Sliding-induced non-uniform pre-tension governs robust and reversible adhesion: a revisit of adhesion mechanisms of geckos

Q. H. Cheng1, B. Chen1, H. J. Gao2 and Y. W. Zhang1,*

1Department of Engineering Mechanics, Institute of High Performance Computing, Singapore 138632, Singapore
2School of Engineering, Brown University, Providence, RI 02912, USA

Several mechanisms have been proposed in the literature to explain the robust attachment and rapid, controllable detachment of geckos' feet on vertical walls or ceilings, yet, it is still debatable, which one is ultimately responsible for geckos’ extraordinary capabilities for robust and reversible adhesion. In this paper, we re-examine some of the key movements of geckos’ spatula pads and seta hairs during attachment and detachment, and propose a sequence of simple mechanical steps that would lead to the extraordinary properties of geckos observed in experiments. The central subject under study here is a linear distribution of pre-tension along the spatula pad induced by its sliding motion with respect to a surface. The resulting pre-tension, together with a control of setae’s pulling force and angle, not only allows for robust and strong attachment, but also enables rapid and controllable detachment.

We perform computational modelling and simulations to validate the following key steps of geckos’ adhesion: (i) creation of a linear distribution of pre-tension in spatula through sliding, (ii) operation of an instability envelope controlled by setae’s pulling force and angle, (iii) triggering of an adhesion instability leading to partial decohesion along the interface, and (iv) complete detachment of spatula through post-instability peeling. The present work not only reveals novel insights into the adhesion mechanism of geckos, but also develops a powerful numerical simulation approach as well as additional guidelines for bioinspired materials and devices.

Keywords: geckos’ spatula; pre-tension; adhesion and detachment; instability; peeling-off

1. INTRODUCTION
With an aim to reveal the mechanical principles of biological materials as well as to discover new routes to make novel bioinspired materials and devices with superior properties, researchers have devoted a great deal of attention to geckos’ extraordinary abilities to climb on walls and run on ceilings. Owing to the complex hierarchical structures of geckos’ toes, as shown in figure 1, a complete understanding of the underlying controlling mechanisms has not yet been achieved. A gecko’s toe consists of hundreds of thousands of seta hair in the micro-scale, and each seta in turn contains hundreds of spatula pads in the nano-scale. It is believed that this naturally evolved hierarchical structure enables geckos to accommodate surfaces with various scales of roughness. Through extensive research in recent years, important progresses have been made in understanding the physical nature of the adhesive force exerted by geckos [1–5], the microstructures and associated functions of geckos’ feet [6–10], the effects of surface roughness [11–15] and the roles of multi-level hierarchical structures in gecko adhesion [12,14,16,17]. In addition, inspired by gecko adhesion, several new materials with novel and enhanced properties have been developed [18–28]. Over the years, the mechanisms underlying gecko attachment and detachment have been intensively debated. Several mechanisms have been proposed and rejected, including suction, secretions, electrostatic attraction, friction and microinterlocking [2]. Recent experiments have suggested that gecko adhesion primarily arises from van der Waals interaction [1,29]; while capillary forces might also play a significant role [30].

It is known that the hierarchical structures on geckos’ feet operate in an elaborate and cooperative manner. It was observed that during the initial contact with an external surface, geckos’ toes roll down and slide inward along the surface [2,5]. This action helps to orient and preload setae as well as spatulas, and apparently plays a critical role in switching on the

*Author for correspondence (zhangyw@ihpc.a-star.edu.sg).
adhesion. On the other hand, it was found when a gecko detaches its feet from the surface, its toes would hyperextend and bend backward to peel away from the substrate, more like peeling Scotch tape than detaching a solid body [8,31]. In order to understand the effects of orientation and preloading of setae during attachment and detachment, a single seta was examined experimentally by using a micro-electromechanical force sensor [1,2,31]. Preloading the seta by pulling it parallel along a substrate surface was found to strengthen its adhesion by more than 10 times. Interestingly, the strongly adhering seta could be readily peeled off by just changing its orientation with respect to the substrate, with a critical angle for detachment occurring at about 30°.

