Influence of tilt on hairy adhesive pad detachment

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Abstract

Many creatures ranging from geckos to beetles can easily climb on surfaces with the help of hairy adhesive pads on their legs. The hairy pad's design allows the animal to rapidly switch between strong adhesion during attachment and weak adhesion during detachment. Several studies explain this mechanism based on the asymmetric geometry of the hairs, which imparts direction dependent adhesion properties. Here, we propose a mechanism for controlling adhesion of a hairy pad based on the "spring contact model". We show that the adhesion force can be decreased just by slightly tilting the pad during pull-off. Larger number of hairs can decrease adhesion by a larger factor for similar tilt. Further, deformation of the pad's soft backing layer can trigger its spontaneous detachment at low tilt angles. Our model provides a new approach to switch the adhesion state in bio-inspired synthetic adhesives without the need of asymmetric structures.

1 Introduction

Over the past few decades, there has been numerous studies to understand how animals such as geckos and insects are able to walk on surfaces defying gravity. A microscopic observation reveals that, in many cases, animals have a dense array of hairy structures at the end of their legs[1,2]. These hairy adhesive pads help the animal to stay attached to any surface, supporting its weight, and detach easily at will. Previous attempts to theoretically explain adhesion in hairy pads[3,4] has followed two fundamental approaches: either by energy balance, or by force balance.

In the energy balance approach, adhesion is characterized by "work of adhesion" (W_{adh}) which is the energy required to separate two surfaces from contact. During detachment, elastic energy stored in the hair is dissipated, which increases $W_{adh}$and thus adhesion is enhanced[5,6]. Detachment of the pad can be explained based on Kendall's peeling theory[7], which predicts low forces at high peeling angles.

In the force balance approach, adhesion is characterized by pull-off force (F_p) or stress (σ_p), which is the maximum force necessary to separate two surfaces from contact. Based on a "cohesive zone model", Hui et. al.[8] has identified two regimes of hair detachment: 1) flaw sensitive regime, where contact failure occurs due to crack propagation leading to low σ_p, 2) flaw insensitive regime, where contact interface fails simultaneously, leading to high σ_p. Tian et. al.[9] has shown that the spatula shaped hair tips in a gecko's toe allows it change adhesion by three orders of magnitude by laterally sliding and controlling the pulling angle. Federle[10] has further argued that curved shape of hairs helps the pad to stay attached when pulled proximally, and easily detached by elastic recoil when pushed distally.

The theories presented so far suggests that low detachment force of a hairy pad can be attained by 1) increasing the stress concentration by peeling the pad at high angles, or 2) laterally shearing the pad before pull-off, which requires the hairs have an asymmetric geometry. Fabricating synthetic mimics with asymmetric micro hair structures however are generally difficult. It is thus desired to have alternate strategies to achieve reversible adhesion suited for practical applications.

In this work, we present a new method of detachment by changing the tilt of the pad relative to the surface. Tilling the pad will result in an elastic penalty due to the deformation of hairs, which can potentially reduce the net pull-off force. To investigate this, we model the hairy pad by "spring contact model"[11]. This model is based on the force-balance approach, which assumes the hairy pad to behave like an array of springs. We hope our work to provide new strategies to control adhesion force of an artificial micro-pillar adhesive, with applications in bio inspired robotic systems.

2 Model

The hairy pad is assumed to be a system of $\mathrm{N_t}$ springs as hairs with spring constant, $\mathrm{k_h}$, and natural length, $\mathrm{l_{h,0}}$, making contact with a flat smooth surface (Figure 1). The hairs are attached to a backing layer, assumed to be another spring with spring constant, $\mathrm{k_b}$, and natural length, $\mathrm{l_{b,0}}$. The hairs are spaced apart with width w. The pad is oriented at a tilt angle, θ, with the surface. Each hair can attain a maximum length, $\mathrm{l_{h,p}}$, before pull-off, such that its pull-off force, $f_p = k_h\,(l_{h,p} - l_{h,0})$. The pad is pulled vertically upward will maintaining the given tilt angle. Excess torque in the system is assumed to be balanced externally and is not considered for our analysis. $\mathrm{F_{adh}}$ is the maximum force required to detach all hairs from the surface.

