Effect of surface roughness on adhesion of multi-hair structure

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Abstract
Creatures such as geckos have a multi-hair structure on their foot surfaces to adhere to roof surfaces without any slimy secretion. The effect of the surface roughness on the adhesion force is analysed theoretically based on contact mechanics considering observations. The foot hair has some compliance and is derived to be suitable to grip rough surfaces quantitatively. The surface roughness decreases the adhesion force, however the compliance recovers it. The effect of the roughness and the compliance on the adhesion force is analysed theoretically and discussed quantitatively. We have clarified a mechanism of the geckos to release surfaces to take a quick step with such adhesive feet. The analysis gives a lot of significant knowledge to design or mimic the function of the creatures such as geckos.

Keywords: adhesion, detachment, surface roughness, JKR contact, gecko, grip and release, attach and detach, manipulation, roof-hanging, wall-climbing.

1 Introduction
The climbing ability of geckos attracts the interest of scientists [1,2]. The geckos have about a hundred billion setae per square meters on their foot finger surfaces. Plenty of nano-scaled spatulas at the top of the setae generates adhesion force, so that they can grip the roof surfaces to hang their weight. The compliant seta-spatula structure is believed to be for the purpose of gripping rough surfaces. However, the effect of the roughness and the compliance on the adhesion force has not been expressed clearly.

Micro-fabricated adhesives mimicking the gecko foot hair are reported [3, 4]. They are just like tape, so sometimes they are called “gecko tape”. We cannot simulate the gecko’s quick step using these adhesives. There must exist some
mechanism which decreases the adhesion force. Although a possible release mechanism is proposed considering the single hair structure [4], the mechanism assumes the constant normal adhesion force and cannot express the change of normal adhesion force.

In the present study, a model of the multi-hair structure is proposed which expresses the effect of the roughness and the compliance on the normal adhesion force theoretically, and a release mechanism for the gecko’s quick step is proposed clearly.

2 A model of multi-hair structures

Figure 1 shows schematic illustrations of the gecko’s seta and its model. Each spatula at the top of the seta can be modelled as a sphere-spring unit. Force curves for the sphere-spring unit are obtained theoretically by authors [5, 6] assuming a JKR contact [7]. The force curves are shown in Figure 2, where the force and the displacement are normalized by following parameters

$$f_T = \pi \Delta \gamma R$$  \hspace{1cm} (1)

$$h_T = \left\{ \pi^2 (1 - v^2)^2 \Delta \gamma^2 R \right\}^{1/3} \left\{ \frac{2^5 E^2}{\pi} \right\}^{1/3}$$  \hspace{1cm} (2)

The adhesion force is the maximum force required to detach the contact, therefore, it is expressed as

$$f_{\text{adhesion}} = \frac{3}{2} \pi \Delta \gamma R .$$  \hspace{1cm} (3)

Figure 1: Schematic illustration of the hair structure on the gecko foot finger surface.
Figure 2: Force curve of a single sphere-spring unit and the compliance dependence of it.

The main functions of the gecko feet are the result of multi hair structure. Consider the sphere-spring units arranged as Figure 3. The gripping surface is exactly flat. Since one of the units is placed for each \((4R)^2\) area, the total adhesion stress can be expressed as

\[
\sigma_{\text{adhesion}} = \frac{3}{2} \pi \Delta \gamma R \left/ \left(2R\right)^2 \right. = \frac{3}{8} \pi \Delta \gamma \frac{1}{R},
\]

where \(\Delta \gamma\) is the work of adhesion and it can be obtained from the surface energy \([8]\) and the interfacial energy

\[
\Delta \gamma = \gamma_{s1} + \gamma_{s2} - \gamma_i.
\]

As the result of theoretical consideration \([8]\) and many experimental measurements obtained under well defined conditions \([9]\), we know that the \(\Delta \gamma\) takes the value;

\[
\Delta \gamma \approx 0.01 \sim 1 \text{ J/m}^2
\]
for most of materials. Eq.(4) is plotted in figure 4. Since the stress is proportional to $1/R$, the adhesion stress increases with the decreasing radius.

Note that the adhesion stress is larger than the vacuum suction stress, when the radius is in nano-order. This is the reason that the nano-hair structure has been chosen by the creatures such as geckos etc...

(a) Top view

(b) Side view

Figure 3: Schematic illustration of the multi hair structure for exactly flat surface.

![Diagram](image)

Figure 4: Adhesion stress for multi hair structure.
3 Effect of surface roughness and compliance on adhesion

Actual surface has always some surface roughness. Figure 5 shows a schematic illustration of the contact of the multi-hair structure onto the rough surface which has the surface profile shown in the figure 5 (b). The roughness can be expressed by the height distribution function shown in the figure 5 (c).