In spite of the successful investigations on setae, studies of spatulas, the bottom level in the hierarchical structure on geckos’ toes, proved to be more difficult, as its nano-scale structure is accessible only with advanced experimental techniques such as scanning electron microscopy (SEM) [1], transmission electron microscopy (TEM) [11] and atomic force microscope (AFM) [32]. Nevertheless, the adhesion force of a single spatula has been measured to be approximately 10 nN using AFM [32].

A quantitative analysis of spatula adhesion and detachment was conducted by Chen et al. [33]. To explain experimental observations, they demonstrated that a high level of pre-tension in the spatula pad can be established during its contact with a surface. Chen et al. performed theoretical analysis and numerical simulation to study the effect of a constant pre-tension along the spatula pad on its detachment force and angle, and explained several important observations such as strong adhesion, ready detachment and the existence of a critical angle for detachment, consistent with the experimental observations.

While successful in explaining some of the important observations, the constant pre-tension model proposed by Chen et al. [33] is unable to address other issues in spatula adhesion and detachment. In measuring spatula adhesion force [32], a shearing movement of the spatula parallel to the substrate surface was performed. This shearing was believed to be responsible for the generation of a pre-tension in the spatula, as demonstrated in Chen et al. [33]. However, the distribution of pre-tension along the spatula is still unknown. Another issue is the transition between adhesion and complete detachment. As discussed above, it was observed that geckos’ toes roll down and slide inward along the surface to generate adhesion, while they hyperextend and bend away from the surface during detachment. These movements seem to suggest that the detachment is not instantaneously completed as predicted by the constant pre-tension model [33], but may involve a series of transitions from the fully pre-tensioned state to an intermediate partially relaxed state, and then to complete detachment through stable peeling.

By re-examining the movements of geckos’ toes during attachment and detachment, we propose a non-uniform pre-tension model of the robust and reversible adhesion of geckos. We perform both computational and analytical modelling to support and validate the proposed model, and show that the model is not only able to explain the observed strong adhesion, ready detachment as well as the critical angle for detachment, but can also reproduce the detailed movements of geckos’ feet observed in experiments.

2. MODEL FORMULATION

Based on experimental observations of geckos [1], we consider a spatula pad interacting with a substrate through van der Waals forces. From the observed movements of geckos’ feet during adhesion and detachment, we propose the following hypotheses for the spatula to adhere and detach from a substrate, as illustrated in figure 2:

— when a gecko approaches a surface, its toes stretch and the setae move outward, which then pull the spatula pads. As a consequence, the pads slide and spread on the substrate. The above process produces a linear distribution of tension, referred to as pre-tension, and stores elastic strain energy in the pad. Concurrent with the generation of the linear tension in the pad is a constant shear tension along the adhesion interface;

— when the gecko walks or runs, it controls the force magnitude and angle of its toes and setae to create a mechanical instability by releasing the stored elastic energy in the pad, leading to partial detachment of spatula from the substrate.
— finally, when the gecko’s toe bends backward, its setae rotate and pull the spatula pads at a larger angle to facilitate complete detachment.

To prove and validate the above hypotheses, we study the whole adhesion and detachment cycle of the spatula pad as shown in figure 2. We consider a simulation model including a spatula pad, a substrate and an adhesion interface under plane-strain conditions (figure 2). The spatula is modelled as a linear-elastic material while the substrate is assumed to be rigid. A simple triangular traction–separation relation between the spatula pad and substrate as shown in figure 3 is employed to model van der Waals interactions. Under pure normal loading (figure 3a), the critical normal traction is \( f_n \) and the cut-off separation distance (beyond which no interaction is allowed) is \( \delta_c \). Under pure shear loading (figure 3b), the critical shear traction is \( \tau_c \) and the cut-off separation distance is assumed to be also \( \delta_c \). The normal traction \( f \) and shear traction \( \tau \) follow the following relations:

\[
f = \begin{cases} \frac{\delta}{\delta_0} f_n, & 0 \leq \delta \leq \delta_0 \\ \frac{\delta - \delta_0}{\delta_0} f_n, & \delta_0 \leq \delta \leq \delta_c \end{cases}
\]

and

\[
\tau = \begin{cases} \frac{\xi}{\delta_0} f_n, & 0 \leq \xi \leq \delta_0 \\ \frac{\xi - \delta_0}{\delta_0} f_n, & \delta_0 \leq \xi \leq \delta_c \end{cases}
\]

(2.1)

where \( \delta \) and \( \xi \) are the separation and slippage of the cohesive element, respectively, and \( \delta_0 = \delta_c / 2 \).

