How a Gecko Sticks to a Wall

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Abstract

Aristotle observed that geckoes not only climbs trees, they can run in downward direction, or even horizontally across. The source behind the gecko's amazing ability to climb has been found to be London dispersion forces generated by extremely close contact to a the wall from micro-fine hairs (setae) ending in keratinous tips (spatulae). Literature values indicate that a gecko with a total footpad area of 4 cm^2 can produce 88N of adhesive force, enough to support many times its body weight. We examine several reasons for this seemingly generous endowment from nature. The physical details of the gecko's adhesive ability are analyzed: the contact area of individual spatulae is deduced from electron micrographs, the theoretical packing arrangement is deduced statistically. Using a Hamaker constant of 10^{-19} J for keratin, we determine the nominal and maximal adhesive force generated. Finally, we examine the feasibility of learning from this marvel of evolution to create a device that will allow us to have superhero powers and climb walls like Spiderman.

Introduction

Geckoes are able to stick onto almost any surface on land and underwater by producing a bonding attraction using the van der Waals force. The ability for geckoes to climb on surfaces is important for their survival. Climbing gives the gecko a competitive advantage over other animals when looking for food. Most geckoes hunt for flying inserts from trees and suck the secretion off tree bark. Climbing also gives them another means of escaping from ground predators such as snakes.

A gecko can generate enough adhesive force to support 40 times its body weight. This appears to be an extremely large safety factor for the gecko.

We hypothesize that the gecko does not really have such a large overbuild once we examine the challenges posed by its environment. We examine how nature has evolved mechanisms to help the gecko cope with all the challenges in its habitat.

Background

Gecko skin is a three-level hierarchy seemingly designed by nature to make intimate contact with a surface. The hierarchy begins with lamellae, the soft ridges that compress easily so that contact can be made with rough, bumpy surfaces such as tree bark or rock faces. The lamellae can be seen to compress when the gecko climbs up a sheet of glass.

Embedded in the lamellae are setae, tiny curved hairs with the length of 30 to 130 μm (the width of two human hairs). The setae are curved so they compress more easily than a straight hair would. The setae conform to microscopic pits on a surface.

The end of the setae is tipped with 400 to 1000 spatulae. The spatulae are incredibly small, having a contact surface of 0.2 μm x 0.3 μm. They come within 1Å though typically 3Å close to a surface. And distance beyond tens of Å fails to generate any significant van der Waals force.

Despite the remarkable ability of the gecko skin to conform to large and microscopic texturing of a surface, we will examine the environmental factors that work to diminish the ideal contact surface, and any known workarounds nature has provided for the gecko.

Methods

We analyze the gecko's wall-climbing ability by looking at gecko skin from three levels of a hierarchy: lamellae, setae, and spatulae. We examine the effect of the gecko's walking motion and the effect of debris and uneven surfaces as we explore the levels of the hierarchy. We begin by examining the gecko foot motion as it climbs.

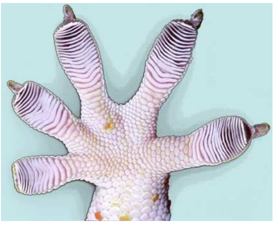
Gecko Foot Motion

The gecko utilizes a peculiar walking motion to attach itself to a surface. By directly affecting the manner in which the lamellae are placed onto a surface, the gecko causes a cascade of forces down the hierarchy until the spatulae reach the optimal angle.

Lamellae

When we observe a gecko walking on glass, we can see that lamellae (ridges) on the bottom of its feet deforming significantly. We can infer that the deformation process will also occur when the gecko is climbing a tree. It appears that the ridges are designed to give the gecko the greatest contact with a surface.

The gecko first uncurls its toes as it places a foot onto the wall. This spreads out the lamellae and maximizes the interface between lamellae and the tree. As the foot is placed down, additional downward pressure is exerted to allow the lamellae to fit into the uneven bumps in the surface.



