

# Mechanisms of detachment in fibrillar adhesive systems

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## Abstract

Several creatures can climb on smooth surfaces with the help of hairy adhesive pads on their legs. A rapid change from strong attachment to effortless detachment of the leg is enabled by the asymmetric geometry of the tarsal hairs. In this study, we propose mechanisms by which the hairy pad can be easily detached, even when the hairs possess no asymmetry. Here, we examine the possible function of the tibia-tarsus leg joint and the claws. Based on a spring-based model, we consider three modes of detachment: vertically pulling the pad while maintaining either a 1) fixed or a 2) free joint, or by 3) flexing the pad about the claw. We show that in all cases, the adhesion force can be significantly reduced due to elastic forces when the hairs deform non-uniformly across the array. Our proposed model illustrates the design advantage of such fibrillar adhesive systems, that not only provide strong adhesion, but also allow easy detachment, making them suitable as organs for fast locomotion and reliable hold. The presented approaches can be potentially used to switch the adhesion state in bio-inspired fibrillar adhesives, by incorporating artificial joints and claws into their design, without the need of asymmetric or stimuli-responsive fibrillar structures.

*Keywords:* fibrillar adhesion, reversible adhesion, contact splitting, beetle, biomechanics

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## 1. Introduction

Over the past few decades, there have been numerous studies to understand how animals, such as geckos and insects, are able to walk on surfaces of any direction while seemingly defying gravity. A microscopic observation reveals that, in many cases, animals have a dense array of fibrillar structures at the end of their legs [1, 2]. These *hairy* adhesive pads help the animal to stay attached to any surface or detach easily at will for countless cycles, a property that is referred to as *reversible adhesion*. Previous attempts to theoretically explain adhesion in hairy pads [3, 4, 5] has followed two fundamental approaches: either by energy balance, or by force balance.

In the energy balance approach, adhesion is usually characterized by *work of adhesion* ( $W_{\text{adh}}$ ), which is the energy required to separate a pad from the surface. During detachment, the elastic energy stored in the hair is dissipated, that increases  $W_{\text{adh}}$  and thus adhesion is enhanced [6, 7]. Detachment of an individual hair can be explained based on Kendall's peeling theory [8, 9], which predicts low adhesion at high peeling angles.

In the force balance approach, adhesion is characterized by *pull-off force*,  $F_p$  (or stress,  $\sigma_p$ ), which is the minimum force necessary to separate two surfaces from contact. Based on a *cohesive zone model*, Hui et. al. [10] have identified two regimes of single hair detachment: 1) a *flaw sensitive* regime, where, for large hair radius, contact failure occurs due to crack propagation, initiated by a stress singularity at the edge of the hair, leading to low  $\sigma_p$ ; 2) a *flaw insensitive* regime, where, for small hair radius, the contact interface fails simultaneously, leading to high  $\sigma_p$ . Likewise, Tian et. al. [11] have shown that the spatula-shaped hair tips in a gecko's toe allows it to change adhesion by three orders of magnitude by laterally sliding and controlling the pulling angle to disorient the hairs. The detailed mechanics of the spatula-shaped hair design for controlling adhesion have been extensively studied by theoretical modelling [12, 13, 14, 15, 16, 17], artificial mimics [18, 19, 20, 21, 22] as well as in several biological systems [23, 24, 25]. Federle [26] has further argued that the curved shape of the hair

1 helps the pad to stay attached when pulled proximally and easily detached by  
2 elastic recoil when pushed distally.

3 The theory presented so far suggests that a low detachment force of a fibrillar  
4 adhesive pad can be achieved either by increasing the stress concentration by  
5 peeling the pad at high angles, or by laterally shearing the pad before pull-off,  
6 which requires the hairs to have an asymmetric geometry or curvature. However,  
7 some insects like male dock beetles predominantly possess mushroom-shaped  
8 hairs with flat discoid terminals on their pads [27], that are relatively less asym-  
9 metric compared to the spatula-shaped hairs. These mushroom-shaped hairs  
10 have in fact been shown to possess superior adhesion compared to the spatula-  
11 shaped hairs [28, 18] and are generally resistant to detachment via lateral shear  
12 [29]. Yet, how does the beetles possessing such mushroom-shaped hairs still  
13 easily detach their legs during locomotion? Besides, from an application per-  
14 spective, introducing asymmetry into the pillar geometry to construct spatula-  
15 shaped artificial biomimetic adhesives for easy detachment is challenging due  
16 to current limitations in fabrication techniques and difficulty in scaling-up [18].  
17 Alternate strategies are thus desired to switch the adhesion state of symmet-  
18 ric pillar arrays in a reversible manner. This can be achieved, for example, by  
19 buckling the pillars under compressive load leading to their contact loss [30] or  
20 by using special materials reacting to external stimuli such as magnetic field  
21 [31], UV light [32] or temperature [33].

22 Employing the force-balance approach, in this work we theoretically model  
23 the possible mechanisms by which adhesive pads with axially-symmetric hairs  
24 can be easily detached, without the need of any spatula-like asymmetry. Here,  
25 we focus our analysis on normal adhesion force necessary to separate the pad  
26 from a flat surface under a purely mechanical action. We found that the max-  
27 imum force necessary to detach the leg can be significantly reduced by strate-  
28 gically controlling the tilt, joints and claws of the adhesive system. We hope  
29 our work to provide new approaches to control the adhesion force of an artifi-  
30 cial micro-pillar adhesive, that has applications in bio-inspired climbing robots,  
31 pick-and-place operations and reusable adhesives.

## 1 2. Model

2        Similar to previous approaches [34, 35], the fibrillar adhesive pad is assumed  
3        to be a one-dimensional array of  $N_t$  hairs, each behaving like a spring with spring  
4        constant,  $k_h$ , and natural length,  $l_{h,0}$  (Figure 1). The array backing is assumed  
5        to be stiff. The pad is attached to a linearly deformable leg (tibia), assumed to  
6        be another spring with spring constant,  $k_l$ , and natural length,  $l_{l,0}$ . The leg is  
7        hinged to the array at a distance,  $s$ , from the right end of the array. The hinge,  
8        analogous to the tibia-tarsus leg joint of an insect, is at a vertical distance,  $d_s$ ,  
9        from the surface. The hairs are spaced apart by a width,  $w$ , and the array is of  
10       length,  $L = (N_t - 1)w$ . The pad is oriented at an instantaneous angle,  $\theta$ , while  
11       making contact with a flat smooth surface. Each hair can attain a maximum  
12       length,  $l_{h,p}$ , before pull-off, such that its pull-off force,  $f_p = k_h (l_{h,p} - l_{h,0})$ .  $F_{net}$   
13       is the net normal force on the pad and  $M_{net}$  is the the net moment about the  
14       hinge, at a particular instant during the detachment process. We focus only  
15       on vertical detachment modes and thus lateral friction forces between the hairs  
16       and surface are not considered for our analysis.