![Figure 5: Schematic illustration of the contact on rough surface, the surface roughness, and the height distribution function.](image)

See figure 6, and consider the case that the multi-hair structure approaches to a rough surface, which has some height distribution function A or B. If there exist a width of the height distribution function, the adhesion force is less than the case of the contact onto exactly flat surface. The distribution decreases the adhesion force, because all units cannot contact onto the surface simultaneously. The decrease for the distribution B is larger than that for the distribution A, because the width of the distribution B is larger than that of the distribution A.

On the other hand, when the compliance of the multi-hair structure is high enough as plotted with broken line in the figure 6(b), the adhesion force does not decrease so much even if the surface roughness has a wide height distribution function. It is because the compliance absorbs the height distribution.

The total force between the multi-hair structure and the rough surface can be calculated by the convolution of the height distribution function and the force curve for the single sphere-spring unit, if the wave length of the roughness is enough smaller than the width of the contacting sphere-spring unit. The adhesion force can be calculated as a maximum force required for detachment. The adhesion force is a function of the surface roughness and the compliance.

Figure 7 shows the relation between the maximum adhesion force and the width of the height distribution function shown in the figure. Although real surface roughness does not always have such distribution, such simple function is used for the understanding.
Figure 6: Schematic illustration of the effect of the compliance and the surface roughness on the adhesion force.
Figure 7 shows the effect of the surface roughness on the adhesion force. With increasing roughness the adhesion force decreases. The figure 7 also shows the compliance dependence on the effect. The compliance recovers the decreased adhesion force. The figure suggests that an appropriate compliance exists even for rough surfaces, if one wants to generate large adhesion force. Note that the height distribution function in the figure 7 is just an example for understanding, under the assumption that the wavelength of the roughness is enough smaller than the width of the contacting sphere-spring unit and all of the units are independent of the other units.

When the sphere-spring unit interacts with the other units, the present model would approach to a continuum or a film between adhering objects. Adhesives are usually made of soft polymers. The compliance of them seems to increase the adhesion force to rough surfaces in the similar manner, although correlation length of the roughness should be taken into account as well as the height distribution function [10,11] for such extrapolation. Although our model is for just one of the extreme cases, the present theory clearly expresses the effect of the roughness and the compliance on the adhesion force under the assumption of the model.

Figure 7: Adhesion force as the function of the surface roughness assuming the rectangular height distribution function.
4 Release mechanism for quick step

Figure 8 shows a schematic illustration of the release mechanism for a quick step. The spatulas at the top of the seta adheres to the surface. When the normal load $F_n$ is applied to the seta, a moment is generated at the top of the seta, and consequently a stress distribution appears at the contact area. If the maximum stress is larger than a critical stress, detachment occurs.

Consider the case that a tangential force $F_t$ is applied simultaneously when the $F_n$ is applied. Because of the $F_t$, the moment at the contact area decreases, i.e.,

$$M_n > M_{n+t}$$  \hspace{1cm} (7)

and then,

$$\max(\sigma_n) > \max(\sigma_{n+t})$$  \hspace{1cm} (8)

Consequently the maximum adhesion stress can be controlled by the tangential force. When the gecko wants to hang his weight from the roof, he probably gives a positive $F_t$. Then, the moment at the seta top decreases and he can generate large adhesion force. When he wants to release his finger from the roof surface, he probably give a negative $F_t$. Then, the moment is enhanced and he can easily release from the surface. This is the mechanism of the geckos’ quick step with their very adhesive foot. Although the gecko’s unique distally directed peeling motion during the detachment has been suggested to be a cleaning mechanism [12], however, it must be the mechanism to control the normal adhesion stress by giving the tangential force. The present mechanism is quite different from the mechanism proposed in ref.[4]. The single unit in ref.[4] never changes the normal adhesion force.

![Figure 8: Schematic illustration of the release mechanism. By giving tangential force geckos can control the normal adhesion stress. The gecko’s unique distally directed peeling motion during the detachment would seems to be for the purpose of decreasing normal adhesion stress.](image)

The geckos have the first finger and the fifth finger which take opposite directions. The geckos tend to arrange their fingers to cover all direction when...
they hang themselves on the roof surface. This is one of the evidence of this mechanism. Also the curved shape of the seta is consistent. The curve enhances the effect of the tangential force to control the normal adhesion force. These structure and behaviour would have been the fittest to survive.

5 Conclusion

The effect of the surface roughness and the compliance on the adhesion force is discussed quantitatively based on contact mechanics. And a mechanism is proposed with which the geckos grip and release the surface to take the quick step.

These results suggest that the function of the gecko foot can be mimicked even without nano-hair structures. For example, the spatula part can be replaced by adhesive films on flat contact area. In this case, the seta structure is still essential, because the compliance of the seta can absorb the surface roughness and normal adhesion force can be controlled by giving tangential forces. The size of the seta structure is not fixed to be micro-sized. The size can be designed considering the roughness, the compliance, and the controllability of the adhesion force. Such system can be applied to not only the robots’ foot but also tools for lifting, sticking, etc...

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References


