Micropatterned Adhesives Inspired by Climbing Plants

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***Abstract*— In this work, we propose novel micropatterned devices for reversible attachment inspired by climbing plants. We designed and fabricated bioinspired artificial microhooks (MH) using two-photon lithography. The MH-based adhesives were fully characterized in terms of attachment forces both as individual and arrays. Specifically, the adhesives were tested on several rough surfaces (i.e., fabrics and skin tissues), producing remarkable shear forces up to 13.8 N/cm^2. Also, a miniaturized mobile platform with directional hooks demonstrated climbing ability over slopes up to 45°. This research opens new opportunity for soft-and micro-robotics, biomedical fields and textile industries.**

Keywords*— *plant-inspired devices, reversible attachment, 3D micromanufacturing, climbing robots

I. Introduction

One of the main challenges in robotics regards the development of novel multifunctional materials able to adapt to unpredictable and unstructured environments [1]. Living organisms can give ingenious cues to solve technological challenges [2, 3]. Especially, climbing plants represent a perfect model to mimic due to their unique adaptation capabilities to almost all terrestrial habitats [4, 5]. One of the most wonderful example of adaptation was related to the hook-climber *Galium aparine* L., which used a parasitic ratchet-like attachment mechanism with different microhooks to climb always on the bright side of the hosts [6, 7]. Here, we report a novel micropatterned device for reversible attachment inspired by the climbing mechanism of *G. aparine* [8]. Firstly, we designed and modeled artificial microhooks (MH) based on natural hooks morphometric features. Secondly, we microfabricated MH structures in an array on flexible substrates using two-photon lithography, a high-precision additive manufacturing technique which allows micro/nanoscale resolution, and high reproducibility and scalability for soft robotics applications [9]. Thirdly, we investigated the pulling forces of individual MH, and the normal and shear forces achieved by the MH-based adhesives on different rough surfaces, including textiles and artificial skin tissues. Finally, we developed a proof of concept prototype to demonstrate the feasibility of our adhesives for climbing robots applications.

II. From Natural to Artificial Microhooks

In natural environments, *G. aparine* always attaches itself onto the upper leaf side of a host plant (i.e. *Arum italicum*, **Fig. 1a**) using microhooks for mechanical interlocking. Thanks to the different features of its microhooks [6], *G. aparine* uses a self-tightening attachment mechanism, where one surface ratcheted, while the other surface slipped (**Fig. 1b**). SEM imaging characterizations of natural abaxial and adaxial leaf hooks were performed on freshly chemically fixed biological samples (**Fig.1d, g**, respectively), showing that their morphology differs both in shape and size. We extracted the main geometrical parameters (i.e. diameters,

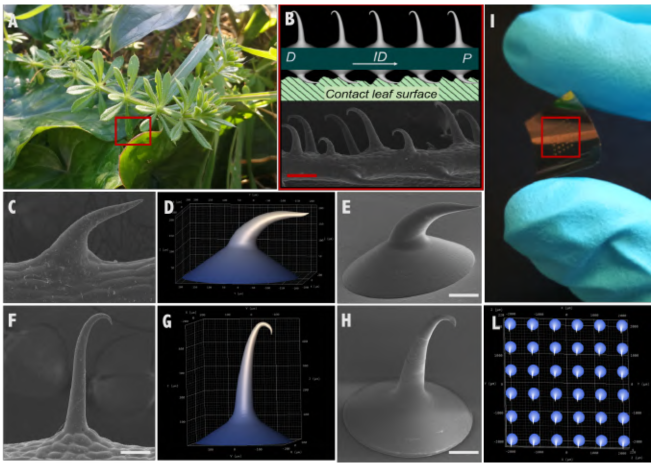

Fig. 1. Bioinspired design and fabrication of *G. aparine* hooks. a, b) G. aparine in natural habitat climbing over the host plant (*Arum italicum*). c-h) From natural to artificial abaxial (c-e) and adaxial (f-h) MH. I, l) MH-based micropatterned adhesives. Part of the figure is adapted from [8].

lengths) from the SEM micrographs of natural samples to design the artificial microhooks in SolidWorks® (**Fig. 1e, h**). We microfabricated a three-dimensional patterns of 6x6 MH structures on flexible Mylar sheet using Nanoscribe Photonic Professional (GT) system (Nanoscribe GmbH) (**Fig. 1i, l**). The structures were printed using IP-S negative-tone photoresist in DiLL configuration using 25X objective, at a scan speed of 20 mm/s and a laser power at 28% (14 mW). Overall, the MH structures were outstandingly microfabricated, showing high resolution and reproducibility even at tip level (**Fig. 1e, h**, for abaxial and adaxial MH, respectively).