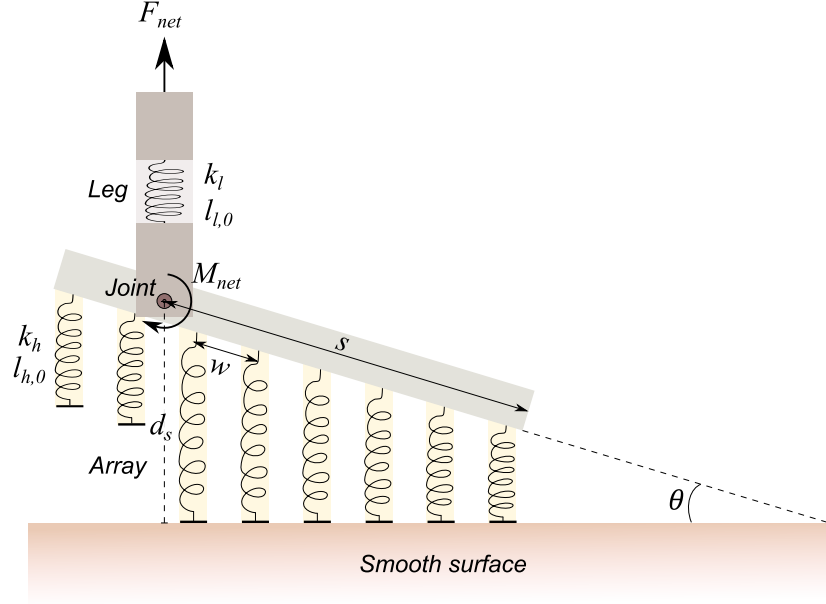


Figure 1: **Spring contact model of a fibrillar adhesive pad.** The pad consists of an array of  $N_t$  hairs connected to a deformable leg at the joint. At a particular distance,  $d_s$ ,  $n$  number of hairs are in contact and the array is oriented at a tilt angle,  $\theta$ , with the surface.

- 1 Suppose at a particular instant, there are  $n$  hairs in contact with the surface.
- 2 The net force on the whole pad will be,

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

- 3 Simplifying, we get (see Appendix B for derivation):

$$F_{net} = nk_h [d_s - l_{h,0} - \Psi \sin \theta] \quad (1)$$

- 4 where,  $\Psi = s - \frac{n-1}{2}w$ . For a particular value of  $n$ , equation (1) is valid
- 5 until a certain distance,  $d_{s,max}$ , above which the left most hair will detach. Just
- 6 before detachment, this hair will be at its maximum length,  $l_{h,p}$ . From simple
- 7 geometry we can thus find:

$$d_{s,max} = l_{h,0} + \frac{f_p}{k_h} + [s - (n-1)w] \sin \theta \quad (2)$$

1 Equation (1) will be valid for  $d_s \leq d_{s,max}$ .

2 The maximum possible adhesion of the array would be the case when all  
3 hairs detach simultaneously ( $\theta = 0^\circ$ ):

$$F_{max} = N_t f_p \quad (3)$$

4 The net moment,  $M_{net}$ , about the joint can be similarly derived (see Ap-  
5 pendix B):

$$M_{net} = n k_h \cos \theta \left[ (d_s - l_{h,0}) \Psi - \left\{ \Psi^2 + \frac{n^2 - 1}{12} w^2 \right\} \sin \theta \right] \quad (4)$$

6 Let us now consider the scenario where even the leg above the joint can  
7 undergo elastic stretching together with the hairs. When a hair detaches from  
8 the surface, the leg undergoes an elastic recoil due to the stored elastic energy.  
9 Suppose the leg relaxes upward by a recoil length,  $\Delta l$ . For  $n$  hairs in contact,  
10 the force balance before and after a hair detaches is given respectively by:

$$\begin{aligned} \sum_{i=1}^n k_h (l_{h,i} - l_{h,0}) &= k_l (l_l - l_{l,0}) \\ \sum_{i=1}^{n-1} k_h (l_{h,i} + \Delta l - l_{h,0}) &= k_l (l_l - \Delta l - l_{l,0}) \end{aligned}$$

11 Solving the above two equations for  $\Delta l$ , we get:

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

12 Thus,  $d_s$  shifts by  $\Delta l$  in equations 1 and 4 at each event of hair detachment  
13 (i.e. when  $d_s = d_{s,max}$ ).

14 We express the forces and distances in non-dimensional forms, as below:

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

15 Here,  $\hat{f}_p$  is a parameter which encapsulates the hair's adhesion force, stiffness  
16 and array density. Unless specified, positive force values represent attraction by  
17 convention.

### 1   **3. Detachment mechanisms**

2        We consider three tentative scenarios to detach the adhesive pad from a  
3   surface: 1) *Fixed pull*, where the pad is pulled vertically up while keeping a  
4   fixed joint; 2) *Free pull*, where the pad is pulled vertically up while keeping  
5   the joint free to allow rotation of the array; 3) *Flex*, where the pad is hinged  
6   to an external point (claw-hinge), and detached in a rotary fashion, emulating  
7   the claw function in insects. To investigate each case in detail, let us assume a  
8   pad to be a one-dimensional analogue of a dock beetle's adhesive pad [27, 36]  
9   with  $N_t = 25$  hairs and  $\hat{f}_p = 0.1$  (see discussion on *detachment pathways* for  
10   details) attached to a stiff leg (or tibia) with  $k_l \rightarrow \infty$ . The situation of a soft  
11   leg with  $k_l/k_h = 10$  is also considered for the first two cases involving vertical  
12   detachment.