Tokay Gecko foot

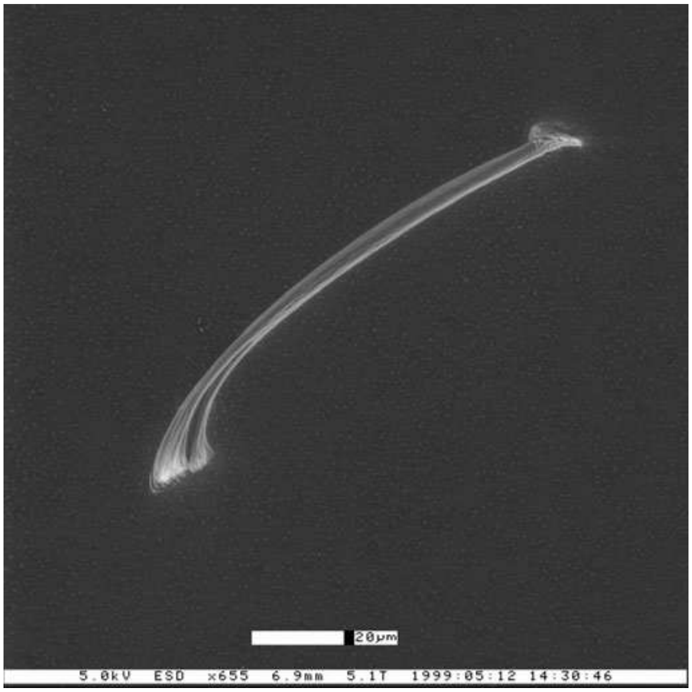
The lamellae are aligned perpendicular to the length of its body. The adhesive force generated by a foot is greater than the strength of the gecko. So, during detachment, the gecko raises its heel, causing the lamellae to form a 30° angle with the surface[1]. Once the 30° angle is reached, the spatulae automatically detach. By having the lamellae detach one row at a time, the gecko can detach its foot with very little overall effort.

Setae

For the gecko to generate an adhesive force, its toes must be placed at a proper angle, and pressure applied so setae can bind. The setae resemble long, curved hairs and are constructed of keratin. Liang[2] proposes that setal hairs deform under modest loads:

> "The compliant setal structure can conform to the topography of a surface to form large area of very intimate contact, which increases the magnitude of van der Waals forces."

[1] Autumn, Adhesive force of a single gecko foot-hair.
[2] Liang, Adhesion Force Measurements on Single Gecko Seta



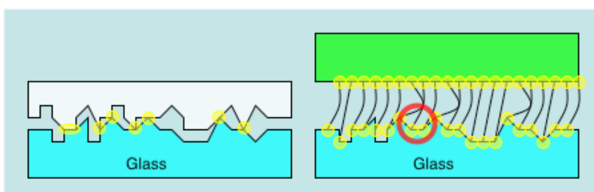
Measurements

$L_M = 111.1\mu m$

$D = 5.0\mu m$

There are several reasons for the curvature of gecko setae:

1. A curved keratinous cylinder will compress significantly more than a straight cylinder of the same diameter and length.
2. Setae hairs need only bend a fraction of their length to maintain complete contact with a rough surface.



