How does dry adhesion work?

Geckos are the world's supreme climbers. Over 2,000 years ago, Aristotle commented on the surprising ability of geckos to "run up and down a tree in any way, even with the head downwards". But how are these animals able to cling to and walk on almost all surfaces, no matter how vertical or inverted, rough or smooth? In a recent study at the University of Waterloo, Department of Chemical Engineering, and Institute for Polymer Research (IPR), PhD students Hadi Izadi and Kate Stewart, working with Professor Alex Penlidis, have discovered that the toe pads of geckos become charged upon contact with the surface (substrate) they are walking on or clinging to, which leads to the development of large electrostatic forces between the toe pads and the substrate with which they are in contact. When geckos detach from the substrate, however, the acquired charge is discharged into the substrate, preventing the animal from becoming overcharged during locomotion. These recent research findings and refinements on our understanding of dry adhesion, and more specifically on the dominance of electrostatic interactions in gecko adhesion, represent a major digression from accepted theories in over a thousand papers, reviews, and book chapters, that have been previously published on both dry adhesion of geckos and also synthetic gecko-inspired dry adhesives, all focused on the dominance of van der Waals interactions, and to a lesser extent capillary forces, in order to explain adhesion.

This improved (fundamental) understanding about the role of electrostatic interactions in gecko adhesion is not only very important for appreciating the principles of the supreme adhesion of geckos, but is also very crucial in the (applied and practical) design and fabrication of synthetic fibrillar dry adhesives. For instance, the surprising ability of Peter Parker – of the Spider-Man movie fame – to climb smooth walls and windows, or the death-defying climb of Ethan Hunt – in Mission: Impossible – over the world's tallest skyscraper with the help of special adhesive gloves, as shown in Figure 1, raise the same question for all of us: How are they able to climb such surfaces? Just fiction and film imagination?

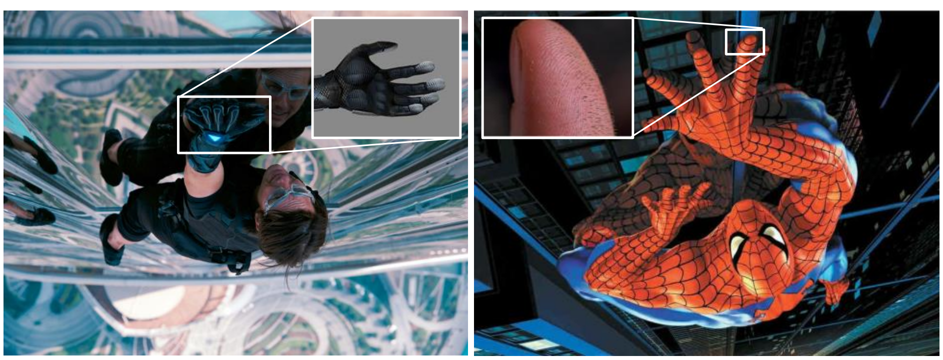

Figure 1. On the left, Ethan Hunt (a super-spy in Mission: Impossible) is performing a death-defying climb up the world's highest skyscraper, Burj Khalifa, with the help of his high-tech gloves [the large and small images are from abcnews.go.com and comicbookmovie.com, respectively]. On the right, Spider-Man is climbing up a skyscraper only using the tip of his fingers which are covered with very fine micro-hairs [the large and small images are from layoutsparks.com and scifi.stackexchange.com, respectively].

In principle, what makes the fingertips of Spider-Man or the gloves of Ethan Hunt sticky is the same mechanism that lots of insects and animals, such as spiders and geckos, employ for their locomotion. Scientists call it dry adhesion. Dry adhesion, of both natural and synthetic dry adhesives, relies on the fine microscopic fibrils that cover the surface of the adhesive. Without having any glue-like material, the fibrils on the dry adhesive bring the adhesive into intimate contact with the contacted substrate, allowing the development of a large number of contact points. Although the adhesion between each fibril and the substrate is naturally weak, since the fibrils are extremely small, formation of a large number of contacts with the substrate leads to generation of strong adhesion (forces) between the dry adhesive and the substrate. The microscopic hairs on Peter Parker's fingertips are what give him the ability to climb. Similarly, Ethan Hunt's gloves have a textured pattern on the fingertips that resemble the toe pads of geckos.

Although we are certain of the necessity and role of these tiny fibrils on adhesion of dry adhesives, there is a question scientists were not yet sure of its answer: How does each fibril of a dry adhesive adhere to the contacted substrate? To answer this seemingly simple, but fundamentally complicated question, intense research over several centuries has attempted to unveil the secrets behind the dry adhesion systems that animals and insects, like geckos and spiders, employ for their locomotion. This also led to the creation of synthetic bio-inspired fibrillar dry adhesives almost a decade ago. Dry adhesion of geckos has captured most of the attention, certainly making it the most well-studied natural dry adhesion system. This is simply because geckos possess the finest and densest fibrils on their toe pads and for that reason, have the most advanced dry adhesion system for locomotion than any other animal or insect (see Figure 2).