### 3.1. Fixed pull

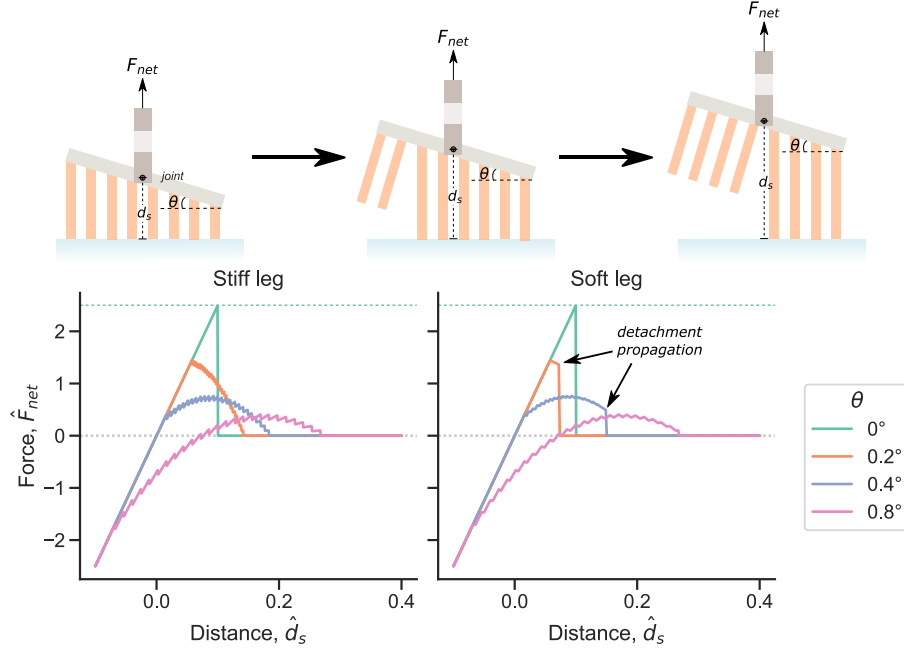


Figure 2: **Detachment by Fixed Pull.** Force-distance curves for a fibrillar adhesive pad, pulled vertically upwards with a fixed joint. The tilt angle,  $\theta$ , of the array is kept fixed during detachment. The leg (tibia) is either stiff ( $k_l \rightarrow \infty$ ) or soft ( $k_l/k_h = 10$ ). Positive force values represent attraction between the array and the surface. The green dashed line represents the maximum possible adhesion for the pad. All values are normalized to dimensionless forms, as described in text.

The fibrillar adhesive pad can be detached by pulling it vertically upwards while maintaining a constant tilt angle,  $\theta$ , with the surface. This can be achieved if the joint is kept fixed. Equations 1, 2 and 3 can be used to get the resulting force-distance curves for such a scenario.

Increasing the tilt of the pad decreases its maximum force or adhesion (Figure 2). Tilting the pad causes an inhomogeneous deformation of hairs, where, on one end they are stretched, while, on the other end they are compressed. The balance of the respective attractive and repulsive elastic forces of the hairs ultimately results in a decrease in the net force. The tilted orientation also



1 causes the individual hairs to detach distinctly rather than simultaneously, fur-  
2 ther reducing the maximum adhesion of the array. We term this effect of loss  
3 in adhesion due to a non-uniform hair deformation across the array as *elastic*  
4 *weakening*. When there is no tilt ( $\theta = 0^\circ$ ), all the hairs undergo identical defor-  
5 mation and ultimately detach simultaneously after a distance,  $\hat{d}_s = 0.1$ . Here,  
6 no *elastic weakening* occurs and the pad shows the maximum possible adhesion.

7 For the case of a stiff leg (tibia), we see that at small distances, all hairs  
8 of the pad are in contact with the surface, resulting in a linear force response.  
9 On further pulling, the hairs will start to detach sequentially from left to right,  
10 indicated by a characteristic saw-tooth jitter in the force curves. The hairs of  
11 the pad with a higher tilt angle will start to detach first, followed by the ones  
12 with a lower tilt.

13 For the case of a soft leg (tibia), we observe a similar effect of tilt angle on the  
14 force curves as before. The maximum adhesion force at a particular tilt is the  
15 same as that for the stiff leg. The saw-tooth jitter are however minimized due  
16 to the leg's deformation, leading to a dampened force response. Interestingly,  
17 the force abruptly drops to zero for the angles  $0.2^\circ$  and  $0.4^\circ$ . This is an effect of  
18 the elastic recoil of the leg while each hair loses contact during the detachment  
19 process (equation (5)). The length difference between the detached hair just  
20 before it breaks contact and its adjacent hair is  $w \sin \theta$ . If the leg's recoil length,  
21  $\Delta l > w \sin \theta$ , the adjacent hair will be stretched more than its maximum length  
22 ( $l_{h,p}$ ), and thus will also detach, leading to further recoil of the leg. Equation (5)  
23 shows that  $\Delta l$  increases with every subsequent loss of hair contact if  $\theta$  is kept  
24 constant. This implies that, once initiated, the leg's recoil will always be large  
25 enough to detach every remaining hair, resulting in a spontaneous propagation  
26 of the detachment front until the pad completely breaks contact with the surface.  
27 This is consistent with a recent report of catastrophic failure, due to a similar  
28 recoil effect of the measurement system, seen in micro-fibrillar adhesives with a  
29 narrow variance of individual fibril adhesive strengths [37].

### 3.2. Free pull

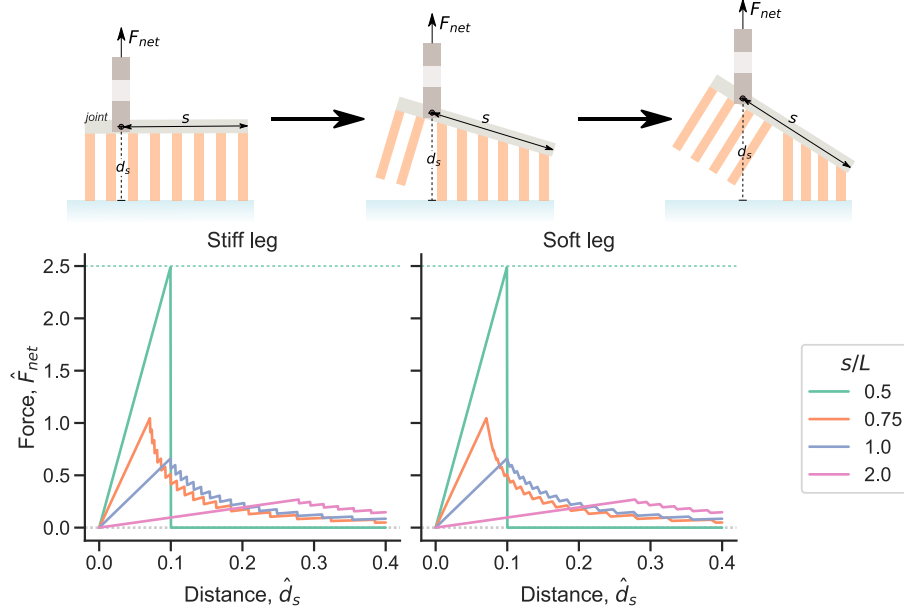


Figure 3: **Detachment by Free Pull.** Force-distance curves for a fibrillar adhesive pad, pulled vertically upwards with a free joint.  $s$  is the distance between the joint and the right end of the array and  $L$  is the array length. The free joint allows further tilting of the array during the vertical pull. The leg (tibia) is either stiff ( $k_l \rightarrow \infty$ ) or soft ( $k_l/k_h = 10$ ). Positive force values represent attraction. The green dashed line represents the maximum possible adhesion for the pad. All values are normalized to dimensionless forms, as described in text.