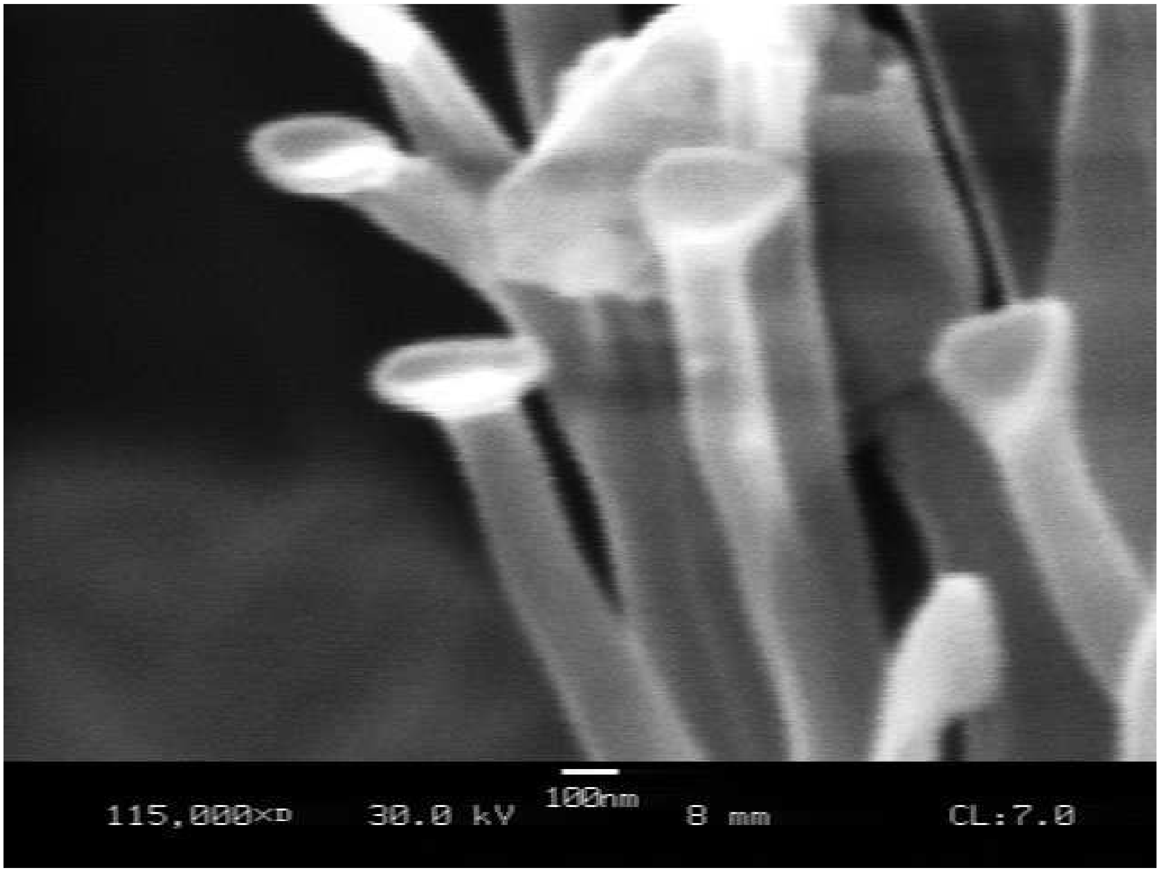
3. The compression only becomes ineffective if the setae are deformed to the point that the spatulae no longer mate with the surface.
4. Mother nature uses straight cylinders (elephant or human femur) where non-compressibility is needed, and curved cylinders (ribs) where compressibility is needed.
5. Finally, surface irregularities that are greater than the setae's feasible maximum are already taken care of, by lamellae in the previous section.

From our calculations (see appendix), the gecko only needs 0.3 N to compress 5% of its contacting setae a distance of $1\,\mu m$.

Since we have established that setae are likely compressible, then we can assume the lamellae, setae, and spatulae work in conjunction to resolve the visible and microscopic irregularities on a surface.

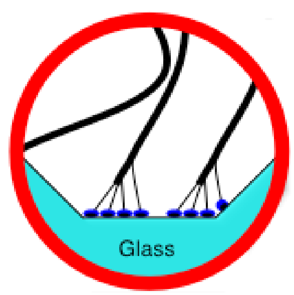
Spatulae

It is at the level of spatulae that the van der Waals forces come into play. At the tip of each seta are 400 to 1000 spatulae (average 700 spatulae).



Measurements: $L = 0.3\mu m, W = 0.2\mu m$

When the spatulae are placed at a certain angle and pressure against a surface, van der Waals forces spontaneously form and the spatulae bond to the surface. This attraction force is approximately 194 micro Newtons per seta.[3]



[3] Liang, Adhesion Force Measurements on Single Gecko Seta

Brief Introduction to van der Waals Forces

The van der Waals forces actually comprise of three related phenomenon[4]:

1. Keesom force between two permanent dipole moments
2. Debye force between a permanent dipole and non-polar molecules
3. London dispersion force between non-polar molecules – the predominant force[5], used in our calculations.