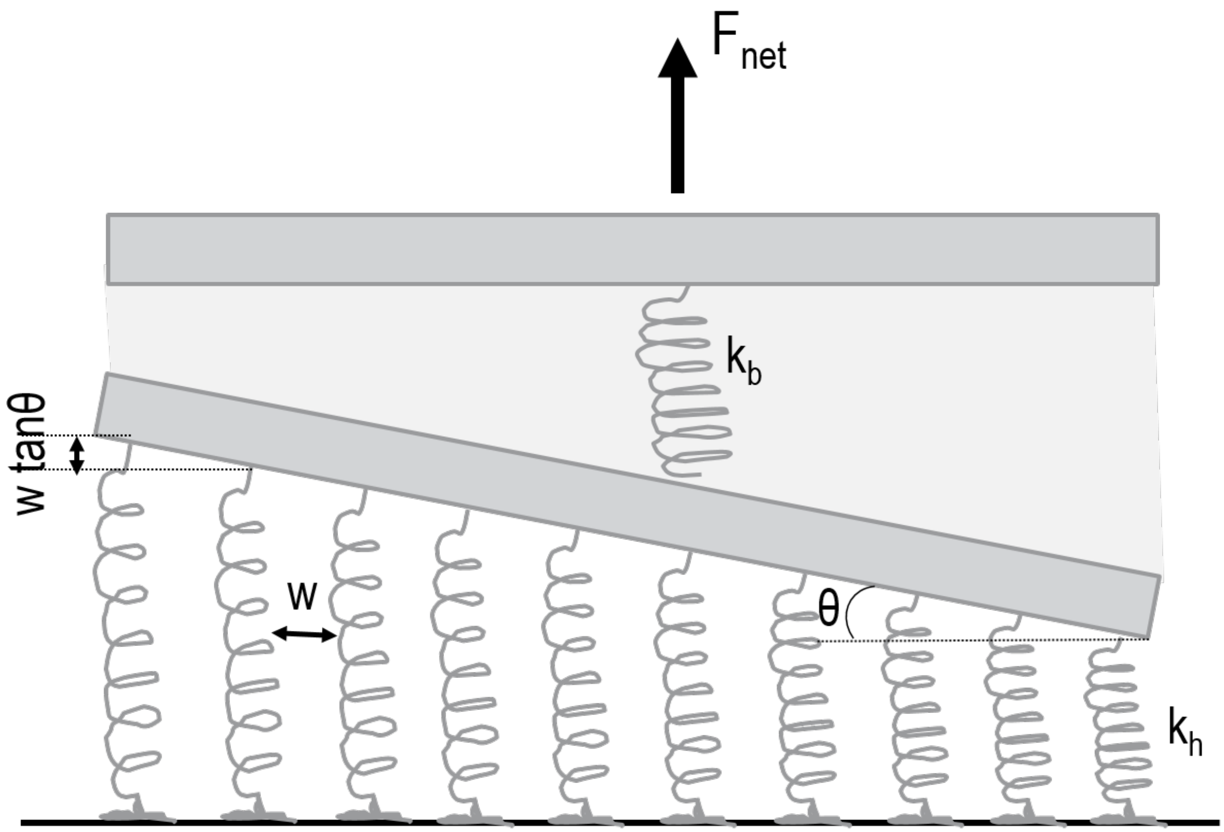

Figure 1: Schematic

We consider three modes of detachment:

Simultaneous detachment: All hairs detach simultaneously when $\theta = 0°$. Here the hairy pad shows the maximum possible adhesion, given by

$$F_{adh} = F_{max} = N_t f_p \tag{1}$$

Sequential detachment: When $\theta > 0°$, the hairs will detach sequentially from left to right (Figure 1). Let us consider the situation when the left most spring is stretched to its maximum length, $l_{h,p}$, just before pull-off. The net force on the pad when n hairs are in contact with the surface is:

$$F_{net}\left(n\right) = \sum_{i=1}^{n} k_h\left(l_{h,i} - l_{h,0}\right)$$

This can be simplified into:

$$F_{net}\left(n,\theta\right) = nf_p - \frac{n\left(n-1\right)}{2}k_h w \sin\theta \qquad\qquad n \leq N_t \tag{2}$$