Similar to the previous case, we once again consider the situation where the adhesive pad is pulled vertically upwards for detachment. However now, the joint is assumed to be freely movable. In this case, the array will reorient itself to maintain a zero net moment about the joint during the entire detachment process. At any given instant, the tilt angle,  $\theta$ , can be found by setting  $M_{net}$  to zero in equation (4) to get:

$$\theta(\hat{d}_s, n) = \arcsin \left[ \frac{(\hat{s} - \frac{n-1}{2}) \hat{d}_s}{(\hat{s} - \frac{n-1}{2})^2 + \frac{n^2-1}{12}} \right] \quad (6)$$

Using the above relation together with equations 1, 2 and 3, we can find

1 force-distance curves during a free vertical pull of the adhesive pad. Since the  
2 position of the joint will influence the net moment, we use the ratio,  $s/L$ , to  
3 study its effect on the detachment forces.

4 Maximum adhesion is seen when the joint is positioned at the centre of the  
5 array, i.e.  $s/L = 0.5$  (Figure 3). Here, the net moment due to the hairs is  
6 balanced by symmetry and the array remains parallel to the substrate until  
7 all hairs detach simultaneously at  $\hat{d}_s = 0.1$ . Shifting the position of the joint  
8 further away from the array centre leads to lower forces or adhesion. The re-  
9 sulting moment imbalance will tilt the array, which reduces the net force due to  
10 the *elastic weakening* effect, as described in the previous section. Higher  $s/L$   
11 increases the net moment to be balanced, leading to a higher tilt of the array  
12 and thus lower net force.

13 The force curves look qualitatively different compared to the previous case of  
14 *fixed pull*. A sharp maxima is seen, coinciding with the point when the first hair  
15 detaches. Beyond this, the force starts to decrease sharply and once again shows  
16 the characteristic saw-tooth jitter as the subsequent hairs detach in sequence.  
17 Nearly identical trend is seen for both a stiff and a soft leg (tibia). The elastic  
18 recoil of the leg does slightly reduce the amplitude of the jitter for the soft leg  
19 case. However, no abrupt drop in the force is seen like before. As the hairs  
20 detach, the array gets tilted more and more, making it less likely for the recoil  
21 length,  $\Delta l$ , to exceed  $w \sin \theta$  and detach the next adjacent hair. Thus here, we  
22 don't see any propagation of the detachment front when the leg is soft.

### 3.3. Flex

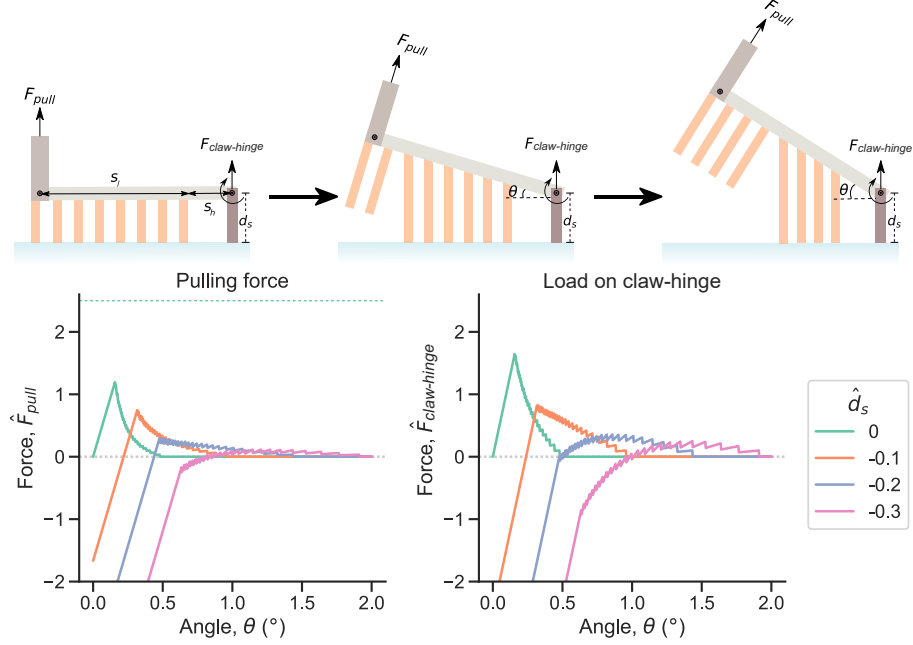


Figure 4: **Detachment by Flex.** Force curves for a fibrillar adhesive pad detached by flexing it about the claw.  $\hat{F}_{pull} = \frac{F_{pull}}{k_h w}$  is the normalised pulling force necessary to apply the moment about the claw-hinge for detachment,  $\hat{F}_{hinge} = \frac{F_{hinge}}{k_h w}$  is the normalised reaction force on the claw-hinge,  $\hat{d}_s = \frac{d_s - l_{h,0}}{w}$  is the normalized vertical distance of the claw-hinge from the surface. Here,  $s_l/L = 1$  and  $s_h/w = 10$ . The green dashed line represents the maximum possible adhesion for the pad.

Instead of a vertical pull, the adhesive pad can also be detached by rotating it about the claw-hinge, located outside the array. Such a mode of detachment will be driven by a moment applied by the leg (tibia) to rotate the pad around the claw-hinge until all the hairs lose contact. Let  $s_h$  be the distance between the claw-hinge and the right end of the array;  $s_l$  be the distance between the joint and the right end of the array. The joint is assumed to be fixed here. To illustrate the mechanism, let us fix  $s_l/L = 1$  and  $s_h/w = 10$  and vary the vertical claw-hinge distance,  $d_s$ . At any particular instant, the pulling force applied by the leg,  $F_{pull} = M_{net}/(s_l + s_h)$ , where  $M_{net}$  is obtained by setting

1  $s = -s_h$  in equation (4). Equation (1) will give us the reaction force acting on  
 2 the claw-hinge,  $F_{claw-hinge}$ .

