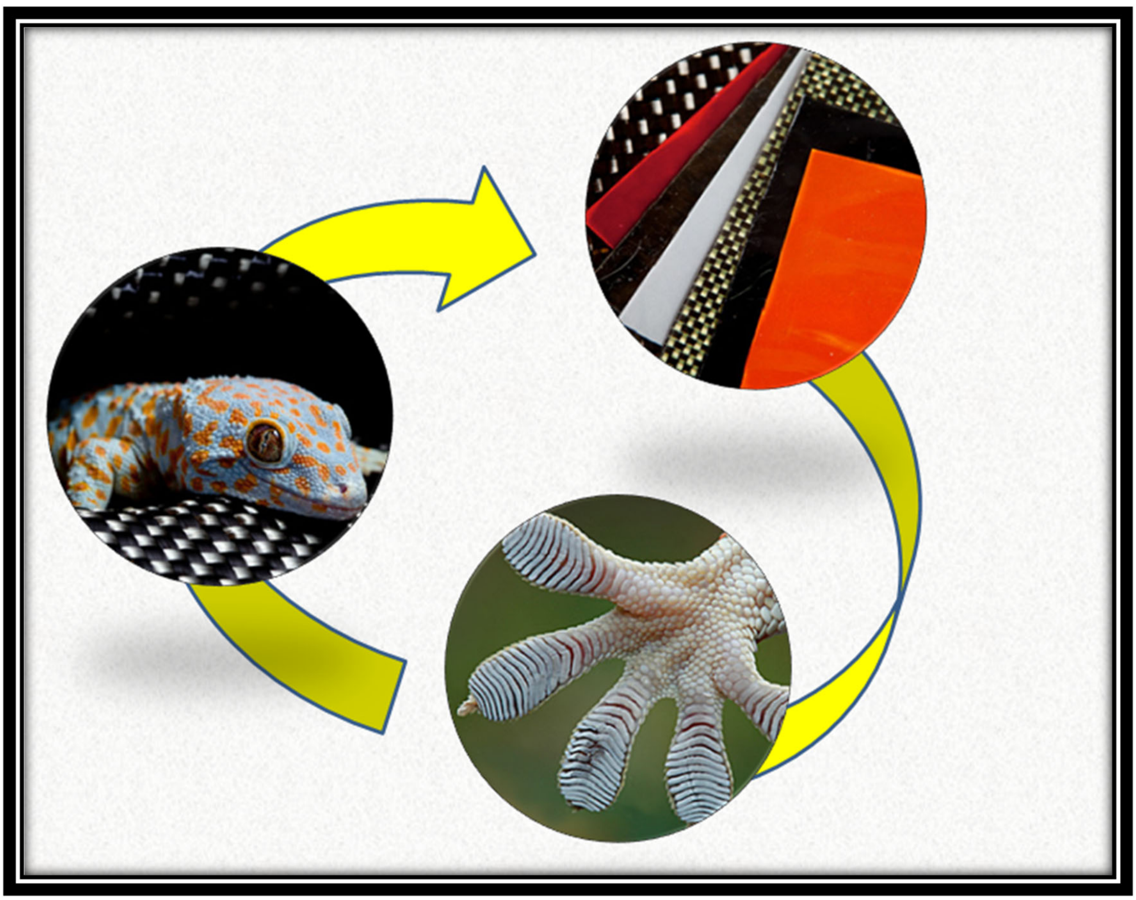
PERSONAL VIEW

Walking through the biomimetic bandages inspired by Gecko's feet

Sayan Basak[1]

Received: 16 February 2020 / Accepted: 31 March 2020 / Published online: 17 April 2020

Graphic abstract



Keywords Adhesion · Gecko · Biomimetic · Bandages · Smart materials

✉ Sayan Basak
sayancupst@gmail.com

1 Department of Polymer Science and Technology, University of Calcutta, 92, A.P.C Road, Kolkata, West Bengal 700009, India