In the London dispersion force, uneven charge distributions lead to dipole moments (for any arbitrary molecule, the electron charge distribution will fluctuate around the average coordinates). When the fluctuation leads to an asymmetric charge distribution, the molecule is said to have acquired a dipole moment. As this molecule approaches another, its dipole moment induces a corresponding dipole moment on the neighboring molecule, and the result is a net attraction.

Liang states that the Hamaker constant (see Appendix) is in the order of $\approx 10^{-19}\,\mathrm{J}$, and does not change much from material to material, we follow his assumption.

$$F_{\mathrm{vdW}} = \frac{H}{6\pi D^3}$$

The typical separation distance is 3Å, though it ranges from 1Å to tens of Å[6]. The typical force generated is $1.95\times10^4\,\mathrm{N/cm^2}$, and with a 2.5% contact area per spatulae, we have $4.91\times10^2\,\mathrm{N/cm^2}$.

Kinematics

There are around 5300 setae per mm^2, and are around 700 spatulae per setae.[7] The spatulae are shaped like inverted cups, so only the rims (2.5%) come into contact with the surface. Each spatulae generates about $2.95\times10^{-7}\,\mathrm{N}$ of force (see appendix).

	per mm^2	on each foot	on the gecko
Setae available	5300	530,000	2.12 million
Spatulae available	3.71 million	371 million	1.48×10^9
Spatulae in use	742 thousand	74.2 million	2.97×10^8
Force generated	0.219N	21.9N	87.6N

Real world values give about 22N per square cm, so a total of 20% of the spatulae are in contact with a surface (this is only 4.5% of the skin area). Over the entire surface area of gecko feet, only 1.1% is actually used for contact force!

[4] Franz, Measurement of Surface Forces of Adsorbed Layers on Smooth Substrates
[5] Franz, Measurement of Surface Forces of Adsorbed Layers on Smooth Substrates
[6] Liang. Adhesion Force Measurements on Single Gecko Seta
[7] Liang, Adhesion Force Measurements on Single Gecko Seta - Average of a given range

Hanging Upside Down

The gecko must be able to support its own weight, which in turns implies that the adhesive force must be greater then the force due to gravity.

Assume the average mass of an average gecko is around 225g. This means that the force of gravity on that gecko is approximately 2.2N.

Using an average area of contact of 1 cm^2 (per foot), an average gecko foot produces an adhesive force of 22.105N per foot (see appendix).

If the gecko uses only one foot on the ceiling, there is still a reserve upward force of 19.898N.

Running Up a Tree to Get Away From a Snake

In the above calculation, we assumed that the gecko was stationary.

Now we're going to consider if the gecko were in motion on a vertical surface, such as a tree. Let us assume that the gecko needs at least two feet in contact with the surface to run. Then the new net adhesion force is 42N.

Assuming the gecko can accelerate from stationary to top speed (1 m/s) in 0.1 s (a very fast gecko), a gecko weighing 225 grams will experience an acceleration of $10\,\mathrm{m/s^2}$, requiring a net force of 2.25N. Its legs actually need to generate 4.46N of force to counter gravity and run up the tree.

This is more than enough to adhesive strength to stick on the ceiling and run away from a predator. This leads to the question - Why do geckoes need such a large adhesive force?

Environmental Factors

If the gecko is in a rush (running away from a predator or pouncing toward a meal), we can assume that dynamic forces would cause some of the setae and spatulae to lodge in an imperfect fashion.

Dusty Conditions

Dust, sand, and debris affect adhesion by occupying contact area on the skin. A 25 μm diameter dust particle covers around 491 μm^2. The size of spatulae is around 0.2 μm x 0.3 μm[8], which is around 0.06 μm^2. This means that a single dust particle will affect close to 8200 spatulae!

