Bioinsp. Biomim. 2 (2007) 1–8 doi:10.1088/1748-3182/2/1/001

Structural properties of a scaled gecko foot-hair

Jose Berengueres[1], Shigeki Saito[1] and Kenjiro Tadakuma[2,3]

[1] Department of International Development Engineering, Tokyo Institute of Technology, Tokyo, Japan
[2] Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan

Received 27 September 2006
Accepted for publication 20 December 2006
Published 12 January 2007
Online at stacks.iop.org/BB/2/1

Abstract
Experimental measurements on a cm-scale replica structure of a gecko foot-hair where magnets are used in place of (the usual) van der Waals force are reported. We conduct naked-eye experiments and investigate the mechanical properties of such hair structure and shapes that constitute it. Links between *shapes* and mechanical properties (*functions*) useful in geckos for clinging onto walls and adhering to rough surfaces are explained in terms of energy efficiency.

(Some figures in this article are in colour only in the electronic version)

1. Project framework

1.1. The need for better adhesion

Cheap, reliable adhesion remains a seemingly unsolved engineering problem. In wall mobility applications, reliable adhesion is a precondition for the development of autonomous robots. Lack of it seems to hinder development in two fields: (i) robots for surveillance/security that can cling and move on vertical surfaces; (ii) robots for the maintenance/inspection of manmade structures such as building facades, wind turbine towers, nuclear plants and oil pipelines. In the case of wind turbine tower, for instance, such a robot would obviate the need to mount scaffoldings each time the tower needs to be repainted, with subsequent savings.

On the other hand, in factory automation (and particularly where mechanical gripping is not suitable) adhesion mechanisms such as suction cups and electrostatic chucks are widely used. However, in terms of maintenance and capital investment such systems do not come cheap. Here, too, reliability is paramount. In a flat display production line, for instance, a single failure to grip a large glass substrate properly may cause a line stoppage.

In this context an adhesion system that combines the reliability, robustness, performance and durability of gecko-like adhesion at a reasonable cost seems desirable.

[3] Present address: Department of Mechanical Engineering, 3-469A, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA.

1.2. Antecedents

The discovery in the year 2000 [1, 2] that gecko foot-hair (seta) adhere to surfaces by means of van der Waals force sparked a good deal of research on the area. Particularly, synthetic structures (gecko tape) that try to replicate gecko–van der Waals adhesion have been manufactured with varying degrees of success, as in [3–6]. However, a gecko spatula is typically 200 nm in diameter and mimicking such a tiny structure is relatively expensive.

In this text we introduce a cm-scale gecko foot-hair for wall mobility application where adhesion force is not provided by van der Waals interaction but by attaching a small magnet at the tip of each foot-print (seta). Such a device is naturally limited to use in ferromagnetic substrates. However, there are in the world many iron manmade structures—pipes, bridges—that need periodic maintenance and corrosion checking.

1.3. The starting point of this research

This research is based on the fact that gecko seta and spatulas (from now on referred to as foot-hair) exhibit interesting shapes such as a characteristic cantilever curvature that provides surface roughness adaptability [7–9], and footprints with triangular shapes as seen in [10, 11]. (An account on the relation between spatula shapes in living creatures and adhesion properties can be found in [12]). This research is supported by three hypotheses:

(i) If foot-hair shapes are not causal they must be related to some kind of survival advantage such as energy efficiency or better grip. By this we assume that the shapes must be somehow related to mechanical properties that make the gecko walk and/or adhesion mechanism efficient.

(ii) Such efficiency is independent of the adhesion force at work, van der Waals [2] and capillary force [13] in the case of geckos (magnets in the case of the device we are going to introduce).

(iii) (i) + (ii) → A scaled up version of gecko foot-hair where magnets are used in place of van der Waals force (VdW) should inherit gecko foot-hair properties (including energy efficiency).

Whereas (i) seems plausible, we have no proof of (ii). In the text, instead of (ii) we use the so-called force substitution hypothesis which is introduced in section 2.