Equation 2 describes the net force required to detach the left most hair. The maximum adhesion force for given N_t hairs can then be calculated as:

$$F_{adh}\left(\theta\right) = \begin{cases} \frac{f_p}{2}\left[\frac{f_p}{k_h w \sin\theta} + 1\right] + \frac{k_h w \sin\theta}{8} & N_t \geq N_{max} \\ N_t f_p - \frac{N_t\left(N_t-1\right)}{2}k_h w \sin\theta & N_t < N_{max} \end{cases} \tag{3}$$

$$N_{max} = \frac{f_p}{k_h w \sin\theta} + \frac{1}{2} \tag{4}$$

Here, N_{max} is the number of hairs required to get maximum adhesion at a fixed tilt angle.

Detachment propagation: Let us consider a special case of sequential detachment where the backing layer deforms. When a hair detaches from the surface, the backing layer undergoes an elastic recoil due to an unbalanced force. Suppose the backing layer spring relaxes upward by a length Δl (Figure 1). For n hairs in contact, the force balance before and after a hair detaches is given respectively by:

$$\sum_{i=1}^{n} k_h\left(l_{h,i} - l_{h,0}\right) = k_b\left(l_b - l_{b,0}\right)$$

$$\sum_{i=1}^{n-1} k_h \left(l_{h,i} + \Delta l - l_{h,0}\right) = k_b \left(l_b - \Delta l - l_{b,0}\right)$$

Solving the above two equations for Δl, we get:

$$\Delta l = \frac{f_p}{k_h (n-1) + k_b} \tag{5}$$

The length difference between the detached hair and its adjacent hair just before it breaks contact is $w \sin\theta$. If $\Delta l > w \sin\theta$, the adjacent hair will be stretched more than $l_{h,p}$and thus also detach. Equation 5 shows that Δl increases for lesser number of hairs in contact. This implies that hair detachment will propagate and the pad completely breaks contact with the surface. The critical number of hairs, N_c, necessary for detachment propagation at a given tilt angle is thus given by:

$$N_c = \frac{f_p}{k_h w \sin\theta} - \frac{k_b}{k_h} + 1 \tag{6}$$

Alternatively, for a given pad with N_t hairs, the critical tilt angle below which detachment propagates is:

$$\theta_c = \arcsin\left[\frac{f_p}{k_h w}\left(\frac{1}{\frac{k_b}{k_h} + N - 1}\right)\right] \tag{7}$$

Hairs will propagate when $n < N_c$ or $\theta < \theta_c$. If we assume the hairs to be softer than the backing layer (i.e. $k_b/k_h > 1$), then from equation 4 and 6, we get $N_c < N_{max}$. This implies that, for a given pad with N_t hairs, the adhesion force will be given by equation 3, like sequential detachment. The backing layer deformation has no effect on the adhesion. It only affects the dynamics by spontaneous detachment of hairs when $n < N_c$ or $\theta < \theta_c$, independent of the retraction speed.

For our analysis, we define non-dimensional forces as below:

$$\hat{f}_p = \frac{f_p}{k_h w} \quad \hat{F}_{net} = \tfrac{F_{net}}{k_h w} \quad \hat{F}_{adh} = \frac{F_{adh}}{k_h w}$$

Here, $\hat{f}_p$ is a parameter which encapsulates the hair's adhesion force, stiffness and geometry. Positive force values represent attraction by convention.

We introduce a parameter to quantify reversibility of adhesion as:

$$r = \frac{F_{max}}{F_{adh}\left(\theta\right)} \tag{8}$$

Reversibility, r, represents the extent to which adhesion can be controlled by changing tilt. A large value of r implies a greater range of force, and thus is more suitable to achieve reversible adhesion.