Fortunately, when the gecko is walking, the spatulae rub against the ground, helping the gecko dislodge any dust particles stuck to its feet.

The gecko's feet are self-cleaning[9]. While a specific mechanism has not been mentioned, it is easy to imagine the feet would act as a toothbrush would. When we run our fingers over the brushing surface of a toothbrush, particles that were stuck on it will flake off. The same principle might apply to a gecko's foot. Keratin is a fibrous protein that is part of your fingernails and hair, and its spring constant allows it to acts as the bristles on toothbrushes.

Water

Water does not seem to have a significant effect on adhesive strength. Unlike other creatures that have smooth skin on their feet, water cannot intercalate between the surface and the gecko's skin; the gecko's skin has ample channels for the water to escape when pressure is applied downward on the foot. Thus, the gecko could theoretically climb underwater as well (but cannot breathe).

Rough Bark

If the tree bark has ridges and grooves, and the lamellae are unable to wrap around the grooves well enough, then the gecko will not be able to form a bond as strong as on a smooth surface.

Damage

Sharp rocks may damage the setae and spatulae, and objects with deep pits may trap spatulae as the gecko picks its foot up. Malnutrition may cause improperly formed setae and spatulae, or have weaker-than-normal setae and spatulae that are easily damaged.

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[8] Liang, Adhesion Force Measurements on Single Gecko Seta
[9] Autumn, Adhesive force of a single gecko foot-hair

When walking on a surface that is not safe for their feet damages some of the spatulae, the gecko must have enough spares to ensure they can climb up vertical surfaces.

Molting

During molting, the gecko's entire skin is shed. If the gecko's new skin has not yet hardened, then adhesion will be negatively affected.

Geckoes produce an adhesive force that is far greater then the required amount to ensure climbing ability even when one or two of its feet are damaged or covered in old skin.

Is the Gecko Over-Equipped?

The maximum force generated by the gecko is 88N under *ideal* conditions:

- Clean surface
- Smooth surface topology
- All contacting setae are 'seated' correctly
- All contacting spatulae are making optimal contact (3Å) with surface
- No setae dislodged by dynamic forces

However, the natural environment has dust and sand. For example:

> If a piece of bark is 95% covered in dust particles, the gecko has only 4.4 N of available traction force. If a snake suddenly surprised the gecko, the gecko would stumble trying to run up the tree. What is considered an oversupply in the lab is barely sufficient in nature!

Results

Of the gecko's roughly 1.5 thousand million spatulae, only 300 million (1.1% of area, or 20% of spatulae) are in contact with the surface at any given moment. This amounts to $22\,\text{N}/\text{cm}^2$, or an astounding 88N of force for the entire gecko under ideal conditions. In its natural habitat, this figure is sharply reduced by debris such as dust and sand.

	Ideal conditions	95% dust
Spatulae in use	2.97×10^8	1.48×10^7
Adhesive force	87.6N	4.38N

Because the natural environment poses additional challenges for the gecko, it has merely sufficient adhesion to accelerate away from a predator under dusty conditions. During normal conditions it has a lot of spare adhesive force.

Applying our model to Spiderman

Assumptions: Spiderman weighs 75 kg.
He requires at least one hand and one foot on the surface in order to walk up the wall: $122\,\text{cm}^2$ + $236\,\text{cm}^2$ (1 hand + 1 foot) for a total of $358\,\text{cm}^2$.

Now, Peter Parker is a physics student, so he knows that the time he takes to accelerate to top speed will affect how much shear force is placed on his gear. His top speed is 5.907m/s (that's an overweight Spiderman trying to run at comparatively the same speed as the gecko, 3.3 body lengths per second).

With one hand and one foot, Spiderman has $7.8\times10^3\text{N}$ of available adhesive force. His weight alone will negate 736N of that force. He decides to some trials on a clean wall.

Time to accelerate to 5.9m/s	Maximum force expended	Stays on wall?
1.0s	740N	Yes
0.1s	5166N	Yes

Now, Peter Parker tries climbing a dusty tree in his back yard (95% dust coverage).

