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Advanced Electro-active Dry Adhesive Actuated by an Artificial Muscle Constructed from an Ionic Polymer Metal Composite Reinforced with Nitrogen-doped Carbon Nanocages

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Abstract

An advanced electro-active dry adhesive, which was composed of a mushroom-shaped fibrillar dry adhesive array actuated by an Ionic Polymer Metal Composite (IPMC) artificial muscle reinforced with nitrogen-doped carbon nanocages (NCNCs), was developed to imitate the actuation of a gecko's toe. The properties of the NCNC-reinforced Nafion membrane, the electromechanical properties of the NCNC-reinforced IPMC, and the related electro-active adhesion ability were investigated. The NCNCs were uniformly dispersed in the 0.1 wt% NCNC/Nafion membrane, and there was a seamless connection with no clear interface between the dry adhesive and the IPMC. Our 0.1 wt% NCNC/Nafion-IPMC actuator shows a displacement and force that are 1.6 – 2 times higher than those of the recast Nafion-IPMC. This is due to the increased water uptake (25.39%) and tensile strength (24.5 MPa) of the specific 3D hollow NCNC-reinforced Nafion membrane, as well as interactions between the NCNCs and the sulfonated groups of the Nafion. The NCNC/Nafion-IPMC was used to effectively actuate the mushroom-shaped dry adhesive. The normal adhesion forces were 7.85 mN, 12.1 mN, and 51.7 mN at sinusoidal voltages of 1.5 V, 2.5 V, and 3.5 V, respectively, at 0.1 Hz. Under the bionic leg trail, the normal and shear forces were approximately 713.5 mN (159 $mN\cdot cm^{-2}$) and 1256.6 mN (279 $mN\cdot cm^{-2}$), respectively, which satisfy the required adhesion. This new electro-active dry adhesive can be applied for active, distributed actuation and flexible grip in robots.

Keywords: electro-active dry adhesive, bionic, ionic polymer metal composite, Nafion membrane, carbon nanocage

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1 Introduction

Geckos can easily move on various substrates, even on walls and ceilings, owing to their remarkable toes, which are covered with hierarchical adhesive structures. The mechanism of the van der Waals force generated by dry adhesion of the millions of setae on the gecko's toes has been a focus of academic research for more than a century[1]. Adhesion tests on single seta have shown that a small normal preloading force, in concert with a rearward displacement, is necessary to engage adhesion[2,3]. It has also been found that geckos extend or crimp their toes by neurarchy to attach or detach from a surface (Figs. 1a–1d)[4]. The combination of the precise control of the toes and the size effect of the setae contributes to the gecko's ability to "run up and down a wall in any way, even with the head downwards"[5]. Therefore, to achieve the biomimetic gecko pad's effective movement and control, it is necessary to develop a controllable active actuation/adhesive mechanism that is adaptable to various circumstances and surfaces. This will be very important for the development of a gecko-inspired robot.

The development of an active actuation/adhesive mechanism has been hindered by several challenges. First, traditional actuation technologies (*e.g.*, miniature motors and gear transmissions) cannot satisfy the high flexibility, high redundancy, and large load-to-weight ratio found in geckos, which causes the performance of

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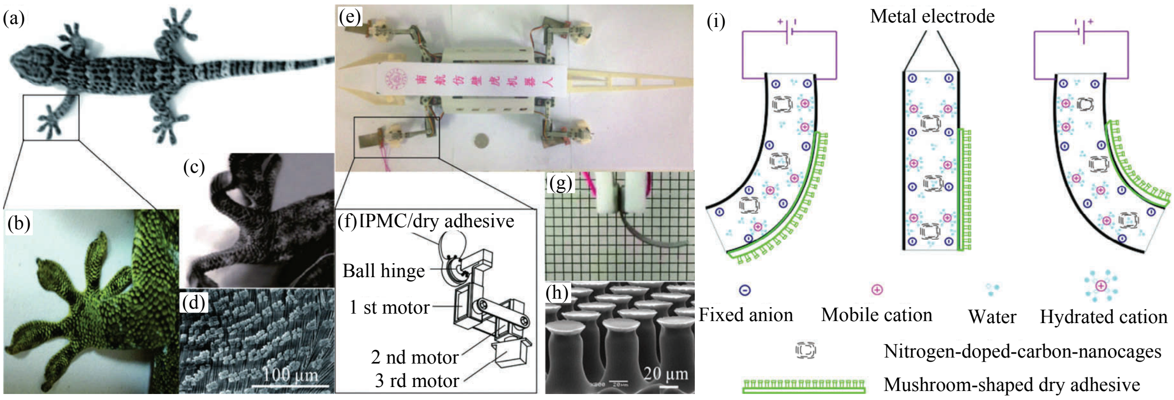

