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 a simple spring model. We show that the adhesion force can be decreased just by slightly tilting the pad during pull-off. Larger number of hairs are shown to decrease adhesion by a larger factor for a similar tilt. Further, deformation of the pad's soft backing layer can trigger its spontaneous detachment at low tilt angles due to an elastic recoil effect. 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 in any direction 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 a pad from the surface. During detachment, elastic energy stored in the hair is dissipated, which increases W_{adh} and thus adhesion is enhanced[5,6]. Detachment of an individual hair 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] had identified two regimes of hair detachment: 1) a flaw sensitive regime, where contact failure occurs due to crack propagation leading to low σ_p, 2) a flaw insensitive regime, where the contact interface fails simultaneously, leading to high σ_p. Tian et. al.[9] had 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] had further argued that the 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 to 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 unbalanced elastic force 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 one dimensional system of N_t hairs, each behaving like a spring with spring constant, k_h, and natural length, $l_{h,0}$ (Figure 1). The hairs are attached to a backing layer, assumed to be another spring with spring constant, k_b, and natural length, $l_{b,0}$. The hairs are spaced apart by width w. The pad is oriented at a tilt angle, θ, while making contact with a flat smooth surface. The center of the pad is at a distance d from the surface. Each hair can attain a maximum length, $l_{h,p}$, 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 while maintaining the given tilt angle with the surface. Excess torque in the system is assumed to be balanced externally and is not considered for our analysis. F_{net} is the net force on the pad at a particular instant during the detachment process and F_{adh} is the maximum force required to detach *all* hairs from the surface. We consider three modes of detachment, described below.

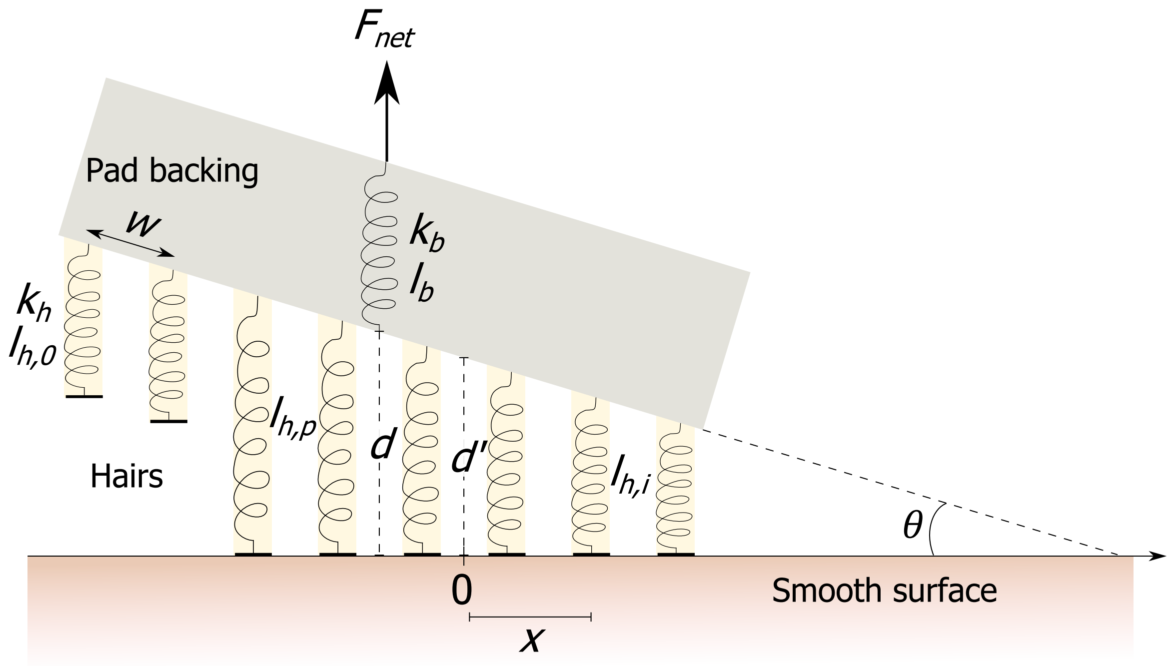

Figure 1: Spring contact model of a hairy adhesive pad with a soft backing layer. The pad is oriented at a tilt angle, θ, with the surface. The pad has a total number of hairs, N_t, of which, n number of hairs are in contact with the surface at a particular instant. The left most hair in contact is at its maximum length, $l_{h,p}$, just before it detaches. The arrow along the surface indicates positive axis direction, and its corresponding origin is labeled as thus.