With one hand and one foot, Spiderman has only 390N (5% of his original grip).

He started with both hands and both feet. (Smart!)
The moment he takes one hand off… WHAM! He lands on the floor. (That smarts!)

Spiderman can climb up clean glass skyscrapers. He can't climb anything covered in 95% dust (so the gecko mocks him). We recommend he carry Windex® on his tool belt!

Conclusions

Our hypothesis was that the gecko does not really have as large of an adhesive force overbuild as lab measurements of per-setae force would indicate. Within its (dusty) natural environment, the gecko has just enough adhesion to run away from a predator.

We assumed that a dusty environment would leave a surface covered in 95% dust. If the amount of dust coverage increases, the adhesive force decreases. We also assumed a gecko could accelerate to its top speed in 0.1 seconds. If the gecko is actually slower, then it will have more adhesive force to spare. We also used a constant distance in our van der Waals force calculations – in reality, the contact range would likely follow a normal distribution centered at 3Å. We also assumed that Spiderman could take his entire body weight as a sideways load on the palms of his hand and the soles of his feet.

Geckoes are truly amazing animals. We were so excited we nearly drove down to Surrey to go to the zoo to see them. In such a small package, using devices that are smaller than the resolving power of visible light, they climb a variety of surfaces with reckless abandon. Humans often try all kinds of creative ideas to mimic animal behavior – one particularly inventive fellow in Germany made the Gekkomat, a vacuum-powered device he claimed would allow someone to climb a wall. Because the gecko's climbing ability was not yet understood at the time, he generated climbing force with vacuum pumps powered by a huge compressed air tank strapped on his back.

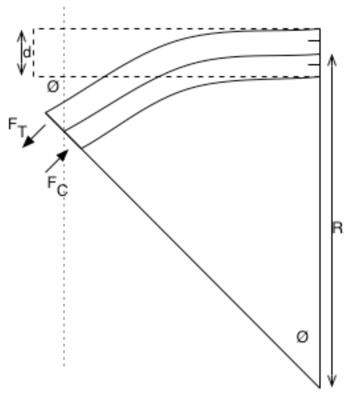
Thanks to a combination of both biology and physics, we can make better sense of results observed in the lab, and see how forms and forces in physics apply in the natural environment.

At this time, humanity's finest manufacturing methods are unable to mimic the complexity of the gecko skin hierarchy. Microprocessor manufacturing methods work as small as $0.09\mu m$, but only for depths of several atoms. We are left with clumsy replicas that perform as designed, but lacking the 3-dimensional structure, or lacking resilience of keratin used by nature, perform nowhere nearly as well as natural gecko skin.

Given provisions to perform lab experiments, one could deduce the statistical distribution of contact distance, and thus properly calculate safety margins of adhesion – we can develop the testing methodology that must be employed before gecko-like devices can by certified for use as search-and-rescue equipment.

Appendix

Setae
The setae are not straight cylinders (like toothbrush bristles) but rather show a significant curvature. In the diagram below, the seta is 111.1 μm long, with the end hanging 22 μm below horizon of its straightened form.



$$L_T = 25.5\text{cm} \times \frac{20\mu\text{m}}{4.5\text{cm}} = 113.3\mu\text{m}$$
$$L_B = 24.5\text{cm} \times \frac{20\mu\text{m}}{4.5\text{cm}} = 108.9\mu\text{m}$$
$$L_M = 111.1\mu\text{m}$$
$$D = 1.125\text{cm} \times \frac{20\mu\text{m}}{4.5\text{cm}} = 5.0\mu\text{m}$$

With the assistance of Dr. Ahlborn, we modeled the compressibility of a curved seta as a simultaneous compression on the bottom half and tension force on top half of a cylinder.

$$L_T = \left(R + \frac{d}{4}\right)\phi \qquad L_C = \left(R - \frac{d}{4}\right)\phi \qquad L_{setae} = R\phi$$

$$\Delta L_C = L_C - L_m = \left(R - \frac{d}{4}\right)\phi - R\phi = \frac{-d}{4}\phi \qquad \Delta L_T = L_T - L_m = \left(R + \frac{d}{4}\right)\phi - R\phi = \frac{d}{4}\phi$$

From the literature[10] range of Young's modulus for keratin (1-15GPa), we assumed an average Young's modulus is $\frac{15-1}{2} = 8\text{GPa} = 8 \times 10^9\ \text{N/m}^2$.