In the present work, four different types of simulations were carried out, as described below. More details are available in the electronic supplementary material. Type I simulations study the formation process of a linearly distributed pre-tension in the spatula, i.e. figure 2a. Figure 4 illustrates the force equilibrium in the spatula pad at a typical time during the pre-tension formation. We define three zones along the spatula, i.e. figure 2.

Figure 2. Schematic of a sequence of movements of geckos’ setae and spatula pads during attachment and detachment: (a) with a sliding motion on substrate, a seta moves outward and stretches the spatula pad; (b) as a result, the spatula pad, with a linear pre-tension in it, spreads on the substrate, forming van der Waals adhesion along the interface; (c) instability takes place by tuning the pulling force and angle of the setae, breaking portion of the adhesion; (d) finally, when pulled at a larger angle through the hyperextension of the gecko’s toe, the spatula pad is peeled off completely from the substrate. (Online version in colour.)

Figure 3. Traction–separation relations under (a) normal and (b) shear loadings. The shaded areas represent the energies \( \gamma_t \) owing to normal traction and \( \gamma_s \) owing to shear traction, respectively, at a specific time \( t \). (Online version in colour.)

Figure 4. Force equilibrium in a spatula pad. (Online version in colour.)

where \( F_z \) is the normal traction integrated over a range from point A to C in figure 4. For given values of \( f_n \) and \( \delta_c \), \( F_z \) will increase with reducing angle \( \theta \). To facilitate discussion in the following, we define the normalized pre-tension as \( \sigma_0 / E = P_0 / EH \).

The formation of adhesion was conducted in an incremental manner. To advance adhesion by a small
amount under a linear distribution of pre-tension, we adjust the loading at the end D through a combination of a small increase of pulling force $P$ and a small decrease of pulling angle $\theta$. The mechanical equilibrium state is found when point B touches the substrate, at which the length AB joins the adhesion zone OA and point B becomes the new adhesion front. We proceed to the next step, and the simulation cycle is repeated until the whole spatula is fully adhered on the substrate as illustrated in figure 2b. Considering force equilibrium, the left end O has zero pre-tension, the right end A has the maximum pre-tension $P_0$ and a linearly distributed pre-tension is established in between: accordingly a constant shear force exists along the adhesion interface.

Type II simulations aim to investigate the stability of the adhered spatula with a linear pre-tension, i.e. configuration in figure 2b. Note that equilibrium of the configuration relies on the pulling force $P$ and angle $\theta$. The observed movements discussed in the introduction suggest that these two parameters can be used to control the detachment. We have studied the effects of magnitude and angle of the pulling force on the stability of the spatula, and identified the conditions for the instability. To obtain in-depth understanding, configurations with various spatula lengths and pre-tension distributions have been considered.

Type III simulations aim to obtain the configurations followed by the instability studied in type II simulations. For a gecko to move, its toes need to change from inward gripping to outward extending. Since these two states yield opposite stretching forces, there would be an instant at which there are no stretching forces on the seta. Hence, we consider the case in which the pulling force at the right side is fully relaxed, as shown in figure 2c. As the pulling force $P$ vanishes, the pre-tension in the spatula would be re-distributed and portion of the stored elastic energy in the spatula would be released. The released elastic energy serves as the driving force to detach the pad partially along the interface. We again consider the effect of various spatula lengths and pre-tension distributions.

Finally, type IV simulations study the detachment of the spatula from the state after the instability. A pulling force is applied again at the right end of the spatula, representing being stretched by the seta. By changing the pulling angle, various peeling forces can be obtained for a configuration with specific spatula length and pre-tension. The relationships between the pulling force and angle for various configurations are analysed.