Sequential detachment: When $\theta > 0°$, the hairs will detach sequentially from left to right. Suppose at a particular instant (Figure 1), there are n hairs in contact with the surface. The origin is assumed to lie at the midpoint along the surface where the n hairs are making contact. The pad is at a vertical distance, d', from the origin. For a particular tilt angle, θ, the net force on the whole pad at a distance d from the surface is,

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

$l_{h,i}$ is the length of the i^{th} hair, which is at a distance x from the origin. From simple geometry, $l_{h,i} = d' - x\tan\theta$. Substituting in above and noting that $\sum_{i=1}^{n} x = 0$ by symmetry, we get:

$$F_{net}\left(d,n,\theta\right)=nk_h\left(d'-l_{h,0}\right)$$

From geometry, d and d' is related as:

$$\frac{d}{\tan\theta}-\frac{d'}{\tan\theta}=\frac{\left(N_t-1\right)w\cos\theta}{2}-\frac{\left(n-1\right)w\cos\theta}{2}$$

Eliminating d' from the above two equations, we find the net force on the pad as a function of distance to be:

$$F_{net}\left(d,n,\theta\right)=nk_h\left(d-l_{h,0}-\frac{N_t-n}{2}w\sin\theta\right) \tag{1}$$

For a particular value of n, equation 1 is valid until a certain distance, d_{max}, above which its left most hair will detach. Just before detachment, this hair will be at its maximum length, $l_{h,p}$. Once again from geometry, we see that d_{max} and $l_{h,p}$ is related as:

$$\frac{l_{h,p}}{\tan\theta}-\frac{d_{max}}{\tan\theta}=\left(n-1\right)w\cos\theta-\frac{\left(N_t-1\right)w\cos\theta}{2}$$

Substituting $l_{h,p}=\frac{f_p}{k_h}+l_{h,0}$ in above and simplifying, we get:

$$d_{max}\left(n,\theta\right)=l_{h,0}+\frac{f_p}{k_h}+\left(\frac{N_t+1}{2}-n\right)w\sin\theta \tag{2}$$

Equation 1 is valid for $d\leq d_{max}$. We can substitute d_{max} in equation 1 to get the force at which the left most hair detaches from the surface:

$$F_{net}\left(n,\theta\right)=nf_p-\frac{n\left(n-1\right)}{2}k_hw\sin\theta \qquad d=d_{max} \tag{3}$$

Equation 3 is the maximum force necessary to detach one hair of the pad when there are n hairs in contact. During this sequential detachment of hairs, there exists a maxima in force at a particular number of contacts, N_{max}. Differentiating equation 3 and equating it to zero we find:

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

Substituting the above in equation 3, the maximum adhesion force of a pad during a sequential detachment of its N_t hairs will be:

$$F_{adh}(\theta) = \begin{cases} \frac{f_p}{2}\left[\frac{f_p}{k_h w \sin\theta} + 1\right] + \frac{k_h w \sin\theta}{8} & N_t \geq N_{max} \\ N_t f_p - \frac{N_t(N_t-1)}{2} k_h w \sin\theta & N_t < N_{max} \end{cases} \tag{5}$$

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

$$F_{adh} = F_{max} = N_t f_p \tag{6}$$

Force as a function of distance can be obtained by setting $n = N_t$ in equation 1.

Spontaneous detachment by propagation: Let us consider a special case of sequential detachment where even the pad backing layer deforms, along with the hairs. When a hair detaches from the surface, the backing layer undergoes an elastic recoil due to the stored elastic energy. 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:

$$\Delta l = \frac{f_p}{k_h\,(n-1) + k_b} \tag{7}$$

The length difference between the detached hair just before it breaks contact and its adjacent hair is $w \sin\theta$. If $\Delta l > w \sin\theta$, the adjacent hair will be stretched more than its maximum length ($l_{h,p}$), and thus will also detach. Equation 7 shows that Δl increases with every loss of hair contact due to decreasing value of n. This implies that, hair detachment will propagate and the pad completely breaks contact with the surface. The critical number of hairs in contact, N_c, below which detachment propagates for a given tilt angle can be calculated by substituting Δl from equation 7 into the above inequality condition, to get:

$$N_c = \frac{f_p}{k_h w \sin\theta} - \frac{k_b}{k_h} + 1 \tag{8}$$

Substituting the above in equation 2, we can find the critical distance, d_c, above which detachment propagates:

$$d_c = \left(\frac{k_b}{k_h} + \frac{N_t - 1}{2}\right) \sin\theta \tag{9}$$

Equation 8 can also be rearranged to give us the critical tilt angle, θ_c, below which detachment propagates for a given pad with N_t hairs:

$$\theta_c = \arcsin\left[\frac{f_p}{k_h w}\left(\frac{1}{\frac{k_b}{k_h} + N_t - 1}\right)\right] \tag{10}$$