3 Discussion

Detachment mechanism: The three modes of detachment can be understood by looking at the net force as hairs detach from the surface (Figure 2). We use equations 1, 2 and 6 to describe the forces. Let us assume that the pad has $\mathrm{N_t}$=25 hairs. We consider two cases: a pad with stiff backing ($\mathrm{k_b} \rightarrow \infty$) and a pad with soft backing ($\mathrm{k_b}/\mathrm{k_h} = 10$). Figure 2 shows that by increasing the tilt angle, the detachment force shows lower attraction or even repulsion as the hairs detach sequentially. Tilting the pad compresses the hairs at one end, which ultimately results in a decrease in the net force. In comparison, when the hairs detach simultaneously (i.e. $\theta = 0°$), the pad shows much larger attractive force.

For a stiff backing, the detachment progresses smoothly for both values of θ. For a soft backing, we observe that for a tilt angle of 2°, the force abruptly drops to zero after the 6^{th} hair breaks contact (n = 20). This represents the spontaneous propagation of hair detachment as a result of the elastic recoil of the backing layer once the 6^{th} hair snaps off.

No such force drop is seen when $\theta = 8°$, because N_c is too small. Thus here, the hairs detach exactly like for a pad with stiff backing.

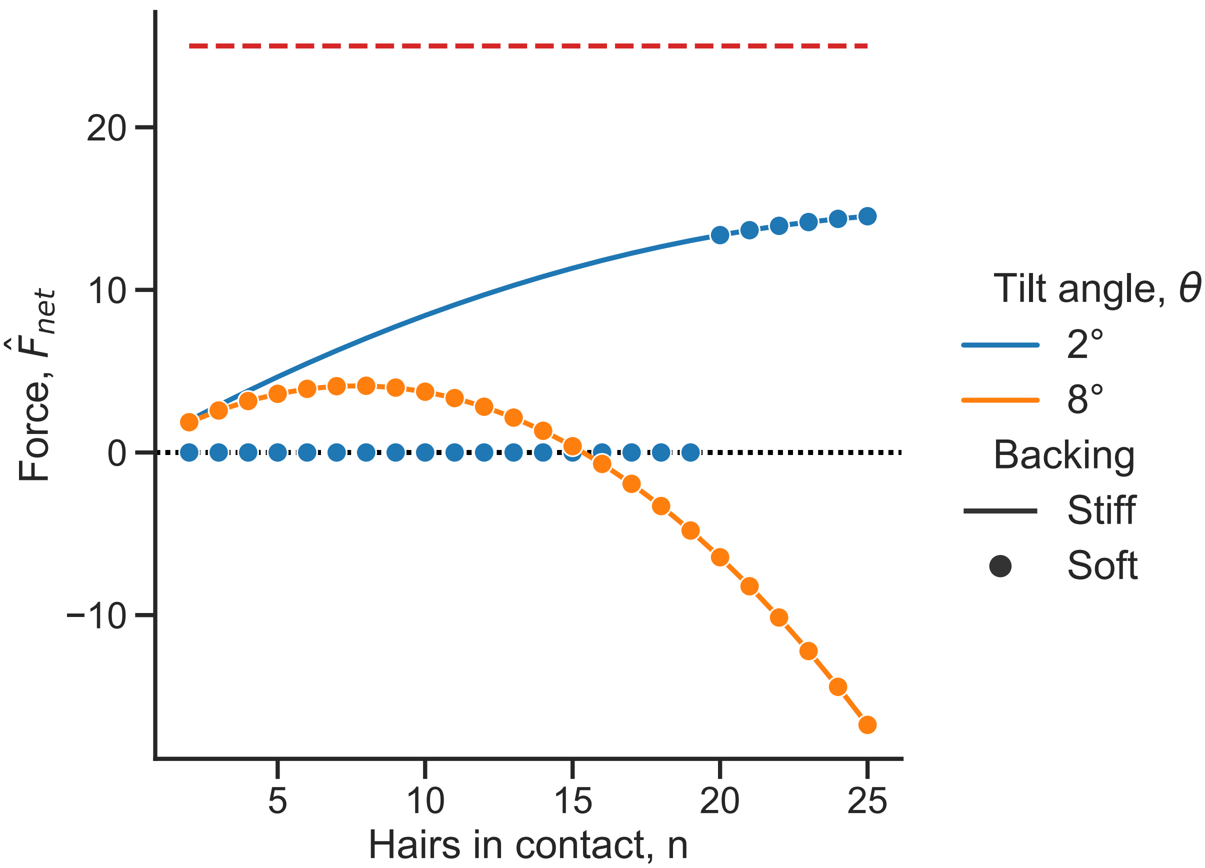