All simulations were conducted using the commercial finite-element code ABAQUS [34]. The spatula pad is modelled by membrane elements. The cohesive interactions between the spatula pad and the substrate are considered as an adhesion layer modelled by the Cohesive Element in ABAQUS. (see the electronic supplementary material for more details).

The following values of system parameters are used in the simulations [33]. The spatula pad is considered to be 200 nm long, 100 nm wide and 5 nm thick (figure 1). The spatula’s Young’s modulus $E = 2$ GPa, thickness $H = 5$ nm and length $L$ lies in a range 100–300 nm. The cut-off distance for both normal and shear cohesive interactions is taken to be $\delta_c = 1$ nm. The peak traction for both normal and shear cohesive interactions is set at $f_c = \tau_c = 20$ MPa. Integration of the traction–separation relation gives an adhesion energy $\gamma = 0.01$ N m$^{-1}$. It should be noted that the thickness of a spatula is typically in the range 5–20 nm, and a change in the spatula thickness may affect the adhesion strength between the spatula and substrate surface [35].

3. RESULTS AND DISCUSSIONS

3.1. Formation of linear pre-tension in spatula pad

In type I simulations, initially an arbitrary value is assigned to the angle $\theta$, which also serves as an upper bound. The angle will be readjusted to the initial value if the relationship $\tan \theta = P_y/P_x$ yields a larger angle. Here, an initial value of 30° is used. Subsequently, the angle $\theta$ gradually decreases while both forces $P_x$ and $P_y$ increase, with $P_x$ increasing more than $P_y$ (see a detailed description in the electronic supplementary material). It is noted that the variation of the horizontal force $P_x$ determines the distribution of pre-tension in the spatula pad, while the
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Figure 7. Stability envelopes of magnitude and angle of the pulling force under various pre-tensions in the pad, (a) for $P_0/\omega H = 0.1$, (b) for $P_0/\omega H = 0.07$ and (c) for $P_0/\omega H = 0.04$ and $P_0/\omega H = 0$, $L = 200$ nm. (a,b) Squares with dashed line, $L = 200$ nm; circles with dashed line, $L = 300$ nm; solid line, Chen et al. [33]. (c) Squares with dashed line, $L = 200$ nm $P_0/\omega H = 0.04$; solid line, Chen et al. [33] $P_0/\omega H = 0.04$; triangles with dashed-dotted line, $L = 200$ nm; $P_0/\omega H = 0$; dashed line, Chen et al. [33] $P_0/\omega H = 0$. (Online version in colour.)

gradient of pre-tension along the $x$-axis yields the shear traction in the adhesion layer. Figure 5 shows the calculated distribution of both pre-tension in the spatula and shear traction along the interface. Results of two lengths are shown, i.e. $L = 100$ nm and 200 nm, respectively. It can be seen that the pre-tensions have approximately linear distributions, and the shear tractions can be considered nearly constant. From a physical point of view, the formation of linear pre-tension in the spatula pad could be understood from the fact that the shear traction along the interface should be approximately equal to the critical shear strength of the interface during sliding, and an approximately constant shear would immediately lead to a linearly distributed pre-tension from simple mechanical equilibrium.

The normalized peak values of pre-tension are $\sigma_0/E = P_0/\omega H = 0.087$ for the 100 nm spatula and 0.1204 for the 200 nm spatula, corresponding to normalized average shear force $\tau/\tau_c = 0.435$ for the 100 nm spatula and 0.301 for the 200 nm spatula.

Figure 6 shows the variation of pulling angle $\theta$ as the adhesion progresses. In the early stage, the angle remains at 30°. This is because the vertical force $P_z$ has a value determined by the normal traction force $f$, but the horizontal force $P_x$ is still very small in equilibrium with a small adhesion length. So a larger angle is calculated from the relationship, $\tan \theta = P_z/P_x$, and the angle is readjusted to the initial value of 30°. In the next stage, the angle decreases abruptly as the rapidly growing adhesion length demands a horizontal force $P_x$ to increase faster than the vertical force $P_z$. As the angle reduces, the force $P_z$ increases accordingly. In the final stage, the adhesion grows to a level at which the remaining cohesive-free zone becomes very small, leading to a very low vertical force $P_z$. As a result, the angle reduces rapidly to zero, indicating full adhesion of the spatula pad.

