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A glimpse of superb tribological designs in nature

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ABSTRACT

Creatures realize extraordinary motion abilities in diverse environments with certain superb tribological designs, which are classified into four aspects of friction, adhesion, wear, and lubrication, and reviewed in this paper. The anisotropic friction design, such as in the claws of animals and insects, scales of snakes, tongues of felid animals, and fascicle tip of female mosquito, is helpful for achieving swift motion or acquiring food through mechanical interlocking. Gecko and orthopteran insects can attach onto a vertical or inverted wall by using van der Waals force based on adhesion, in contrast to capillary adhesion of tree frog, and underwater suction of octopus. However, super-hydrophobic surfaces such as lotus leaf have very low affinity to other materials to prevent pollutions. Hierarchically composite structures in pangolin, mole cricket, shells, sandfish, wood and bamboo could provide remarkable wear resistance. In an aquatic environment, fish, loach, and eel swim fast with their lubricious mucus, but sharks have special wedge-shaped scales to change the local flow field. Based on these superb tribological designs in nature, various bionic surfaces and materials have been invented to realize or exceed specific functionalities in creatures. Nevertheless, more comprehensive fundamental studies and sophisticated fabrication techniques are still in great demand.

Contents

1. Introduction

Tribology is a discipline on the theories and applications of the interaction between two relatively moved surfaces. According to Darwinism, living species are chosen to survive through natural selection [1], which is actually survival of the fittest. The appearance of organs with extraordinary tribological properties in these animals is also the result of the survival of the fittest in nature millions of years ago, which has a close connection with the living performance of the current corresponding creatures. Thus, creatures have evolved some unique tribological performances to survive in diverse environments. Some typical examples are shown in Fig. 1.

Numerous excellent tribological properties have also been observed in other animals, insects, and plants. For instance, cheetahs are among the fastest animals with hair on their epidermis that reduces air resistance. The divided wing tips of birds also reduce the air drag resistance to attain very high energy efficiency [5]. The bent barbs on the surface of cocklebur adhere to the fur of animals for spreading seeds [6,7]. Insects slip on the wax inside the surface of nepenthes pitcher to serve as food

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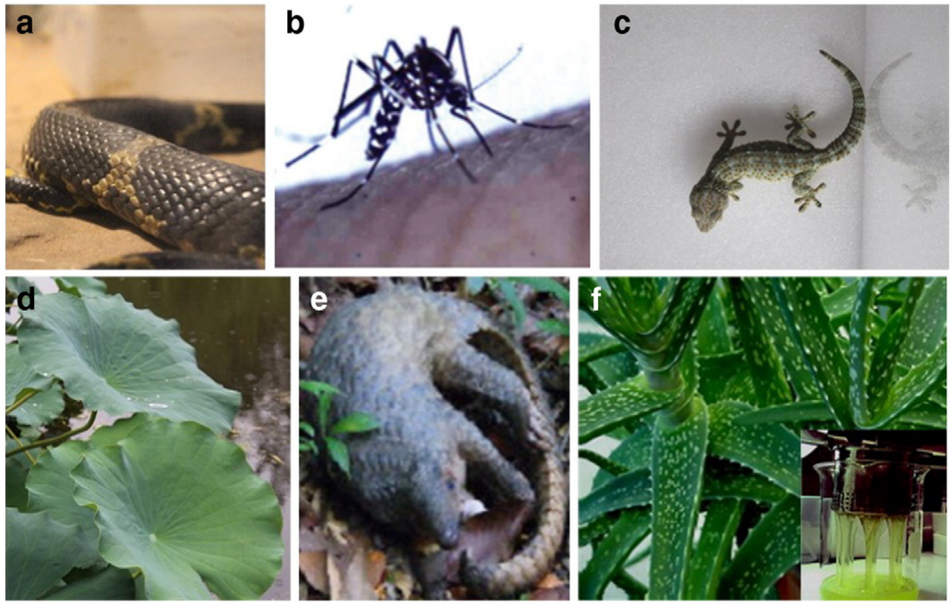

Fig. 1. Typical examples of superb tribological designs in nature. a) Snakes have scales that provide much friction, which facilitates their movement; b) The fascicle tip [2] of a female mosquito inserts into human skin without pain; c) The setae on the pad of gecko strongly adhere to the substrate; d) The lotus leaf is super-hydrophobic, which contributes to its self-cleaning; e) The scales of a pangolin [3] have high wear resistance against the soil particles; f) Aloe vera mucilage [4] is a kind of natural lubricant. (b) — ("Reprinted from J Bionic Eng, Vol. 6, Kong X, Wu C, Measurement and prediction of insertion force for the mosquito fascicle penetrating into human skin, pp. 143–52. Copyright 2009, with permission from Elsevier."). (e) — ("Reprinted from Acta Trop, Vol. 126, Hassan M, Sulaiman MH, Lian CJ, The prevalence and intensity of Amblyomma javanense infestation on Malayan Pangolins (Manis javanica Desmarest) from Peninsular Malaysia, pp. 142–5. Copyright 2013, with permission from Elsevier."). (f) — ("Reprinted from Int J Eng Sci, Vol. 59, Kameneva MV, Microrheological effects of drag-reducing polymers in vitro and in vivo, pp. 168–83. Copyright 2012, with permission from Elsevier.").

of this plant [8]. The gradient composite structures in bamboo are responsible for its high wear resistance [9].