Introduction

We all very accustomed to the emergency room of a critical care unit, which is indeed captivated with accidental injury and internal bleeding, making the duo one of the highest causes of mortality to date. The conventionally used adhesive-based materials such as tapes or duct tapes depend only on the viscoelastic compounds to exhibit their adhesive abilities [1–4]. The present generations of tapes have a quasi-sticky fluidlike state on their bottom, which at times remains when the tapes are peeled off [2, 3]. The primary adhesion phenomenon observed in these materials is due to the Van der Waal's force of interaction which often fails when it is applied to the various surfaces having numerous functionalities [5]. The enhancement of the Van der Waal's force of interaction by adding different surface-active viscoelastic groups leaves a sticky residue behind upon removal. The traditional tapes are designed in a way to sandwich the viscoelastic material in-between the polymer framework. Thus, when peeled off and applied, each of the exposed surfaces retains half of the 'stickiness' which accelerates the wearing-off process after applying a couple of times. Additionally, these tapes, majorly operating on the viscoelasticity behavior, are time-dependent, and hence the efficiency degrades with time regardless of how many times the tapes have been used [6, 7].

Although there has been a burgeoning interest in fabricating medical adhesives inspired by geckos, a few of them have been proven to work in a wet tissue-like environment [3, 7]. For instance, the communication by Messersmith et al. had described a synthesized gecko-inspired adhesive that forms covalent bonds to inorganic moieties underwater [3]. However, in the case of medical sciences, the adhesives should possess robust irreversible bonds (specifically to organic species) to prevent the dislocation of the surrounding tissues and cells [3]. Moreover, the analytical techniques to characterize these gecko-inspired adhesives are not well developed. The current researches employ evaluation constructed on submicrometer atomic force microscopy measurements, which might not be the exact replication when tested on a macroscopic scale [3, 7].

To address the issue, a research team from the Massachusetts Institute of Technology headed by Dr. Jeffry Karp and Dr. Robert Langer has fabricated a novel 'bandage-type' material that upgrades the existing bandaging technology by improving its adhesive property and the sealing efficacy [8]. Experimental results have proven that the fabricated bandage is capable of working with the same potential even with the resistance provided by the heartbeat. The invention is one of the best examples of biomimetic materials that primarily draw an analogy from nature providing us with an insight that these gecko-inspired bandages may be a potential replacement for the traditional dressings in the healthcare sector [3].

The evolution of the gecko biomimetics

The gecko is a class of lizards whose feet soles are comprised of lamellae, which further may be classified into oriented minute hair known as setae. The setae multiply into thousands of 'flat-ended' structures, thus enhancing the surface area of the feet [5]. The escalation of the surface area enables the possibility of various other secondary forces of interaction apart from Van der Waal's forces of cohesion [3, 9]. Gecko's feet are not attributed to the presence of any 'sticky' substance, as in the case of the conventional tapes. Instead, the forces on a nanolevel exhibited by each of the tiny spatula-shaped structures present on each seta are capable of resisting almost 115 kilograms of force. The summation of these nanometric forces is so strong that, theoretically, a gecko may add 40 kilograms of weight and still be able to climb walls profoundly [10].

The advancements in the domains of science have found that a perfect arrangement of setae and the spatula not only supplements the gecko from falling off the ceilings but also aid them to walk through harsh surfaces [11, 12]. Interestingly, most of the biomimetic realms (ranging from snowflake formation to spiderweb jumping) have relied on these minute forces of attraction [13].

The adhesion phenomena in gecko may also be attributed to the participation of several branched contact points that mold accordingly to generate the resultant high-density contact with the surface under observation [14, 15]. Drawing inspiration from these findings, apart from the assembly of novel adhesive surfaces, various superhydrophobic surfaces have been prepared. Superhydrophobic substrates are surfaces which possess a static water contact angles higher than 150° [16]. These 'low adhesive surfaces' often demonstrate a low sliding angle, thus behaving as self-cleaning surfaces for potential applications in various fields from daily life to industry [16]. Similar to the self-cleaning property of the lotus leaves due to the maneuvering of the contact angle, the gecko also exhibits a self-cleaning behavior owing to the energetical deposition of particles on the surface rather than in-between the setae. With the efficient adhesive property and additional features of self-cleaning, medical bandages inspired by gecko's feet are one of the preeminent researched articles [17].