3.2. Stability envelope with linear pre-tension

Once the spatula adheres to the substrate, it is important to examine its mechanical stability. In reality, its stability is dictated by a variety of factors, such as the pulling force and angle exerted by the seta, the pre-tension $P_0$ and length $L$ of the spatula. Figure 7 shows the envelope of the magnitude and angle of the seta’s pulling force for stable adhesion at four different levels of pre-tension, i.e. $P_0/\omega H = 0.1$, 0.07, 0.04 and 0, respectively, and three different values of spatula length, i.e. $L = 100$, 200 and 300 nm. If a combination of the magnitude and angle of the pulling force is within the envelope surrounded by the curves and vertical axis, the adhesion remains intact; otherwise
the adhesion becomes unstable. For the cases of \( \frac{P_0}{EH} = 0.1 \) and 0.07, the envelopes possess both an upper bound and a lower bound. This means that a sufficiently high pulling force would pull the spatula away from the substrate and break the established adhesion. On the other hand, a sufficiently low pulling force would lead to the release of pre-tension in the spatula to break the established adhesion. For the cases of \( \frac{P_0}{EH} = 0.04 \) and 0, the envelopes only possess an upper bound. The absence of a lower bound is due to the fact that the pre-tension in the spatula is insufficient to break the established adhesion even if the pulling force is reduced to zero.

The simulation results can be compared with the analytical solution developed by Chen et al. [33], which is related to the present case of a linear distribution of pre-tension in the electronic supplementary material. It is found that when the spatula length increases, the simulation results approach the analytical solution. This is expected since the analytical analysis assumes an infinitely long spatula.

### 3.3. Adhesion after instability

The above results demonstrate that spatula adhesion is stable if the magnitude and angle of the pulling force fall in the stability envelope. Next, we will study the adhesion instability if the pulling force \( P \) is fully relaxed. Figure 8 shows the redistributed tension in the spatula and the redistributed shear traction along the interface after the adhesion becomes unstable. Results of two levels of pre-tension, \( \frac{P_0}{EH} = 0.1 \) and 0.07, and three values of spatula length, \( L = 100, 200 \) and 300 nm, are presented. The state of force equilibrium becomes complicated compared with the original state of force equilibrium: a linear pre-tension in the spatula and constant shear traction along the interface. Now distributions of both the pre-tension and shear traction fall in three characteristic regimes along the spatula length. Beginning from the spatula tip on the left end, there is a zone in which the pre-tension linearly increases while the shear traction is maintained constant, indicating that the adhesion remains intact. Beginning from the right end, there is a zone in which both pre-tension and traction vanish, and hence the adhesion has been completely destroyed. Between these two zones is a transition zone, in which both pre-tension and shear traction change drastically as shown in figure 8. In the case of \( \frac{P_0}{EH} = 0.1 \), the maximum normalized pre-tension is 0.0252 for \( L = 100 \) nm, 0.0317 for \( L = 200 \) nm and 0.0352 for \( L = 300 \) nm. In the case of \( \frac{P_0}{EH} = 0.07 \), the maximum pre-tension is 0.0347 for \( L = 200 \) nm. Integrating the pre-tension over the spatula length, we obtained the residual elastic energy density (per unit volume) in the spatula is 20.8, 22.1 and 22.5 MPa for \( L = 100, 200 \) and 300 nm, respectively, with \( \frac{P_0}{EH} = 0.1 \), and 32.1 MPa for \( L = 200 \) with \( \frac{P_0}{EH} = 0.07 \). It is evident that the residual elastic energy is insensitive to the change in spatula length.

Figure 9 shows the residual length of adhesion after instability versus initial pre-tension \( \frac{P_0}{EH} \) for spatula lengths \( L = 100, 200, 300, 400, 500 \) and 600 nm. Here, we report two findings. First, when the initial pre-tension \( \frac{P_0}{EH} < 0.0447 \), the adhesion is stable irrespective of the spatula length; this is consistent with the analysis by Chen et al. [33]. Second, when the spatula length increases, the curves of the stable

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length versus the initial pre-tension converge to a limiting case corresponding to a spatula of infinite length.