Hairs will propagate when $n < N_c$ or $d > d_c$ 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 equations 4 and 8, we see that $N_c < N_{max}$. Spontaneous detachment of the pad occurs only after it has reached maximum adhesion force by sequential detachment of hairs. So in this case, for a given pad with N_t hairs, the adhesion force will be given by the same equation as for sequential detachment (equation 5). The adhesion remains unaffected by the backing layer deformation. It only affects the dynamics of detachment. The hairs lose contact spontaneously when $n < N_c$, independent of the speed at which the pad is retracted. One the other hand, the net force as a function of distance will be given by equation 1 when $d \leq d_{max}$. The distance, d, will however be shifted by Δl each time a hair detaches from the surface, due to the backing layer's deformation. For $d > d_{max}$, all hairs will detach spontaneously and the force will drop to zero.

We introduce a parameter, *reversibility*, defined as:

$$r = \frac{F_{max}}{F_{adh}\left(\theta\right)} \tag{11}$$

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

The forces and distance are expressed in non-dimensional forms, as below:

$$\hat{f}_p = \frac{f_p}{k_h w}, \quad \hat{F}_{net} = \frac{F_{net}}{k_h w}, \quad \hat{d} = \frac{d - l_{h,0}}{w}$$

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

3 Discussion

Detachment mechanism: The three modes of detachment can be understood by looking at the net force as hairs detaches from the surface. Let us look at the case when the pad has $N_t = 25$ hairs and $\hat{f}_p = 1$. From equations 1, 2, 6 and 9, we get the force-distance curves for each mode of detachment (Figure 2). We consider two cases: a pad with a stiff backing ($k_b \to \infty$) and a pad with a soft backing ($k_b/k_h = 10$).

At small distances, all hairs of the pad are in contact and under compression, showing a linear Hookian response as the pad is pulled upwards maintaining a tilt. On further pulling, the hairs of the pad with a higher tilt will start to detach first, followed by the ones with a lower tilt. The force curves for the pad with a stiff backing shows a characteristic "saw-tooth" shaped fluctuation, indicating the sequential events of individual hair detachment as the pad is retracted away from the surface. In the case for the pad with a soft backing, such fluctuations are minimized due to the backing layer's deformation after each hair detaches, leading to a "dampened" force response.

Increasing the tilt of the pad decreases its maximum force or adhesion. Tilting the pad compresses the hairs at one end and stretches them on the other end. The balance of the attractive and repulsive elastic forces of the hairs ultimately results in a decrease in the net force. In comparison, when there is no tilt, all the hairs detach simultaneously after a distance, $\hat{d} = 1$, and the pad shows the maximum possible adhesion. Overall, we see that the adhesion force at a particular tilt is same for both types of backing.

For a soft backing, we observe that at a tilt angle of 3°, the force abruptly drops to zero at a certain distance, $\hat{d}_c \simeq 1.15$ (equation 9). This represents the spontaneous propagation of hair detachment due to elastic recoil of the backing layer once the 15^{th} hair ($N_c = 10$) snaps off. No such force drop is seen when $\theta = 6°$, because N_c is less than 1 (equation 8). All its hairs have already detached sequentially before it could trigger a spontaneous detachment. So in this case, the force-distance curves look very similar to that of the pad with a stiff backing.