Redesigning the inspiration sparking from the gecko's feet—Amalgamating tissue adhesive with biomimetics

One of the trending areas for scientists to work nowadays is to decipher the way how the geckos adhere/climb to/on smooth vertical and inverted surfaces. Curiosity has eventually led to the development of these nature-inspired materials [18]. To date, the only surfaces coated with Teflon have been known to the research community, which prevents gecko's adhesive from working on it [18]. Several past researchers have claimed that Van der Waal's interaction plays a pivotal role in adhering to the gecko's feet to the surface of contact [19, 20]. Apart from this, even capillary forces play a vital role in the chemistry of adhesion between the minutely divided setae (having the size in the range of 200 nm) present on the gecko's feet and the surface [20]. The enhanced adhesive property of the geckos, which enables them to attach and detach from surfaces, has been one of the potent inspirations in developing novel dry adhesives. The amalgamation of the hierarchical topography of the delicate tilted and curved columnar structures along with the trapezoidal-shaped terminal pads supplements in the exhibition of strong friction forces (due to the Van der Waal's interaction), thus enabling the animal to climb a variety of surfaces [21]. While the friction forces, when sheared along the gripping direction, help in the generation of the 'adhesion,' the shearing action carried out in the 'opposite/releasing direction' enables geckos to get detached from the surfaces [21]. Although the concept of the mechanically controllable adhesion anisotropy is one of the trending topics in the medical science, fabricating an adhesive material that imparts all of the characteristics of gecko adhesion remains a puzzle to solve [21].

One of the classic developments in the gecko-inspired mimicry traces back in 2007 when Messersmith and Lee had reported functional nanostructured material that imitated the adhesion phenomenon of the geckos [3]. The group had developed several stacks of nanopillars producing a similar effect as that of the setae's, thus providing a significant amount of Van der Waal's force along with capillary forces. The prime disadvantage in the gecko's feet adhesion phenomenon is the fact that they are susceptible to humidity and the presence of water. Messersmith and his colleagues had found a perfect way to overcome this problem and had successfully fabricated the nanopillars, which displayed the same property even on wet surfaces [2].

Mahdavi and his co-workers went a step further with these prevailing ideas and synthesized bandages that could adhere to wet tissues for the potential usage in the biomedical industry [8]. The final material, apart from being elastomeric, along with biocompatible and biodegradable, also had the characteristic trait of having a secondary layer of biomoldable adhesive to assist the bandage to be working even on wet organic substrates of the tissues. The bandages, when tested in the intestines of the pigs and rats after operating them for hernia surgery, displayed satisfactory results [8].

The laboratory used the reactive ion etching technique to create the mold by etching holes into a silicon substrate. Poly(glycerol sebacate acrylate) (PGSA), which defines itself to be a tough biodegradable elastomer, was spin-coated onto the silicon surface and after that cured with the aid of UV radiation [8]. The process helped the PGSA to be molded into the nanopillar-like structures through the holes of the silicon template. The choice of adopting PGSA was kind of obvious to us since PGSA has previously been reported extensively to show an all-round property trait-like elasticity, doping easiness, biodegradability, biocompatibility, and a perfect polymer in drug applications [22].

The adhesion was modified by incorporating a thin layer of oxidized dextran (ODXT) together with aldehyde functionalities [ODXTA], facilitating the covalent cross-linking with the tissue. The aldehyde group in the chain end of the ODXTA reacts with the amine groups present in the proteins and the amino acid present majorly to form into imines [8]. These cross-link structures have shown to double the adhesion strength of these bandages as compared to composites without the cross-link. As an added feature to produce the maximum adhesion, the researchers paid particular attention to optimize the ratio between the tip and the pitch diameter of the nanostructures. They had reported using the shear and the sliding forces, which can be found in the porcine intestine tissue to enact the forces which are felt by the adhesives on the tissues after any surgical operations. The gecko does generally have shear adhesion strength of (8–10) N cm^{-2} on an ideal dry surface. When contrasting with these data, Mahdavi's research group had achieved an adhesion strength of 4.8 N cm^{-2} on a wet intestine tissue with their bandages (Fig. 1). The result synchronizes with the adhesives based on carbon nanotubes and polypropylene microfiber arrays tested on dry surfaces [8].