3 Decreasing the vertical claw-hinge distance reduces the pulling force nec-  
 4 essary to undergo detachment by flexing (Figure 4). One can imagine that  
 5 initially, when the array is parallel to the surface, a lower value of  $d_s$  means the  
 6 hairs are in a more compressed state. When the pad is subsequently rotated  
 7 around the claw-hinge, the tilted array will once again lead to an *elastic weak-*  
 8 *ening* effect due to the inhomogeneous deformation of hairs. This results in a  
 9 decrease in the net moment and thus lower  $F_{pull}$  for smaller values of  $d_s$ .  $F_{pull}$   
 10 can be further reduced of course by increasing the lever arm ( $s_l + s_h$ ).

11 Detachment by flexing requires that the claw remains fixed and stable dur-  
 12 ing the process. We see that generally, the normal load, acting on the hinge,  
 13  $F_{claw-hinge}$ , follows a similar trend as  $F_{pull}$  (Figure 4). For low values of  $d_s$ ,  
 14  $F_{claw-hinge}$  goes to negative values, implying that the claw should adhere well  
 15 with the surface to resist this negative load. As the detachment progresses  
 16 however, the array starts to exert a positive load on the claw.

#### 17 4. Discussion

18 In order to characterize how a particular detachment mechanism influences  
 19 the adhesion of the pad, we introduce a parameter, *reduction factor*, defined as:

$$r = \frac{N_t f_p}{F_{adh}} \quad (7)$$

20 Here,  $F_{adh}$  is the adhesion force required to detach the pad from the surface  
 21 following a given mechanism and  $N_t f_p$  is the maximum possible adhesion of  
 22 the pad (equation (3)). Reduction factor,  $r$ , represents the extent to which the  
 23 adhesion can be reduced by choosing the mode of detachment. A large value  
 24 of  $r$  implies that adhesion can be reduced by a greater factor, and this mode is  
 25 more suitable to easily detach.

26 *Effect of  $\hat{f}_p$ :* The dimensionless parameter,  $\hat{f}_p = \frac{f_p}{k_h w}$ , governs the strength and  
 27 compliance of the array, where, high values represent a dense array of strongly

1 adhering soft hairs. Let us consider the case of an adhesive pad with  $N_t = 25$   
 2 hairs and look at how  $\hat{f}_p$  influences the reduction factor under each mode of  
 3 detachment (Figure 5).

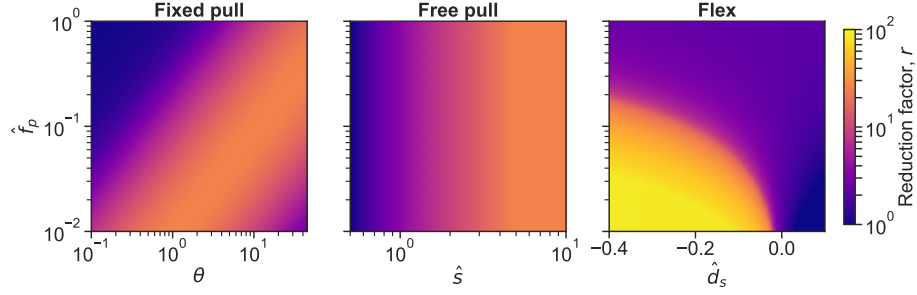


Figure 5: **Effect of  $\hat{f}_p$  on reduction factor.** Colour plots showing the effect of the dimensionless parameter,  $\hat{f}_p$ , on the reduction factor for each mode of detachment. Here, we fix the number of hairs,  $N_t = 25$ . The dimensionless parameters  $\hat{d}_s = \frac{d_s - l_{h,0}}{w}$  and  $\hat{s} = \frac{s}{L}$ , as described in text.

4 When detachment follows the *fixed pull* method (Figure 5), for a constant  $\hat{f}_p$ ,  
 5 the reduction factor increases with increasing tilt angle,  $\theta$ , and then decreases,  
 6 showing a maximum  $r$  of 25 at an intermediate  $\theta$ . Higher values of  $\hat{f}_p$  shifts this  
 7 maximum point to higher values of  $\theta$ . This trend relates to the *elastic weakening*  
 8 effect discussed before. Smaller values of  $\theta$  bring a proportion of hairs under  
 9 compression, reducing the adhesion and thus increasing  $r$ . On further tilting  
 10 the array, eventually the proportion of stretched hairs will overcome the ones  
 11 under compression, which ultimately reduces  $r$  at high  $\theta$ . When the individual  
 12 hairs show strong adhesion (i.e. for high  $\hat{f}_p$ ), a greater tilt is necessary to bring  
 13 the net adhesion of the array down.

14 For the case of detachment via *free pull*,  $\hat{f}_p$  has no influence on the reduction  
 15 factor. On the other hand, shifting the position of the joint further away from  
 16 the array (i.e. high  $s/L$ ) results in large values of  $r$ . In this scenario, the  
 17 higher moment exerted by the array leads to a higher tilt, and thus increases  
 18 the reduction factor via *elastic weakening*, saturating to the maximum value of  
 19 25.

1 For detachment by *flexing*, the reduction factor increases for higher initial  
 2 compression of hairs (low  $\hat{d}_s$ ). The pad notably shows a much higher reduction  
 3 factor at low values of  $\hat{f}_p$  and  $\hat{d}_s$ , with values as high as 100. Since this mode  
 4 of detachment is driven by moment, the pulling force necessary to provide the  
 5 moment can be decreased without any limit simply by having a long lever arm  
 6 ( $\hat{s}_l$ ), i.e., with the joint positioned farther away from the array. In contrast, for  
 7 the previous cases of *free pull* and *fixed pull*, the reduction factor is capped to  
 8 the maximum number of hairs in the array ( $N_t = 25$ ). Here, *elastic weakening*  
 9 can only reduce the array's adhesion force from  $N_t$  hairs down to a single hair  
 10 at most.

11 *Effect of  $N_t$ :* Let us now fix  $\hat{f}_p = 0.1$  and investigate the influence of the  
 12 number of hairs,  $N_t$ , on the reduction factor (Figure 6). The colour plots show  
 13 that high  $N_t$  increases  $r$  irrespective of the mode of detachment. Under a  
 14 tilted state, more hairs are compressed when  $N_t$  is high, which reduces the net  
 15 adhesion. This highlights the advantage of having a split contact design found in  
 16 many biological systems. A higher number of hairs offers a better control over  
 17 adhesion and thus is more suited for reversible attachment and detachment  
 18 during locomotion. The specific trends of reduction factor for each mode of  
 19 detachment can be understood by similar arguments of *elastic weakening*, as  
 20 discussed in the previous section.