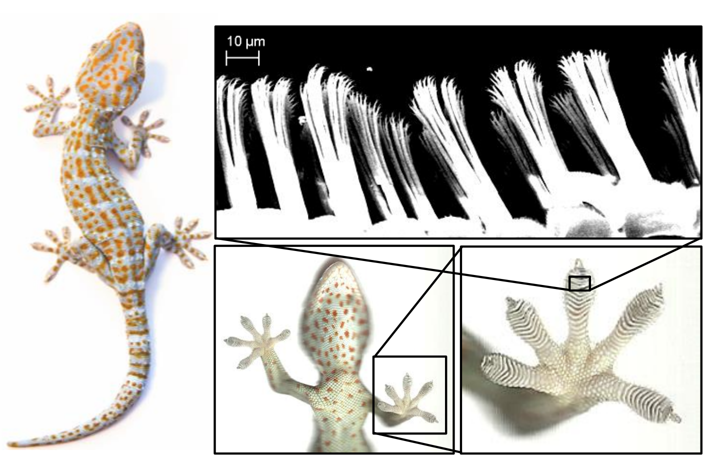

Figure 2. On the left, a Tokay gecko, also known as *Gekko gecko*, is clinging to a surface. A toe pad of a gecko is covered with 10–20 mesoscale setal arrays (referred to as lamellae (bottom right)). Each lamella consists of around 1000 micro-scale fibrils (each ~50–100 μm tall and ~5 μm wide), which branch repeatedly towards the distal end (top right). At the tip, each seta consists of smaller fibrils terminated with triangular spatula-shaped nano-pads (each ~150–300 nm wide and 5–10 nm thick). When gecko toe pads come into contact with a substrate, the nano-spatulas at the tip of the setae spread over the substrate and develop intimate contact with it, thus making the toe pads stick strongly to the substrate.

About the means by which each fibril on the gecko toe pads adheres to the contacted substrate, after over two centuries of research and ruling out different proposed mechanisms (including glue, micro-interlocking, friction, suction, etc.), it was suggested, in the late 1990s and early 2000s, that intermolecular interactions (known as van der Waals interactions) were the main source of gecko adhesion. This was simply because van der Waals interactions are always present between any two materials that come into close proximity to one another. In later years, while studying the effect of humidity, it was found that capillary forces also contribute to gecko adhesion, although to a lesser extent than van der Waals forces. In recent pioneering research, however, Izadi, Stewart and Penlidis have shown that this common perception about the dominance of van der Waals and capillary forces in gecko adhesion is incorrect! Based on experimental evidence, painstakingly collected over several years, the Chemical Engineering researchers have clarified for the first time that it is the electrostatic interactions – arising from surface charging – which dictate the strength of gecko adhesion, and not the van der Waals or capillary forces.

More specifically, when any two materials, similar or dissimilar, touch each other, electric charges are transferred from one to the other, leading to the formation of a net negative charge on one substrate and a net positive charge on the other. Development of an electrical double layer at the contact interface via this contact electrification phenomenon (also known as surface charging), gives rise to the formation of electrostatic interactions between the objects charged upon contact. Since the unique fibrillar feature of the toe pads of geckos allows them to develop an intimate contact with the substrate the animal is walking on or clinging to, the researchers hypothesized that the toe fibrils should exchange significant numbers of electric charges with the contacted substrate via the contact electrification phenomenon.

For the first time, Izadi, Stewart and Penlidis have measured the amount of electric charges and, therefore, the magnitude of electrostatic forces that gecko toe pads develop upon contact with different substrates. Two particular substrates, Teflon AF and polydimethylsiloxane (PDMS), were chosen for the experiments because over one such substrate (Teflon AF), geckos adhere strongly, while over the other (PDMS), they do not! Due to this difference in adhesion and considering the fact that both employed substrates had the ability to generate – more or less – the same amount of van der Waals and capillary forces in contact with gecko toe pads, the research team demonstrated that van der Waals and capillary interactions could not be the primary source of gecko adhesion. Measurements of electrostatic forces that gecko toe pads developed upon contact with these substrates were in agreement with the experimental data and clearly demonstrated that the primary source of gecko adhesion is certainly electrostatic interactions. This University of Waterloo study shows that an effective dry adhesive (like gecko toe pads), not only needs small fibrils to develop an intimate contact, as Spider-Man fingertips do, but also needs to become effectively charged upon contact, as Ethan Hunt's gloves did! According to multiple reviewers of the ground-breaking publication, the results of this study, published in the *Journal of the Royal Society Interface* (Izadi, H.; Stewart, K.M.E.; Penlidis, A.; "Role of Contact Electrification and Electrostatic Interactions in Gecko Adhesion", Journal of the Royal Society Interface, 2014, 11, 20140371), are a "major contribution to the field of dry adhesion" and have "the potential to significantly change the way we think about gecko adhesion and [also] the design of man-made fibrillar adhesives".