Regardless of the functionalities of creatures, several basic principles of two relatively moved surfaces have been formulated through the fundamental studies of tribology. These principles usually describe the complex phenomena in terms of friction, wear, and lubrication [10–13]. The mechanisms of various tribological behaviors have been extensively examined theoretically [14–17] and experimentally [18–21]. It effectively guides the industrial applications in many aspects although it has not been completely elucidated. Therefore, in this review, the superb tribological designs in nature are presented in four aspects, namely, friction, adhesion, wear, and lubrication. Some coprinciples have been summarized and described in these four aspects to provide an overview of tribological behaviors. Finally, some typical bionic studies are introduced and discussed. This study may serve as a reference for additional fundamental studies on the tribological performances in nature for the development of more efficient and flexible control of tribological technologies being aimed to save energy and resources or protect the environment.

2. Friction in nature

Friction is common in nature. In some cases, the friction coefficient varies in distinct relative sliding directions, which is usually called friction anisotropy. According to the classic friction laws [22], sliding friction

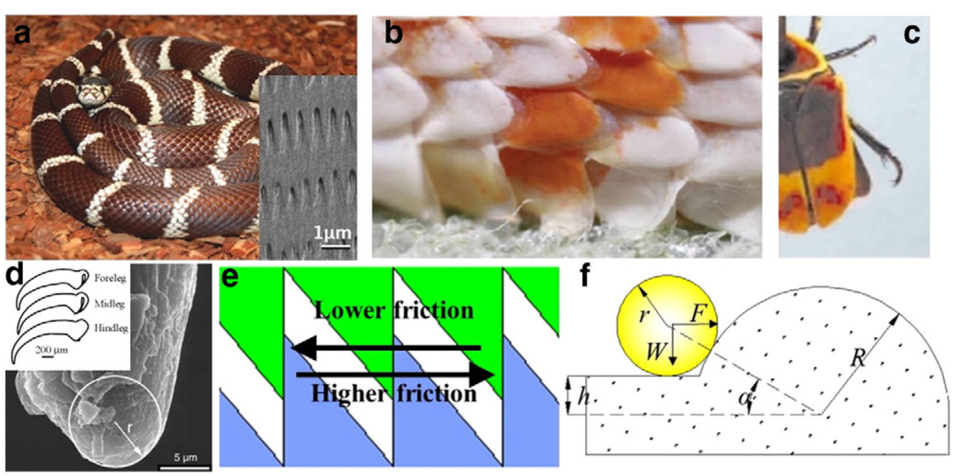

Fig. 2. Friction anisotropy induced by mechanical engagement. a) Terrestrial snake (L. getula californiae) and SEM micrograph of its ventral scales [30]; b) interlocking between snake scales and asperities on substrate [23]; c) Beetle P. marginata (Coleoptera, Scarabaeidae) [31]; d) the tip [10], e) mechanism of mechanical engagement, and f) sphere-to-sphere model for the beetle claw. (a) — ("Reprinted from Tribol Lett, Vol. 54, Baum MJ, Kovalev AE, Michels J, Gorb SN, Anisotropic Friction of the Ventral Scales in the Snake L. g. californiae, pp. 139–50. Copyright 2014, with permission from Springer."). (b) — ("Reprinted from J R Soc Interface, Vol. 9, Marvi H, Hu DL, Sulaiman MH, Lian CJ, Friction enhancement in concertina locomotion of snakes, pp. 3067–80. Copyright 2012, with permission from The Royal Society."). (c) — ("Reprinted from Zoology, Vol. 104, Haas F, Beutel RG, Wing folding and the functional morphology of the wing base in Coleoptera, pp. 123–41. Copyright 2001, with permission from Elsevier."). (d) — ("Reprinted from J Exp Biol, Vol. 205, Dai Z, Gorb SN, Schwarz U, Roughness-dependent friction force of the tarsal claw system in the beetle P. marginata (Coleoptera, Scarabaeidae), pp. 2479–88. Copyright 2002, with permission from The Company of Biologists Limited.").