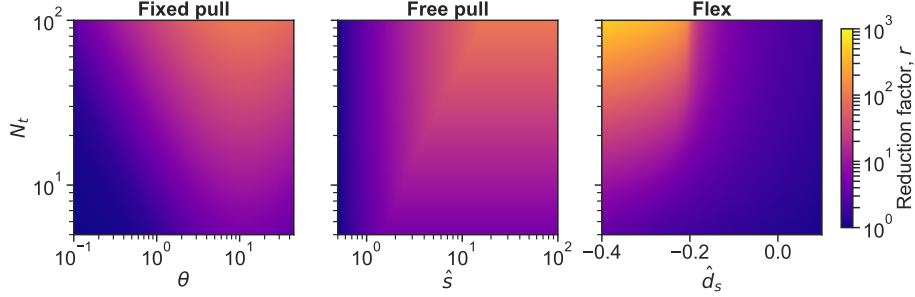


Figure 6: **Effect of  $N_t$  on reduction factor.** Colour plots showing the effect of the number of hairs,  $N_t$ , on the reduction factor for each mode of detachment. Here, we fix the dimensionless parameter,  $\hat{f}_p = 0.1$ . The dimensionless parameters  $\hat{d}_s = \frac{d_s - l_{h,0}}{w}$  and  $\hat{s} = \frac{s}{L}$ , as described in text.

Figures 5 and 6 can be combined into a single set of colour plots by defining a new dimensionless parameter,  $\chi = \hat{f}_p N_t = \frac{f_p N_t}{k_h w}$  (see Appendix A). Overall, we see that *flex* mode of detachment shows the highest reduction factor among the three modes, with the optimal value of  $\chi \sim 1$ .

*Detachment pathways:* Based on the three modes of detachment discussed in the previous sections, one can think of several strategies to detach fibrillar adhesive pads from the surface. To illustrate this, let us consider the adhesive system of a dock beetle. The beetle is known to have 3 sets of hairy tarsal adhesive pads in each of their legs, each possessing hairs of different geometries. To keep our analysis simple, we will assume each leg to have only two adhesive pads, with identical hairs of mushroom-shaped geometry. The distal and proximal pads possess roughly 500 and 1000 hairs, respectively [27]. Assuming the pads to be rectangular arrays of  $20 \times 25$  and  $40 \times 25$  hairs, we can model this as a one-dimensional system of 20 and 40 *effective hairs*, respectively, by combining the hairs along the width. Based on reported measurements [36], the beetle's *effective hair* is thus considered to have an effective pull-off force,  $f_p = 0.5 \times 25 = 12.5 \mu\text{N}$  and effective spring constant,  $k_h = 0.5 \times 25 = 12.5 \text{ N m}^{-1}$ . The beetle's hairs are approximately  $l_{h,0} = 40 \mu\text{m}$  long, spaced  $w = 10 \mu\text{m}$  apart. At end of the tarsal segments, there is a claw, around  $200 \mu\text{m}$  long, and



1 the leg (tibia) is connected roughly at the end of the proximal tarsal pad. This  
2 will put  $\hat{s}_h = 20$  and  $s_l/L = 1$ , measured relative to the right end of the distal  
3 pad. The beetle's leg is assumed to possess two joints which could serve as a  
4 hinge for rotation during detachment ( $H_1$  and  $H_2$  in Figure 7 inset). The claw  
5 can be used as an external hinge ( $H_3$ ) by flexing the tarsal pad around it.

6 Based on the above assumptions, we can come up with force-distance curves  
7 to detach the beetle's leg via various pathways (Figure 7). First, let us assume  
8 the joint  $H_2$  to be fixed, such that both the distal and proximal pads can be  
9 combined to behave like a single long pad with  $N_t = 60$  hairs. Path 1 shows  
10 the case where the pad shows maximum possible adhesion. Here, the combined  
11 pad is vertically pulled upwards while keeping the array perfectly parallel to the  
12 surface. If this combined pad is detached by keeping  $H_1$  fixed and maintaining  
13 a tilt of  $1^\circ$  with the surface (path 2), the forces dramatically reduces, with  
14 around 10 times reduction in the adhesion compared to path 1. We can also  
15 detach the pad by switching between the different mechanisms. Path 3 shows  
16 one such example, where, initially the leg is pulled vertically up while keeping  
17  $H_1$  fixed, stretching the hairs similar to path 1. On reaching point  $a$ ,  $H_1$  is set  
18 free, which results in a sudden drop in force due to the excess moment by the  
19 stretched hairs, tilting the array. Beyond this, the force curve follows the *free*  
20 *pull* mechanism, with  $\sim 3.5$  times reduction in adhesion. An alternate strategy  
21 of switching between mechanisms would be to first apply a load on the pad (path  
22 4) and compress the hairs until point  $b$ . Beyond this point, the claw can be used  
23 as a hinge to detach the pad via flexing it around  $H_3$ , which once again reduces  
24 the adhesion force. Now, if we assume the joint  $H_2$  to be free such that the two  
25 pads can behave distinctly, we can consider the scenario where the proximal pad  
26 is flexed around the distal pad at  $H_2$  while keeping  $H_1$  fixed (path 5). After the  
27 proximal pad has completely detached,  $H_1$  can be freed up at point  $c$  to detach  
28 the distal pad via *free pull* with very little force. This pathway results in a  $\sim 5$   
29 times reduction in adhesion.