The research is one of the fundamental developments in gecko-based adhesives where we find the enhancement of the material by mechanical interlocking with the tissue, unlike the previous events which used spatular surface contact or weak reversible adhesion [8, 23]. Moreover, the research, for the first time, reports the in vivo studies of gecko-inspired surfaces. The results inferred that the gecko tapes demonstrated an insignificant tissue response, which might be a crucial factor for scaling up this material as an advanced biomedical tool.

The bandages were henceforth tested in the Massachusetts General Hospital, where the samples were applied to the abdominal sub-facial tissue. It was observed that the adhesion strength was reduced to 0.8 N cm^{-2} [8]. The biodegradability of the tissues could be tuned by either using chemical means or by using geometrical features, fine-tuning the molded nanopattern in the system. The scientists plan to develop bandages superscribed with growth factors, antibiotics, and anti-inflammatory drugs, which can mainly be used in the tissue regeneration application.

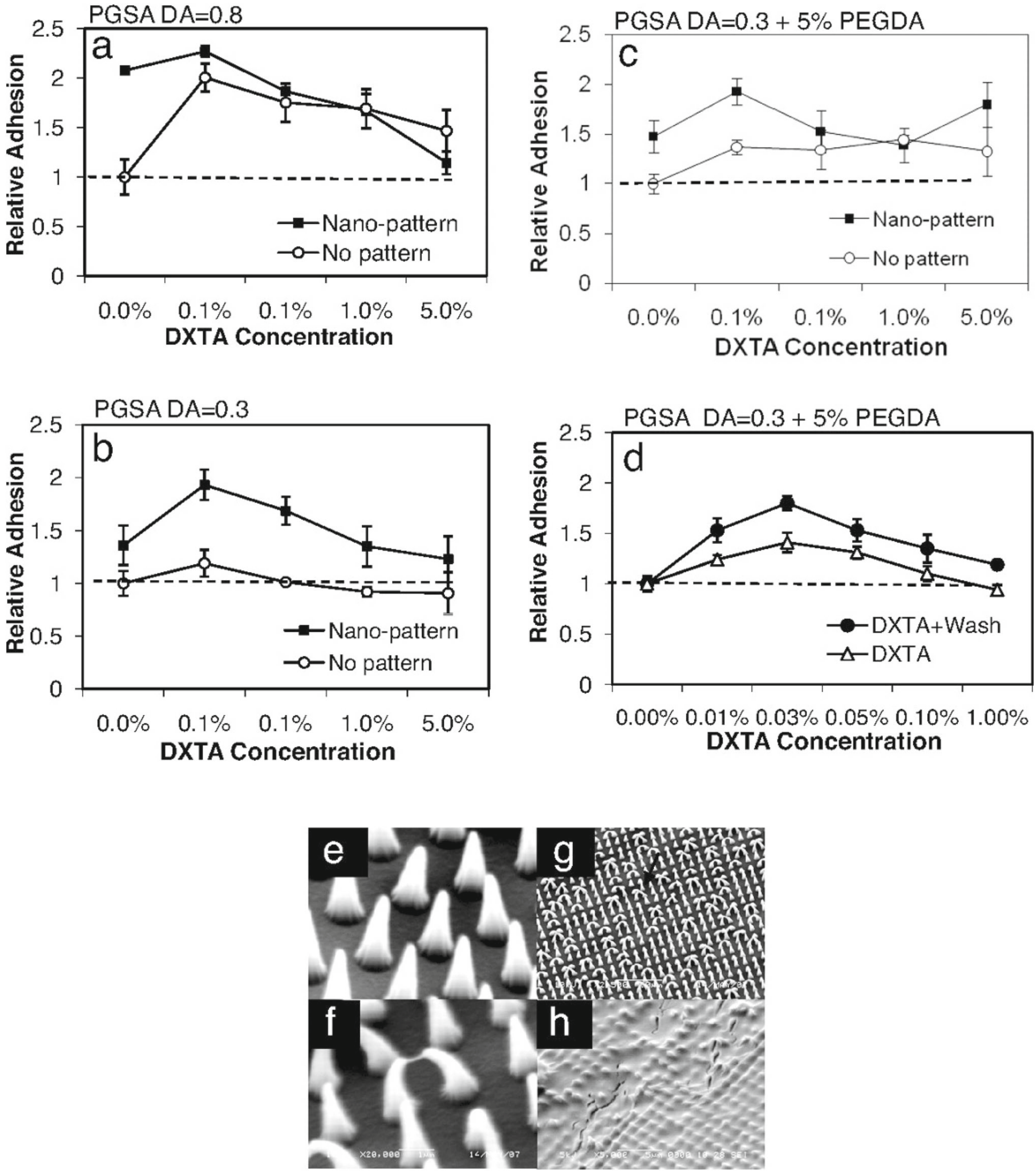


Fig. 1 **a–d** The relative adhesion of nanopatterned versus unpatterned PGSA polymer to porcine tissue slides with an increase in the DXTA surface coating concentration.**e** Nanopatterned PGSA polymer after surface spin coating with water (as control).**f** and**g** Nanopatterned PGSA after surface spin coating with 0.05% DXTA solution. The picture illustrates the adhesion of neighboring pillar tips.**h** Five percent of DXTA completely blocked the developed nanopattern, reprinted with permission from [8], copyright reserved The National Academy of Sciences of the USA, 2008

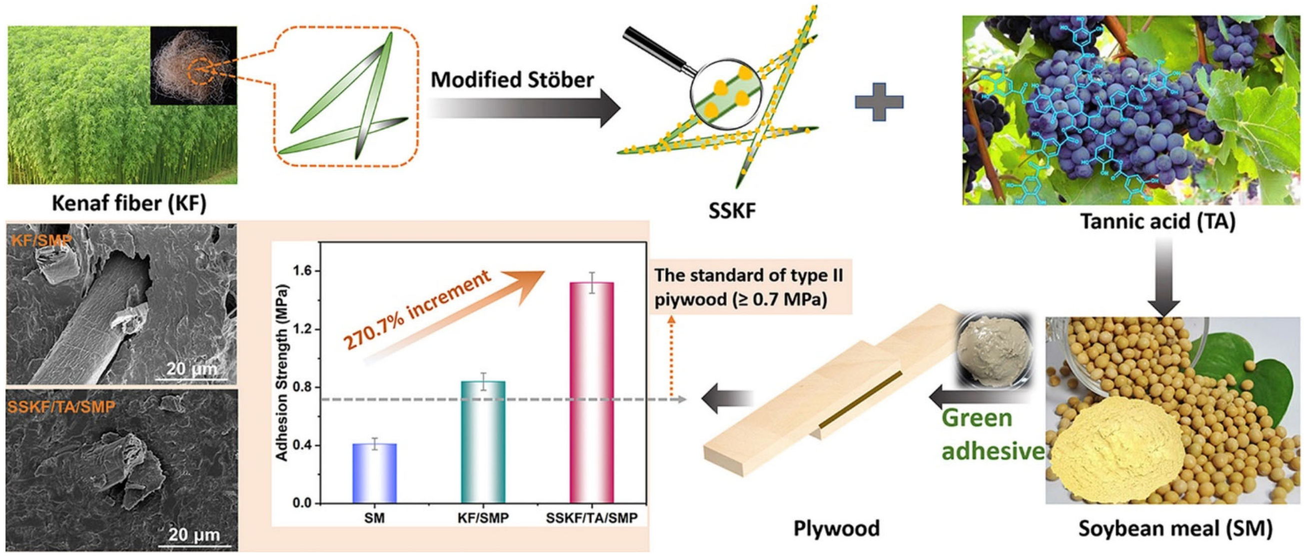


Fig. 2 The fabrication of the gecko-inspired green soybean meal-based adhesives reinforced with modified kenaf fibers used for bonding plywood specimens, reprinted with permission from [23]. Copyright reserved Elsevier, 2019