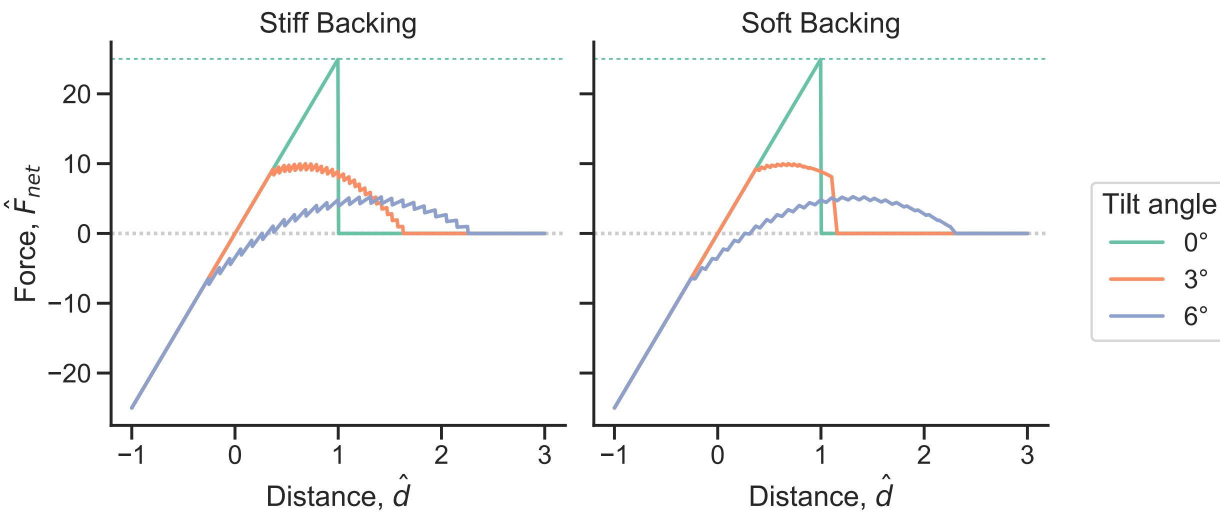

Figure 2: Force distance curves for a hairy pad with a stiff ($k_b \to \infty$) and a soft ($k_b/k_h = 10$) backing, pulled normally upwards while maintaining a constant tilt with the surface. Positive force values represent attraction. The green dashed line represents the maximum possible adhesion for the pad, which occurs at no tilt.

Effect of tilt on reversible adhesion: The reversibility in adhesion (equation 11) is compared for different tilt angles, number of hairs and $\hat{f}_p$ (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, the 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 of adhesion w.r.t. θ (equation 5) to get $F_{min} = f_p$. The corresponding tilt angle, θ_{max}, for maximum reversibility, r_{max}, will be:

$$\begin{aligned} \theta_{max} &= \arcsin\left(\frac{2f_p}{k_h w}\right) \\ r_{max} &= \frac{F_{max}}{F_{min}} = N_t \end{aligned} \tag{12}$$

Larger $\hat{f}_p$ shifts θ_{max} to a larger angle (Figure 3 inset), making it more difficult to reduce adhesion. On the other hand, a larger number hairs increases r_{max}, and is thus more favorable for reversible adhesion. This highlights the advantage of a split contact design of the adhesive pad to control adhesion by tilt.