Figure 2: Mechanism of detachment

Effect of tilt on reversible adhesion: The reversibility in adhesion (equation 8) is compared for different tilt angles, $\hat{f}_p$ and number of hairs (Figure 3). For a fixed value of $\hat{f}_p$, adhesion force shows a maxima with increasing tilt angle. This is because, the net force on a tilted pad depends on a balance between the stretched hairs, on one end, and the compressed hairs, on the other end. When the pad is tilted, initially the compressed hair dominates in its contribution to the new force and thus adhesion force initially decreases, increasing r. On further tilting, more number of stretched hairs increases and eventually dominates the force contribution. This results in an increase in adhesion force at large tilt angles, and thus decreases r.

We can calculate the maximum reversibility from the minima adhesion, F_{min} and the subsequent tilt angle, θ_{max}, at maximum reversibility from equations 3 and 8 as:

$$F_{min} = f_p$$
$$r_{max} = \frac{F_{max}}{F_{min}} = N_t$$
$$\theta_{max} = \arcsin\left(\frac{2f_p}{k_h w}\right)$$

We thus see that a larger number hairs increases r_{max}, and is thus more favorable for reversible adhesion. Larger $\hat{f}_p$ shifts θ_{max} to a larger angle (Figure 3 inset), making it more difficult to reduce adhesion.