III. Main Attachment Tests Results

The attachment behavior of MH-based adhesives was investigated both in individual hooks (**Fig. 2**) and array (**Fig. 3**) configuration. We built a dedicated setup with a multi-axis measurement platform, and we carried out different types of tests, such as contact separation force, detachment force, and

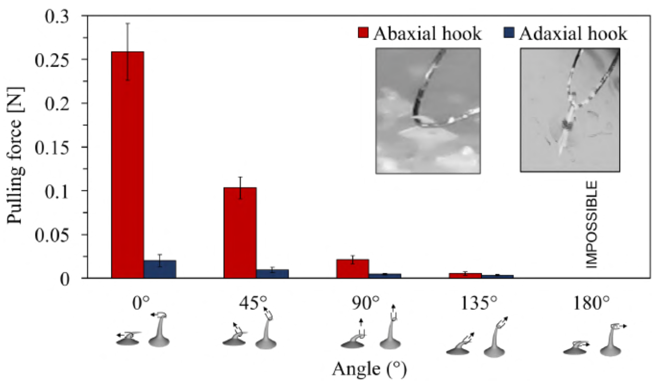

Fig. 2. Contact separation forces of individual abaxial (red column) and adaxial (blue column) MH to load of different orientations. Microscope view of hooks is in the inset. Reprinted from [8].

shear force tests. Contact separation force tests were performed by pulling off a micrometer wire thread loop from the individual hooks. The experiments were recorded by connecting a portable digital microscope to a computer. In general, the increasing of the pulling angle from 0° to 180° is correlated to a decrease in the pulling force. The maximum pulling force of about 0.26 N was obtained with abaxial hooks pulled off against hook orientation (0°) (**Fig. 2**). Then, we investigated the maximum detachment forces and shear forces of abaxial MH-based adhesives on fabrics and skin tissues at different preload (from 0.02 to 1N) (Fig. 3a-e). In general, the forces increased with the increase of the preload, up to a max pull-off force of 0.4 N/cm^2 and a max shear locking force of 13.8 N/cm^2. Especially in shear direction, the adhesives with abaxial hooks were able to strongly interlock or penetrate the tested substrates, without releasing them, achieving remarkable shear locking forces respect to the state of the art [10, 11].

IV. Towards a New Generation of Climbing Robots

A wide range of robots with spine-like hooks have been developed for climbing over rough surfaces, such as rocks and walls [12, 13].

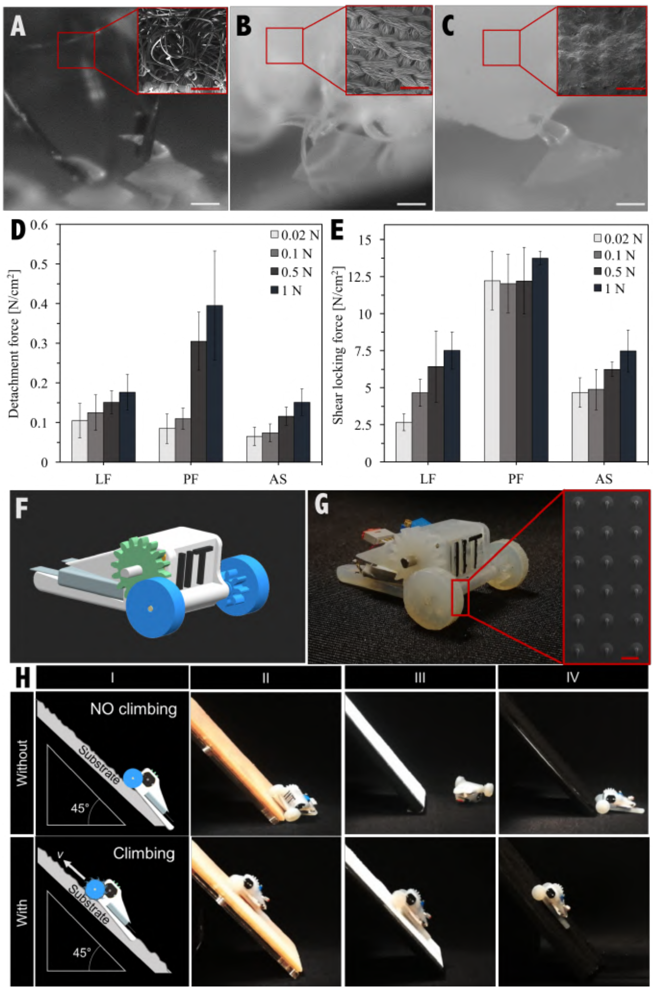

Fig. 3. Main attachment results and demonstration. a-c) Microscope pictures of abaxial hooks interlocking fabrics, such as (a) Velcro or (b) polyester, and (c) skin tissues. D, e) Pull-off and shear locking forces of abaxial MH-based adhesives at different preload over the different substrates (Looped fabric, LF; Polyester fabric, PF; Artificial skin, AS). F, g) Design and fabrication of a miniaturized car equipped with directional MH. H) Demonstration of climbing capabilities of the minicar with and without MH. Adapted from [8].

Differently from the current state of the art, our MH can directionally strongly attach over textiles or skin tissues, opening new applications for climbing robots in medical or textile fields. To demonstrate the feasibility of our prototypes for climbing robots applications, we built and tested a 25g miniaturized car embedded a flexible adhesive tape with directional MH to 45°-inclined rough slopes (**Fig. 3f-h**). The performance of the mobile mini-car was tested with and without hooks. Without the hooks the minicar was not able to climb over the slopes; instead, the mini-car with hooks can easily climb over the slopes, opening new hopes for climbing robots at a small scale.

V. Conclusion and Future Perspectives

Overall, our climbing plant-inspired MH-based adhesives demonstrated great results in terms of microfabrication and attachment performances. Also, we demonstrated the potential of our prototypes for climbing robot applications. We believe that this work will open the way for the next generation of mechanical interlockers: for instance, novel med-patches for skin tissues interlocking, “Velcro-like” micro-snap fastener for textiles and smart adhesives for robotics might be developed.

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