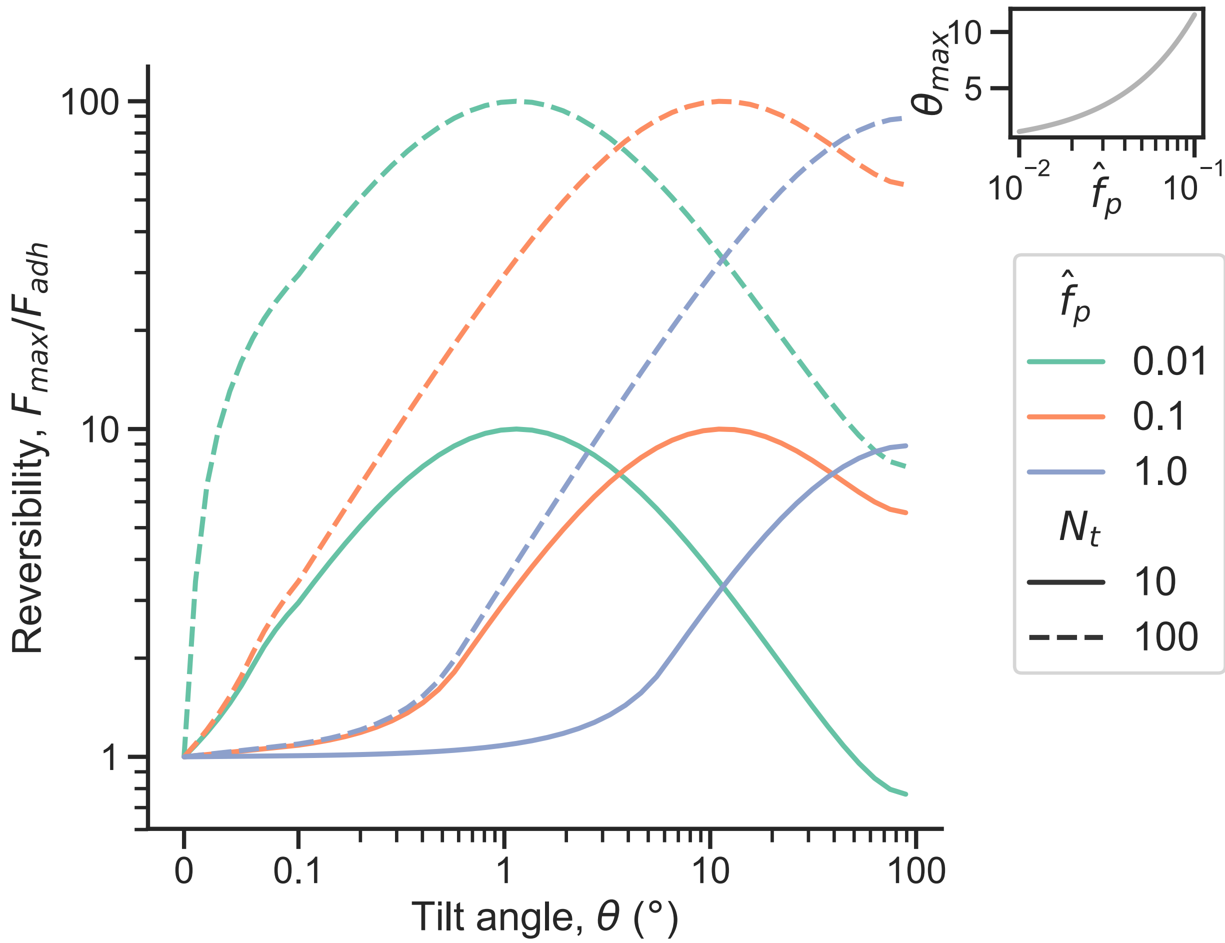

Figure 3: Reversibility of the hairy pad for a range of tilt angles. Inset shows the tilt angle for maximum reversibility as a function of $\hat{f}_p$.

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 10). 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 can be explained from equation 7, 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, a larger value of N_t will decrease θ_c, making it less feasible to trigger spontaneous detachment.