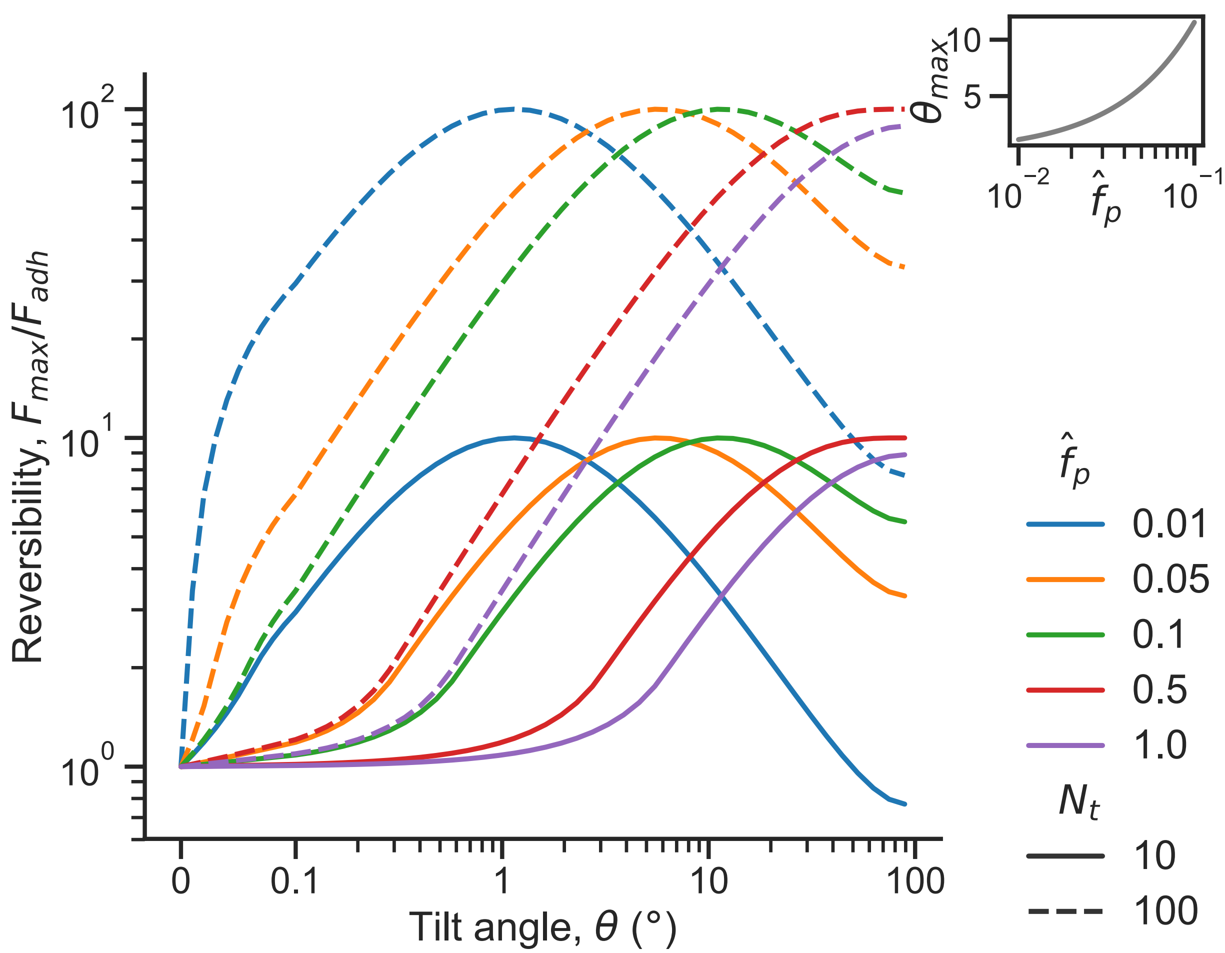

Figure 3: Reversibility of hairy pad

Spontaneous propagation of detachment: Presence of a soft backing layer can trigger a spontaneous detachment of hairs, which propagates by elastic recoil as the they are detached sequentially. Such a mode of detachment is triggered when the tilt angle is less than a critical value, θ_c(equation 7). A softer backing layer (i.e. low k_b/k_h) or a large value of $\hat{f}_p$ shifts θ_c to higher values, thus increasing the available range of tilt angles to trigger spontaneous detachment (Figure 4). This is explained from equation 5, where a high $\hat{f}_p$ or low k_b/k_h will increase the backing layer's elastic recoil when a hair breaks contact, thus increasing θ_c. However, we see that larger value of N_t will decrease θ_c, making it less feasible to trigger spontaneous detachment.

We see a trade-off in the conditions for reducing adhesion or to trigger spontaneous detachment. Low $\hat{f}_p$ and high N_t is suitable for enhanced reversibility in adhesion, while high $\hat{f}_p$ and low N_t is favorable to trigger spontaneous detachment within a feasible θ_c. Depending on whether a higher range of controllable adhesion or an instantaneous detachment is more desirable, one can utilize Figure 3 and 4 as maps to design micropillar adhesives suited for the particular application.