3.3. Complete detachment

Next, we study the final peeling off from the substrate after the adhesion instability. This is to mimic the process in which the gecko fully detaches from a surface by hyperextending and bending the toes away from the surface, thereby peeling off the seta as well as spatulas from the substrate. We compute the peeling-off forces with specific peeling angles. Figure 10 shows the envelopes of peeling force versus peeling angle for detaching the spatula from the substrate after instability. Here, we report four findings. First, a gecko can choose different methods to detach from the substrate, e.g. with a high force but a low angle, or a low force but a high angle. It is seen from figure 10 that the peeling force can be abruptly reduced by increasing the angle, indicating that the angle rotation is the most effort-saving way to complete the detachment. Second, when the angle is larger than 20°, the peeling force becomes insensitive to the pre-tension. Third, when the peeling angle is lower than 20°, the required peeling force increases with increasing magnitude of pre-tension, but becomes saturated when \( P_0/EH > 0.07 \). Finally, the envelopes depend on the pre-tension, but not on the spatula length. For a constant pre-tension, the envelope remains almost the same, irrespective of spatula length.

4. DISCUSSION

Our simulation results indicate that when a gecko grabs a substrate and retracts its toes, a non-uniform pre-tension can be developed in the spatula pads. To the best of our knowledge, our study is the first to quantitatively demonstrate the generation of a linear pre-tension and subsequently investigate its effects on gecko adhesion. Our analysis shows that the adhesion stability of a spatula pad on a substrate is governed by the magnitude and the angle of the pulling force operated by the seta. When the force is too high or too low or the angle is too large, an adhesion instability occurs and portion of the spatula pad adhered on the substrate would be released. This analysis is consistent with the observation that the available adhesion and friction forces of the gecko’s toe could be much higher than the gecko’s body weight [2].

Our analysis of the adhesion instability owing to seta relaxation is another important contribution of the present paper. We have also studied a complete detachment of the spatula pad from the substrate after adhesion instability occurs, which provided an explanation why geckos’ toes would hyperextend and bend away from the surface during detachment.
Interestingly, we find that the peel-off force is independent of the pad length, which is consistent with the classical peeling model of Kendall, and is also independent of the pre-tension if the peeling angle is greater than approximately 20°. The present work reveals a more complete picture of gecko adhesion than those in the existing literature. The extensive results of several types of simulation may enlighten experimentalists to perform corresponding tests on gecko adhesion and detachment, and provide hints to materials engineers to seek design strategies for the innovation of new adhesive materials.

In the present work, a simple triangular traction–separation relation is used to describe the adhesion between the spatula and the substrate surface. A previous study showed that the form of the traction–separation relation may have significant effect on the adhesion strength between the cell membrane and extracellular matrix (ECM) substrate [36]. However, if the cohesive energy and the maximum traction are fixed, the shape of the traction–separation relation plays an insignificant role in interface decohesion [37]. Our current model of the spatula pad may be further extended by incorporating upper-level structures such as setae and toes. To do so, we may need to consider other effects such as more realistic geometry of the toes and the crowding effect owing to the high seta density [38].

5. CONCLUSION

In this work, we have presented a holistic model that accounts for experimentally observed adhesion and detachment behaviour of geckos’ spatulae. Four-types of simulations have been performed to mimic the sliding-induced formation of a linear distribution of pre-tension in the spatula, to study the stability of the resulting adhesion, to examine the post-instability adhesion and finally to examine the mechanism of complete detachment. Theoretical consideration has also been provided for additional support. We have shown that sliding would create a linearly distributed pre-tension inside the spatula adhering on a substrate. We have also shown that, by controlling the magnitude of peeling force and angle, the adhesion could be partially relaxed and that, to complete the detachment, geckos can simply apply a larger peeling angle under a relatively small force. Our work not only provides new insights into gecko adhesion and detachment, but also reveals a possible route to design bioinspired adhesive materials and devices.

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