Fig. 1 Schematic illustration showing the bionic electro-active adhesive applied in the gecko-insipred robot. (a) The Gekko gecko; (b) the leg and toes of the gecko; (c) locomotion of toes that geckos extend or crimp (when peeling from a terminal) by neurarchy to attach or detach from a substrate; (d) Scanning Electron Microscopy (SEM) image of hierarchical adhesive structure; (e) the gecko-inspired robot; (f) bionic robot's single leg; (g) deformation of the NCNC reinforced IPMC under the sinusoidal voltage of 3 V at 0.1 Hz; (h) SEM image of mushroom-shaped fibrillar microstructure; (i) the improved electro-active dry adhesion mechanism.

robots to fall behind that of the animals[6,7]. Thus, active and distributed actuation (muscle actuation) of the gecko's toes is a key technology required to achieve three-Dimensional (3D) movement of a gecko robot[8,9]. Second, the strength of the adhesion is determined by the performance of the adhesive arrays. Large contact areas between the adhesive arrays and the substrate are beneficial for the creation of high normal and shear adhesion. Additionally, the self-cleaning properties and reproducibility of the adhesive arrays are challenging. Finally, the main obstacle to the robust climbing of gecko robots is the need for controllable adhesion, in addition to strong adhesion. This is required to achieve the transition between detachment and attachment.

Artificial muscles that exhibit large deformations and low actuating voltages, for example, Ionic Polymer Metal Composites (IPMCs), attract a lot of scientific interest and have commercial applications[10–17]. IPMCs are electro-active polymers that are comprised of a perfluorinated polymer film plated with metal on both sides. Owing to their many advantages, which include large strain, flexibility, light weight, no noise, and low driving voltage, IPMCs have been applied in many research fields, including as micro-actuators, artificial muscles, soft robotics, and sensors[18–23]. The transportation of hydrated cations in the cation-exchangeable membrane causes IPMCs to bend toward the anode under the input electric potential[24]. The controlled oscillation generated by the IPMC is similar to the actuation style of a gecko's toes, and this inspired us to apply an IPMC artificial muscle to imitate the movement of a gecko's toes. In our previous study, we presented active actuation using an IPMC artificial muscle to imitate the movement of a gecko's toes, and investigated the performance of the directional adhesive structures actuated by a multiwalled carbon nanotube (MWCNT)/Nafion-IPMC actuator[5]. In this previous study, the preloadings were 6.76 mN, 10.00 mN, and 24.01 mN and the corresponding normal adhesion forces were 2.65 mN, 3.92 mN, and 10.49 mN under sine input potentials of 1.5 V, 2 V, and 3 V, respectively. For practical application of the controllable electro- active adhesive mechanism in a gecko-inspired robot, the adhesion must be both controllable and sufficient at the same time. This requires excellent performances from both the IPMC artificial muscle and the dry adhesive.

To better imitate the actuation style of the gecko's toe in a gecko-inspired robot (Figs. 1e and 1f), we have developed an improved, controllable electro-active dry adhesive mechanism (Fig. 1i), which is composed of a mushroom-shaped fibrillar dry adhesive (Fig. 1h) and actuated by an IPMC artificial muscle reinforced by nitrogen-doped carbon nanocages (NCNCs) (Fig. 1g). Three-dimensional hollow NCNCs have high specific surface areas, high capacitance, and excellent wettability, which offer effective interfacial stress transfer, local decrease of stress, and increased tensile strength[12]. For graphene and other layered filler-enhanced polymers, water uptake is greatly decreased, and this strongly influences the electro-mechanical properties of the IPMC owing to the driving mechanism of transportation of hydrated cations[12]. In contrast, 3D hollow carbon nanocages (CNCs) provide extra space for ion and water storage[25,26]. In addition, doping sp^2 carbon structures