Since $k = \frac{YA}{L} = \frac{Y \bullet \frac{\pi (d/2)^2}{2}}{L_m} = \frac{1}{2} \times \frac{8.0 \times 10^9\ \text{N/m}^2 \bullet \pi \left(\frac{5.0 \times 10^{-6}\text{m}}{2}\right)^2}{111.1 \times 10^{-6}\text{m}} = 7.069 \times 10^2\ \text{N/m}$

and $T = k\Delta L$, then

$$T_{compression} = k\Delta L = k\left(\frac{d}{4}\right)\phi = 7.069 \times 10^2\ \text{N/m}\left(1.25 \times 10^{-6}\text{m}\right)0.201 = 1.776 \times 10^{-4}\ \text{N}$$
$$T_{tension} = 7.069 \times 10^2\ \text{N/m}(-1)\left(1.25 \times 10^{-6}\text{m}\right)0.201 = -1.776 \times 10^{-4}\ \text{N}$$
$$T_{total} = T_{compression} - T_{tension} = 2\left(1.776 \times 10^{-4}\ \text{N}\right) = 3.552 \times 10^{-4}\ \text{N}$$

Now we compress the curved setae by 1 μm:

[10] Sitti, Nanomolding Based Fabrication of Synthetic Gecko Foot-Hairs (p. 2)

$$T_{total_2} = 2\left(k\left(\frac{d}{4}\right)\phi_2\right) = 2\left(7.069\times10^2\ \text{N/m}\left(\frac{5.0\times10^{-6}\text{m}}{4}\right)0.209\right) = 3.694\times10^{-4}\ \text{N}$$

$$T_{squish\ 1\mu m} = (3.694 - 3.552)\times10^{-4}\ \text{N} = 1.42\times10^{-5}\ \text{N}$$

Determine if conforming to a surface required 5% of setae to compress 1 μm, is within the realm of a gecko pushing its foot against a wall.

$$4\text{cm}^2 \times \frac{100\text{mm}^2}{\text{cm}^2} \times \frac{5300\ \text{spatulae}}{\text{mm}^2} \times \underbrace{20\%}_{\text{contacting}} \times \underbrace{5\%}_{\text{compressed}} \times 1.42\times10^{-5}\text{N} = 0.301\text{N}$$

Spatulae

The van der Waals forces in Spatulae:

$w(R) = \frac{C}{r^6}$ For interactions of two molecules embedded in a medium. C is a function of the material properties of the interacting molecules, and the medium in which they are embedded.

Derivation

$$W(D) = \frac{\pi^2 C\rho_1\rho_2 r}{6D}$$

$$A = \pi^2 C\rho_1\rho_2$$

Franz provides an equation for the Hamaker constant:[11]

> If the geometry is known, then the Hamaker constant can be expressed as an infinite series, where the first terms are
>
> $$A \approx \frac{3}{4}k_B T\left(\frac{\varepsilon_1-\varepsilon_3}{\varepsilon_1+\varepsilon_3}\right)\left(\frac{\varepsilon_2-\varepsilon_3}{\varepsilon_2+\varepsilon_3}\right) + \frac{3h}{4\pi}\int\left(\frac{\varepsilon_1(iV)-\varepsilon_3(iV)}{\varepsilon_1(iV)+\varepsilon_3(iV)}\right)\left(\frac{\varepsilon_2(iV)-\varepsilon_3(iV)}{\varepsilon_2(iV)+\varepsilon_3(iV)}\right)dV$$
>
> where h is Planck's constant, and indices 1, 2, 3 denote the dielectric constants of sphere, substrate and the medium in between, respectively. The integration is carried out over all frequencies ranging from $v_1 = 2\pi k_\theta T/h$ to infinity.