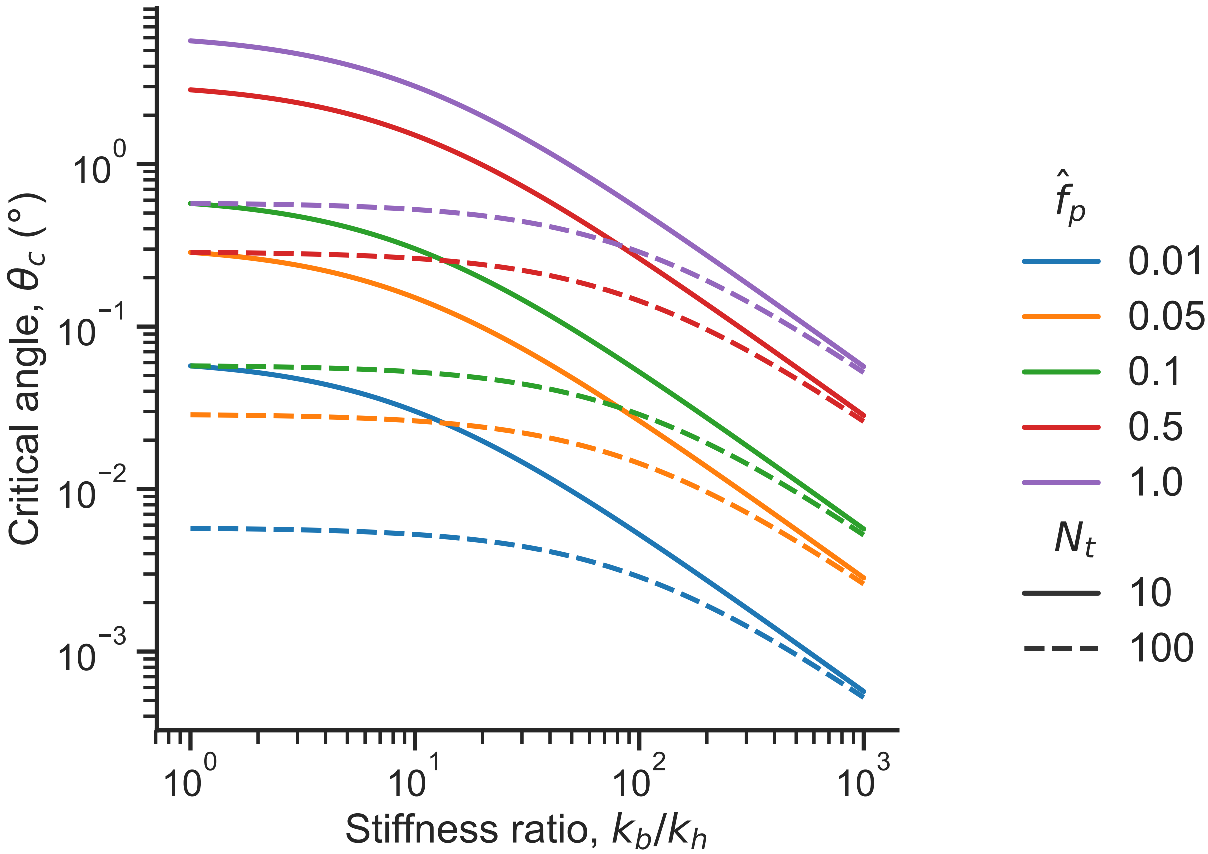

Figure 4: Critical tilt angle

The hairy pad must have a reasonable value of $\hat{f}_p$ such that $\theta_{\max}$ is small enough to be practically feasible. There exists a limit to how much one can tilt a hairy pad. Suppose the hairs of natural length, L, has a maximum linear elastic strain limit, ε_m. We then see from Figure 1 that, the maximum limit in tilt angle is given by, $\theta_{limit} = \arctan \frac{L\varepsilon_m}{(N_t-1)w}$. Thus, $\theta_{\max}$ must be less than θ_{limit} to achieve maximum possible reversibility.

In live animals, as far as our knowledge, there is no experimental evidence that it can modulate adhesion by changing its pad's tilt. If we consider the case of a dock beetle[12], its pointed tipped hair has a pull off force and spring constant of 0.1 μN and 0.2 Nm^{-1}respectively, while its disc tipped hair have the corresponding values of 0.9 μN and 0.7 Nm^{-1}receptively. The beetle's hairs are approximately 50 μm long, spaced 10 μm apart. Let us assume the hairs to have a elastic strain limit of 25%, which is a reasonable estimate considering that the curved geometry of its hairs makes it more flexible. We can us calculate $\hat{f}_p$ for the beetle's pointed and disc tipped hairs to be 0.05 and 0.13 respectively. Since both types of hairs are present in the beetle's pad, let us thus assume an effective $\hat{f}_p = 0.1$. Assuming the pad to have 100 hairs, a one dimensional analogue of the system will put $\mathrm{N_t}$ =10 in our model. θ_{max} and θ_{limit} is thus calculated to be 11.5° and 7.9°, respectively. For the the beetle, θ_{limit} is less than θ_{max}. However, we see from Figure 3 that at 7.9°, the reversibility is 9.6, close to the theoretical maximum (10). The beetle can reduce its adhesion force close to 10 times by roughly tilting its pad by 8°. Thus, the model seems consistent with nature's design of the beetle's pad. Further experimental investigation is required to prove if such a tilting mechanism is employed by animals to switch adhesion.