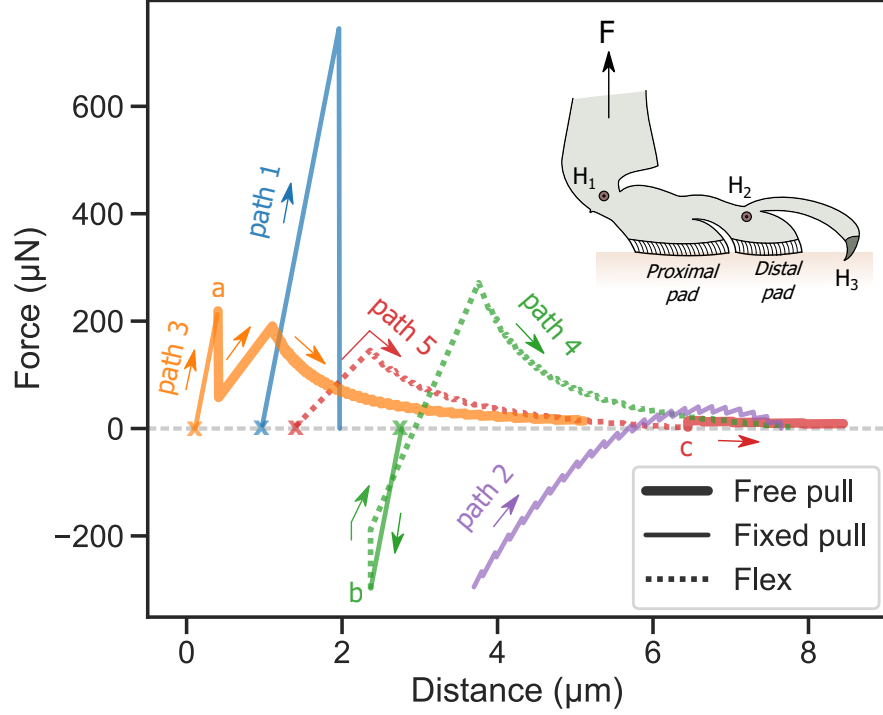


Figure 7: **Beetle leg detachment pathways.** Force curves showing the theoretical detachment pathways possible for a dock beetle's leg, as function of distance between the pad and the surface. The curves are offset laterally for clarity. Colours represent the distinct detachment pathways, labelled as path 1 to 5, with arrows indicating the direction of retraction. Points a, b and c indicate instances of switching between the different detachment mechanisms for paths 3, 4 and 5 respectively (see text for details). The different line style denotes the specific detachment mechanism followed by any region of the pathway. The inset schematic shows the assumed locations of the different joints or hinges ( $H_1$ ,  $H_2$  and  $H_3$ ) employed by the leg.

1 The above analysis illustrates how the design of the beetle's hairy adhesive  
2 pads is suitable for modulating its adhesion. Effective control and release of its  
3 joints can help the insect to reduce the pad's adhesion, allowing it to detach  
4 with little effort. High reduction in adhesion is seen when the pad is tilted  
5 relative to the surface during detachment, as a result of *elastic weakening*. To  
6 the best of our knowledge, there is no direct experimental evidence that beetles  
7 or any other animal can modulate its adhesion by taking advantage of this

1 effect. Considering that hair deformation occurs at length scales below  $10\text{ }\mu\text{m}$ ,  
 2 direct observation of this effect on running beetles would be challenging. A  
 3 recent study on PDMS micro-pillar arrays, however, does indeed show a strong  
 4 reduction in the adhesion force due to slight misalignments with the surface  
 5 [38]. Based on previously reported microscopic investigation of freely walking  
 6 dock beetles [39], we argue that the following experimental observations provide  
 7 support to our proposed model: 1) The detachment was shown to follow a  
 8 three-dimensional twist of the leg, which suggests a complex inhomogeneous  
 9 deformation of hairs across the array, leading to *elastic weakening*, which is  
 10 suited for easy detachment. Similar twisting action during detachment was  
 11 also observed in flies [40] and has been used to easily detach mushroom-shaped  
 12 artificial adhesive arrays [41]. 2) The beetle can at times instantaneously detach  
 13 all its legs and drop itself while upside down. This could be explained by the  
 14 beetle freeing up its joints and using just its body weight to provide the necessary  
 15 force to detach all its legs via *free pull* (similar to path 3 above). 3) Only a  
 16 fraction of the beetle's pads made contact with the surface during locomotion,  
 17 which indicates that the pads should naturally be in a slightly tilted state.  
 18 This not only reduces the contact area, but also non-uniformly deforms the  
 19 hairs, both leading to a reduction in adhesion for easy detachment. 4) Contact  
 20 images showed that the array *peels* from the proximal to distal direction during  
 21 detachment. However, the beetle's hairs are attached to a relatively stiff backing  
 22 [42], so it wouldn't be able to *peel* its array, since peeling, strictly speaking,  
 23 depends on the elastic contribution of a thin flexible backing as it bends during  
 24 the process [8]. Rather, the *peeling* observed in the beetle's case should be a  
 25 result of the pad detaching from the surface in a tilted orientation, causing the  
 26 hairs to distinctly detach in sequence. 5) The time scale of detachment was  
 27 reported to be an order of magnitude shorter than the attachment time scale,  
 28 which could be a result of the elastic recoil of the leg causing a spontaneous  
 29 propagation of the detachment front (Figure 2).

30 There exists a limit to how much the pad can tilt, depending on its geometry  
 31 and material properties. Suppose the hair has a maximum linear elastic strain

1 limit,  $\varepsilon_m$ , and natural length,  $l_{h,0}$ . Based on Figure 1, if the right most hair is  
 2 compressed to its elastic limit, one can derive from simple geometry, that, the  
 3 corresponding maximum limit in tilt angle is given by:

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

4  $\theta_{limit}$  will limit the reduction factor for each of the detachment mechanisms  
 5 presented. Longer hairs can result in a lateral collapse or bundling of hairs,  
 6 imposing an additional constraint on  $\theta_{limit}$ . Large deformation of hairs can  
 7 also lead to buckling, which will further limit the reduction in adhesion due to  
 8 the smaller effective modulus. Buckling could also, interestingly, promote easier  
 9 detachment in the *free pull* mode. When the compressed hairs at one end of the  
 10 array buckle, there would be an excess clockwise moment in the array system  
 11 (Figure 3). This excess moment could subsequently drive the detachment of the  
 12 remaining hairs. In the case of biological systems, the ability of an insect to  
 13 provide the load necessary to tilt and compress its hairy adhesive pad against  
 14 the surface would further introduce limitations to follow any of the detachment  
 15 modes discussed here. All things considered, the geometry and elastic properties  
 16 of the individual hairs are crucial parameters to consider in the design of an  
 17 optimal array system which shows reversible adhesion via *elastic weakening*.

18 Our analysis had been limited to normal forces during detachment. A similar  
 19 analysis considering the energy required to detach the array will however not  
 20 yield any *elastic weakening* effect. Since we had assumed a purely elastic system,  
 21 the initial and final energy of the system would be the same regardless of the  
 22 mode of detachment, and thus the work of adhesion would remain identical in  
 23 all scenarios. The reduction of adhesion force is however advantageous since an  
 24 insect wouldn't then need a strong muscular to system to detach its legs, which  
 25 are typically capable of attachment forces several times its body weight [43].