We will use a simplified equation, taking the Hamaker constant to be 10^{-19} J[12].

$$F_{vdW\ keratin,\ 3Å} = \frac{H}{6\pi D^3} = \frac{10^{-19}\ \text{J}}{6\pi(3.0\times10^{-10}\text{m})^3} = 1.9649\times10^4\ \text{N/cm}^2$$

The force generated per spatulae is

$$\begin{aligned} F_{vdW\ spatulae} &= F_{vdW\ keratin,\ 3Å}\times A_{spatulae} \\ &= 1.9648\times10^8\ \text{N/m}^2 \times (0.2\times10^{-6}\text{m})(0.3\times10^{-6}\text{m})(2.5\%) \\ &= 2.9473\times10^{-7}\text{N} \end{aligned}$$

[11] Franz, Measurement of Surface Forces of Adsorbed Layers on Smooth Substrates
[12] Liang, Adhesion force measurements on single gecko setae

If we calculate using force per area, we have

Since only 2.5% of the spatulae area is in contact with the other surface, we have

$$F_{\text{vdW setae}} = F_{\text{vdW spatulae}} \times 2.5\% = 4.9122 \times 10^2 \,\text{N/cm}^2$$

We estimate 4.5% of the setae are in contact with the other surface, we have

$$F_{\text{vdW skin}} = F_{\text{vdW setae}} \times 4.5\% = 22.1048 \,\text{N/cm}^2$$

Kinematics

$$\frac{5300 \text{ setae}}{\text{mm}^2} \times 4.5\% \times 2.5\% \times \frac{1000 \text{ spatulae}}{\text{setae}} = \frac{5962 \text{ spatulae}}{\text{mm}^2}$$

Hanging Upside Down

$$F_g = mg = 0.225\text{kg} \times 9.81\text{m/s}^2 = 2.207\text{N}$$

$$F_{\text{vdW}} = F_{\text{vdW spatulae}} \times 2.5\% = 4.9122 \times 10^2 \,\text{N/cm}^2$$

$$F_{\text{vdW skin}} = F_{\text{vdW setae}} \times 4.5\% = 22.1048 \,\text{N/cm}^2$$

$$F_{\text{net}} = 22.105\text{N} - 2.207\text{N} = 19.898\text{N}$$

Running Up a Tree to Get Away From a Snake

$$\text{F}_\text{g} = mg = 0.225\text{g} \times -9.81\text{m/s}^2 = -2.21\text{N}$$

$$\text{a} = \frac{(1-0)\text{m/s}}{0.1\text{s}} = 10\,\text{m/s}^2 \rightarrow \text{F}_\text{a} = \text{ma} = (0.225\text{g})(10\,\text{m/s}^2) = 2.25\text{N}$$

$$\text{F}_{\text{leg}} = \text{F}_\text{a} - \text{F}_\text{g} = 2.25\text{N} - (-2.21\text{N}) = 4.46\text{N}$$

Applying our Model to Spiderman

Available force from one hand and one foot

$$F_{\text{skin}} = 358\text{cm}^2 \times 22.1048\,\text{N/cm}^2 = 7913.5184\text{N}$$

Force required to accelerate to 5.907m/s in 1.0s

$$\text{F}_\text{g} = mg = 75\text{kg} \times -9.81\text{m/s}^2 = -735.75\text{N}$$

$$\text{a} = \frac{(5.907-0)\text{m/s}}{1\text{s}} = 5.907\,\text{m/s}^2 \rightarrow \text{F}_\text{a} = \text{ma} = (75\text{kg})(5.907\,\text{m/s}^2) = 443.025\text{N}$$

$$\text{F}_{\text{leg}} = \text{F}_\text{a} - \text{F}_\text{g} = 443.025\text{N} - (-735.75\text{N}) = 740.18\text{N}$$

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