4 Conclusion

We have proposed a method to control the adhesion of a hairy adhesive pad by changing the tilt. Increasing the tilt reduces adhesion due to the elastic force balance between the compressed and stretched hairs. Based on the spring contact model, we show that increasing the number of hairy structures will enhance the range of tunable adhesion force or reversibility. Further, having a soft backing layer can trigger a spontaneous detachment of hairs as a result of its elastic recoil. High $\mathrm{N_t}$ and low $\hat{f}_p$ is suitable for enhancing reversibility of adhesion, while, low $\mathrm{N_t}$, and high $\hat{f}_p$ and softer backing layer favors spontaneous detachment. The model is consistent with the design of a dock beetle's hairy pad and provides new strategies to design artificial reversible adhesives.

5 Acknowledgment

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A Appendix

Derivation

References

(1) Hooke, R. *Micrographia, or, Some physiological descriptions of minute bodies made by magnifying glasses : with observations and inquiries thereupon*; The Royal Society, 1665.

(2) Stork, N. E. Experimental Analysis of Adhesion of Chrysolina Polita (Chrysomelidae: Coleoptera) on a Variety of Surfaces. *The Journal of Experimental Biology* **1980**, *88*, 91.

(3) Labonte, D.; Federle, W. Scaling and biomechanics of surface attachment in climbing animals. *Philos Trans R Soc Lond B Biol Sci* **2015**, *370*, 20140027.

(4) O'Rorke, R. D.; Steele, T. W. J.; Taylor, H. K. Bioinspired fibrillar adhesives: a review of analytical models and experimental evidence for adhesion enhancement by surface patterns. *Journal of Adhesion Science and Technology* **2016**, *30*, 362–391.

(5) Persson, B. N. J. On the mechanism of adhesion in biological systems. *The Journal of Chemical Physics* **2003**, *118*.

(6) Jagota, A.; Stephen, J. B. Mechanics of Adhesion through a Fibrillar Microstructure. *Integrative and Comparative Biology* **2002**, *42*, 1140–1145.

(7) Kendall, K. Thin-film peeling-the elastic term. *Journal of Physics D: Applied Physics* **1975**, *8*, 1449–1452.

(8) Hui, C. Y.; Glassmaker, N. J.; Tang, T.; Jagota, A. Design of biomimetic fibrillar interfaces: 2. Mechanics of enhanced adhesion. *J R Soc Interface* **2004**, *1*, 35–48.

(9) Tian, Y.; Pesika, N.; Zeng, H.; Rosenberg, K.; Zhao, B.; McGuiggan, P.; Autumn, K.; Israelachvili, J. Adhesion and friction in gecko toe attachment and detachment. *Proceedings of the National Academy of Sciences of the United States of America* **2006**, *103*, 19320–19325.

(10) Federle, W. Why are so many adhesive pads hairy? *J Exp Biol* **2006**, *209*, 2611–21.

(11) Schargott, M.; Popov, V. L.; Gorb, S. Spring model of biological attachment pads. *Journal of Theoretical Biology* **2006**, *243*, 48–53.

(12) Bullock, J. M.; Federle, W. Beetle adhesive hairs differ in stiffness and stickiness: in vivo adhesion measurements on individual setae. *Naturwissenschaften* **2011**, *98*, 381–7.