Looking ahead in the future

In today's world, which focuses on developing sustainability, we have nature as the biggest library in front of us to fabricate the framework to protect the Earth and its ecosystem. Nature has amazed us by providing a beautiful ability to the geckos, which can be used by them to climb vertical walls. The conventional sutures which we use today in the emergency rooms may be replaced by these advanced models shortly, which can effectively reduce the total time for a surgical procedure to get completed. However, emerging technology still faces a cluster of scientific barriers to overcome before being scaled up from a potential prototype. The adhesion of the bandages, taking into consideration the wet surfaces, is not very profound to be made applicable for clinical trials. Efforts should be made to increase the life span of the fabricated nanodesigned template for developing the bandages. The current costs for the fabrication of these dressings are quite high. Alternative routes should be evaluated to make the product cost-effective when produced in bulk amounts, which in turn can provide us with various potential primary and secondary applications.

Gecko's structure has further inspired the recent developments of the eco-friendly bio-based adhesives for addressing the environmental challenges and health concerns, especially for the wood adhesive industry. Li and his co-workers fabricated a green soybean meal-based adhesive reinforced with modified kenaf fibers (Fig. 2) [23]. The insights derived from the gecko structure along with the mussel chemistry improved the roughness of the surface, thus enhancing the number of reactive sites, and providing a bolstered mechanical interlocking in the soybean meal-based adhesive system. The novel high-performance gecko-inspired product competes to be one of the potential candidates in replacing the harmful formaldehyde-based adhesives for a sustainable environment [23].

To address the drawbacks concerning wet adhesion, the scientific community is currently researching on the adhesion mechanism of tree and torrent frogs. The tree frogs adhere to the surfaces by wet adhesion due to the presence of a particular fluid layer between the toe pad and the adhering substrates [24]. Although there is a minor influence of Van der Waals forces on the wet adherence, the significant participation arises due to the capillarity and viscosity-dependent hydrodynamic forces, which enable them to generate adhesion in wet surfaces [24]. However, the gecko-inspired structures remain at the crest of attention since the Van der Waal's forces can be applied to various pillar-like structures with different materials and dimensions [24, 25]. The simple hexagonal structures present in the toe pads of tree frogs are usually covered with an array of nanopillars, making the adhesion phenomenon much complicated that gecko's feet. Furthermore, wet adhesion inspired from tree frogs is a relatively new area of research, and thus it leaves us with several unanswered questions; for instance, how do the viscosity-dependent hydrodynamic forces behave in the nanometric scale or how does the volume of liquid in the interface affect the friction and the adhesion properties [24–26] (Fig. 3).

Apart from the gecko, science has found interests in the rainforests, the humpback whale, and flagellates to synthesize new properties by enacting nature [27]. Underwater adhesion has been recently gaining the attention owing to the fascinating properties exhibited by the mussel, sandcastle worm, and octopus. While the mussel-inspired adhesive