## 26 5. Conclusion

27 Inhomogeneous deformation of hairs results in significant reductions in the  
 28 adhesion of a fibrillar system similar to an insect's tarsal hairy adhesive pads.

1 Such a condition can be achieved by either 1) pulling the pad while maintaining  
 2 a constant tilt angle, 2) pulling the pad while maintaining a free tibia-tarsus leg  
 3 joint or 3) flexing the pad around the claw. Strategic control of the joint's mo-  
 4 bility or claw can allow the leg to easily switch between the above mechanisms,  
 5 thus providing a simple way to reduce adhesion as per necessity. The presence  
 6 of a deformable leg can further trigger a spontaneous propagation of hair de-  
 7 tachment due to the leg's elastic recoil, making it suitable for fast detachment.  
 8 Arrays with low  $\hat{f}_p$  and large number of hairs, with a hair geometry that allows  
 9 for large deformations while avoiding buckling and lateral bundling represent  
 10 the optimal design conditions to maximize the range of control over adhesion.  
 11 The proposed model is supported by previously reported experimental observa-  
 12 tions of leg detachment in dock beetles and highlights possible role of the joint  
 13 and claws to enable reversible adhesion. Similar strategies could potentially be  
 14 adopted in the design of bio-inspired artificial fibrillar adhesives to easily switch  
 15 the adhesion state without the need of asymmetric structures.

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## 1 Appendix A. Reduction factor: master plot

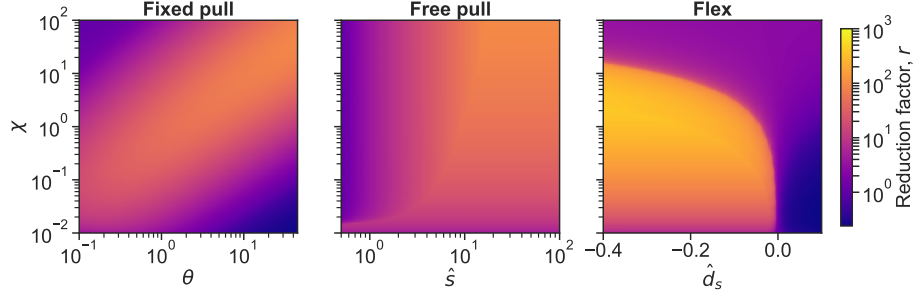


Figure A.1: **Effect of  $\chi$  on reduction factor.** Here, we define a unified dimensionless design parameter  $\chi = \frac{\hat{f}_p N_t}{k_h w}$ , combining  $\hat{f}_p$  and  $N_t$  into a single number. The dimensionless parameters  $\hat{d}_s = \frac{d_s - l_{h,0}}{w}$  and  $\hat{s} = \frac{s}{L}$ , as described in text.

## 2 Appendix B. Derivations

Suppose at a particular instant (Figure 1), there are  $n$  hairs in contact with the surface. The centre of the region of the array in contact is at a vertical distance,  $d'$ , from the surface. The net force on the whole array is,

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

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

$$F_{net} = nk_h (d' - l_{h,0})$$

From geometry,  $d_s$  and  $d'$  is related as:

$$\frac{d_s}{\sin \theta} - \frac{d'}{\sin \theta} = s - \frac{(n-1)w}{2}$$

Substituting for  $d'$ , the net force,  $F_{net}$ , on the pad as a function of distance,  $d_s$ , is:

$$F_{net} = nk_h \left[ d_s - l_{h,0} - \left[ s - \frac{(n-1)w}{2} \right] \sin \theta \right]$$

1 The above equation is valid for  $d_s \leq d_{s,max}$  at a particular value of  $n$ . We  
2 can get  $d_{s,max}$  by considering the situation just before the left most hair is about  
3 to detach (Figure 1). This hair will be at its maximum length,  $l_{h,p}$ . Once again  
4 from geometry, we see that  $d_{s,max}$  and  $l_{h,p}$  is related as:

$$\frac{l_{h,p}}{\sin \theta} - \frac{d_{s,max}}{\sin \theta} = (n-1)w - s$$

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

$$d_{s,max} = l_{h,0} + \frac{f_p}{k_h} + [s - (n-1)w] \sin \theta$$

6 The net moment about the joint due to the deformed hairs of the array is,

$$M_{net} = \sum_{i=1}^n \lambda_i k_h (l_{h,i} - l_{h,0}) \cos \theta$$

7 Here,  $\lambda_i = s - \left(\frac{n-1}{2}w - \frac{x_i}{\cos \theta}\right)$  is the length of the lever arm between the  $i^{th}$   
8 hair and the joint.

9 Substituting for  $l_{h,i}$  and eliminating  $d'$  as before, we get:

$$M_{net} = \sum_{i=1}^n k_h \cos \theta \left[ s - \left( \frac{n-1}{2}w - \frac{x_i}{\cos \theta} \right) \right] \left[ d_s - \left( s - \frac{(n-1)w}{2} \right) \sin \theta - x_i \tan \theta - l_{h,0} \right]$$

10 To calculate  $\sum_{i=1}^n x_i^2$ , we follow:

$$\sum_{i=1}^n x_i^2 = 2 \sum_{i=1}^{\frac{n}{2}} x_i^2 = 2 \sum_{i=1}^{\frac{n}{2}} \left[ w \cos \theta \left( i - \frac{1}{2} \right)^2 \right] = 2w^2 \cos^2 \theta \left[ \sum_{i=1}^{\frac{n}{2}} i^2 - \sum_{i=1}^{\frac{n}{2}} i - \sum_{i=1}^{\frac{n}{2}} \frac{1}{4} \right]$$

11 Using the identities  $\sum_{i=1}^N i^2 = \frac{N(N+1)}{2}$  and  $\sum_{i=1}^N i = \frac{N(N+1)}{2}$  and simpli-  
12 fying, we get  $\sum_{i=1}^n x_i^2 = n \left( \frac{n^2-1}{12} \right) w^2 \cos^2 \theta$ . This, together with  $\sum_{i=1}^n x_i = 0$  (by  
13 symmetry), the expression for  $M_{net}$  above can be simplified to finally get:

$$M_{net} = n k_h \cos \theta \left[ (d_s - l_{h,0}) \left[ s - \frac{(n-1)w}{2} \right] - \left\{ \left[ s - \frac{(n-1)w}{2} \right]^2 + \frac{n^2-1}{12} w^2 \right\} \sin \theta \right]$$

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