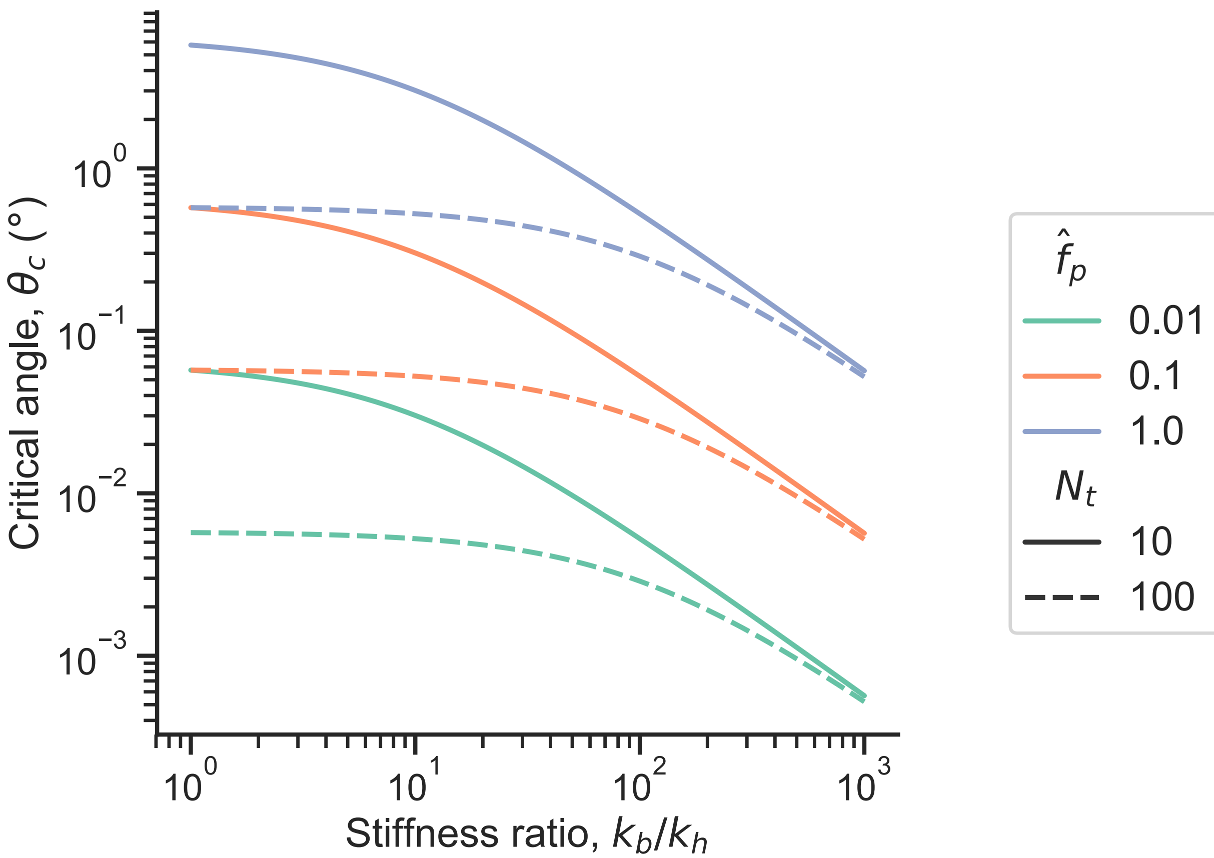

Figure 4: Critical tilt angle, below which spontaneous detachment of hairs is triggered, is shown for a range of stiffness ratios.

Limitation of tilt: There exists a limit to how much one can tilt a hairy pad, depending on the pad's geometry and material properties. Suppose the hair has a maximum linear elastic strain limit, ε_m, and natural length, $l_{h,0}$. Based on Figure 1, if the right most hair is compressed to its elastic limit, we can show from simple geometry, that, the corresponding maximum limit in tilt angle is given by:

$$\theta_{limit} = \arctan \frac{l_{h,0}\varepsilon_m}{(N_t - 1)\, w} \tag{13}$$

θ_{limit} represents the elastic limit in tilting a hairy pad. θ_{max} must be less than θ_{limit} to allow maximum possible reversibility to be feasible. Else, the pad's reversibility will be limited to its value at θ_{limit}, as per Figure 3.

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. At the same time, the hairy pad must have an optimal value of $\hat{f}_p$ and N_t such that θ_{max} does not exceed θ_{limit}. Depending on whether a higher range of controllable adhesion or an instantaneous detachment is more desirable, one can utilize Figures 3 and 4, together with equation 13, as design maps in the fabrication of micro-pillar adhesives suited for the required application.

In live animals, as far as our knowledge, there is no experimental evidence that the animal can modulate adhesion by changing its pad's tilt. Let us consider the case of a dock beetle. It was previously reported that[12], its pointed tipped hair shows a pull off force and spring constant of 0.1 μN and 0.2 Nm^{-1} respectively, while its disc tipped hair has 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 thus 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 value of $\hat{f}_p = 0.1$. Assuming that 100 hairs of the pad are in contact during locomotion, a one dimensional analogue of the system will put $N_t = 10$ in our model. From equations 12 and 13, θ_{max} and θ_{limit} are calculated to be 11.5° and 7.9°, respectively. Thus, for the beetle, the elastic limit imposed by the pad allows it to only tilt it by 7.9°, about 3.6° lower than the tilt necessary to achieve maximum reversibility. However, we see from Figure 3 that, at a 7.9° tilt, the reversibility is 9.6, close to the theoretical maximum (10). The beetle can reduce its adhesion force by ~ 10 by tilting its pad by $\sim 8°$. Thus, the model seems consistent with nature's design of the beetle's pad. A detailed experimental investigation however is essential to prove if such a tilting mechanism is indeed 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 a simple spring model, we show that increasing the number of hairy structures enhances the range of adjustable adhesion force or reversibility, which highlights the advantage of a hairy design for controlling adhesion. Further, having a soft backing layer can trigger a spontaneous detachment of hairs as a result of its elastic recoil. High N_t and low $\hat{f}_p$ are suitable for enhancing reversibility of adhesion, while, low N_t, high $\hat{f}_p$ and softer backing layer favor spontaneous detachment. The model is consistent with the natural design of a dock beetle's hairy pad and provides new strategies to reversibly control adhesion in bio-inspired artificial adhesives.

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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.