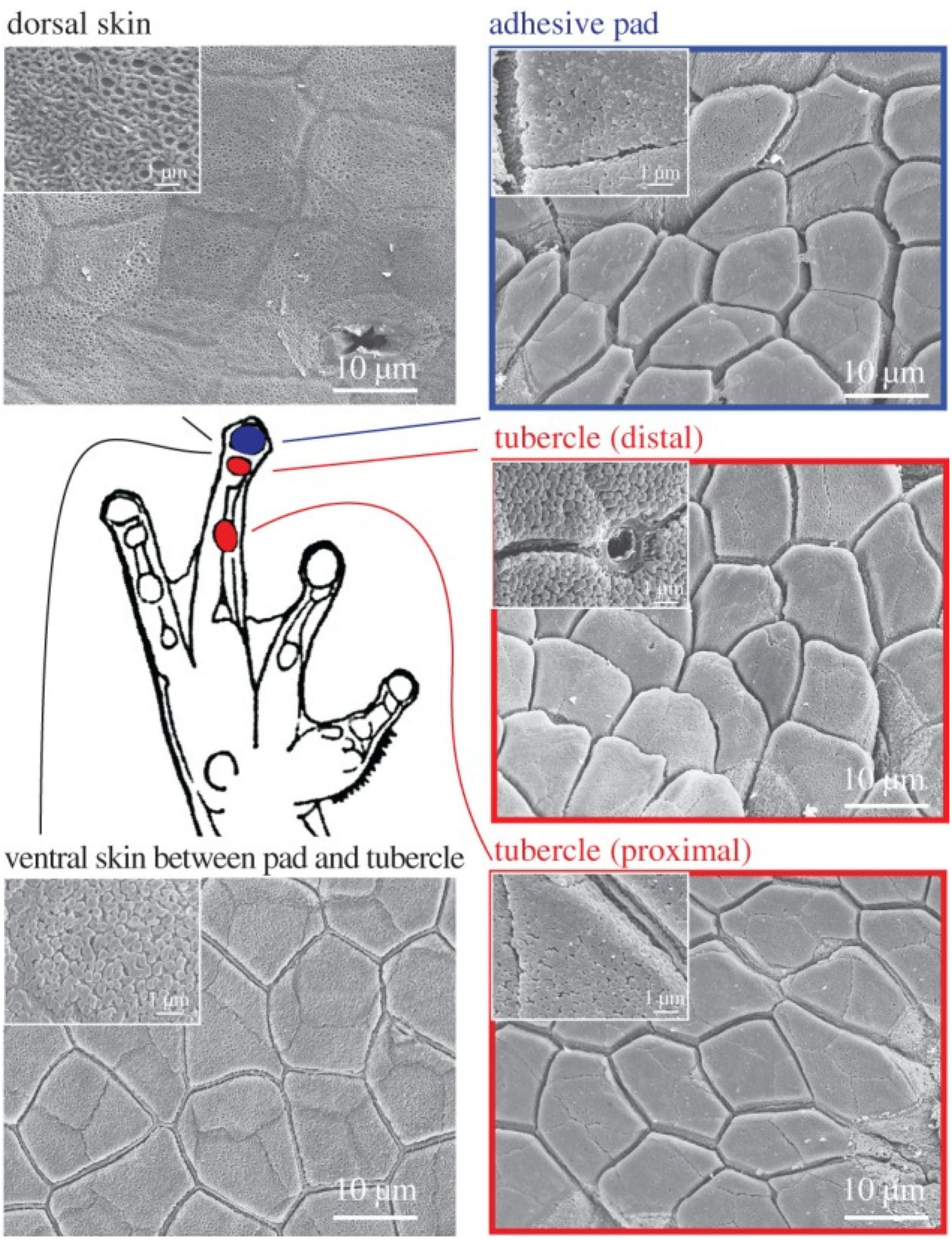


Fig. 3 The illustrations of the pads and subarticular tubercles on a forelimb of *Rhacophorus omeimontis*. While the ventral areas around the pads/tubercles and the dorsal skin exhibited very shallow cells, the ventral surfaces showed nanopillars, reprinted with permission from [25]. Copyright reserved the Royal Society, 2017

substrates mimic the terminal plaque of the mussel byssus, the suction cups (which adhere to wet surfaces) derived from the cephalopods are also gaining the spotlight [27].

We predict that the future realms of scientific trends shall blend the bioinspired elements (for instance, mussel-inspired materials with cephalopod-inspired suction cup microstructure or combining the gecko-inspired surfaces with the water resistivity attributes of tree frog) to develop multi-functional adhesives, resistive toward the water and other chemicals. The human race still waits to experience more such nature-inspired materials that shall evolve the future as DaVinci rightly pointed out that 'in her inventions nothing is lacking, and nothing is superfluous.'

Acknowledgements I want to thank the editors and the reviewers of Bio-design and Manufacturing for going through the work and providing me with feedback and some exciting insights on the topic.

Funding Not applicable.

Compliance with ethical standards

Conflict of interest Sayan Basak declares that he has no conflict of interest.

Human/animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

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