1.4. Brief review of the state-of-the-art biological and manmade climbing systems

As mentioned previously, the fact that geckos can adhere by means of VdW force was confirmed by [2] in 2002. However, for a long time gecko adhesion and particularly adhesion on smooth glass substrate have puzzled many researchers. The first explanation of the phenomena (dating from 1941) was based on the so-called micro-claw concept. It suggested that 'a gecko uses its adhesives pads in essentially the same way a climber uses spiked boots' (re-quoted from [14]). The micro-claw explanation was questioned by [14] in 1964 and finally debunked afterwards [2]. However, in 2006 the successful climbing of a brick wall by a robot based on millimeter-claws (RiSE) [15] offered a new angle on the micro-claw concept. An analysis of the morphology of gecko digits can be found in [16–21]. The otherwise sophisticated gecko locomotion is clarified in [22]. On the other hand, it has been recently confirmed that some spiders not only use hairs to attach to surfaces but that they also can do so by means of secreting silk from the tips of their legs [23].

On the manmade side, apart from the RiSE project there are climbing robots based on suction cups, for example [24], but their autonomy is limited due to the high power consumption of compressors and/or air pumps. Pressure sensitive adhesives have also been revisited recently by [25]. Synthetic gecko tape has been synthesized but durability so far seems to prevent its applications. So far, from all the robots built to date the one design that seems nearest to commercialization is the so-called City Climber [26]. The City Climber is based on an adaptive curtain and a fan-type air pump. The main characteristics are a payload of 2 kg and autonomy of 30 min.

1.5. Magnets as an adhesion force

The advent in 1983 of neodymium-based magnets (capable of adhesion pressures superior to vacuum force) provided a cheap but powerful reliable source of adhesion (at least on iron substrates). Let us visualize a magnet (a bare magnet) used in a leg of a hypothetical robot which is climbing (crawling) an iron wall. Each time the magnet approaches the substrate (magnetic) potential energy is lost. Each time the magnet detaches from the substrate (in order for the leg to make a step forward), energy is consumed, and (most importantly) an actuator capable of generating a force bigger than the peak magnet-substrate adhesion force (also known as breakaway force) is needed. This breakaway force is directly related to the maximum payload the magnet can support and can be considerable. The loss of energy in each step is inefficient.

We can circumvent this problem by using the concept of preventing negative work. By storing the energy that otherwise is lost when the magnet approaches the substrate and using that energy to detach we can realize, in theory, effortless attachment and detachment. That is the basis of the so-called internally balanced (IB) magnet invented 1986 by [27]. An IB-magnetic unit stores that usually lost energy in a nonlinear spring and then uses it to detach from the substrate effortlessly. However, it is reportedly difficult to adjust the spring to perfectly balance the pull between the magnet and a substrate. Substrates vary in thickness and quality, and a slight variation renders the unit unbalanced. The main drawbacks of the IB-magnet are that (i) it cannot be adapted to round or curved surfaces and that (ii) it is difficult to balance. In real tests typically 95% is the maximum percentage of energy that we can recover in each step. The typical peak detachment force needed for successful detachment is 5% of the magnet payload. We take this 5% as an indirect measure of energy efficiency. (By this measure the aforementioned bare magnet would rate 100%.)

As we will show, an implementation based on scaled gecko foot-hair + magnets can reach 1–2%. Additionally, compared to the IB-magnet, this efficiency measure is stable. (It does not depend on the substrate thickness as is the case in [27].)

2. Comparison between van der Waals and magnetic force

2.1. van der Waals force for an object-on-plate system

A cylindrical object (of radius R, height no bigger than R and with its base parallel to a substrate) separated from a flat surface by a distance d will experiment an attractive force. When the object is very close to the surface, $d \ll R$, the force is approximately proportional to d^{-1} (near field approximation). When d becomes comparable to R (we set a threshold at $d = R/20$) the force decreases with the fourth power of the distance [28]. Clearly this system is characterized by two markedly different behaviors. Which one dominates is decided by the d/R ratio.

2.2. Magnetic force for an object-on-plate system

On the other hand, if we suspend a cylindrical magnet over an iron plate, this 'object' will experiment an attractive force towards the plate.

2.3. Comparison

Figure 1 shows, simultaneously, the force-curves of both cases. The X-axis is the normalized gap between an object and a plate. The Y-axis represents the attractive force that the cylindrical

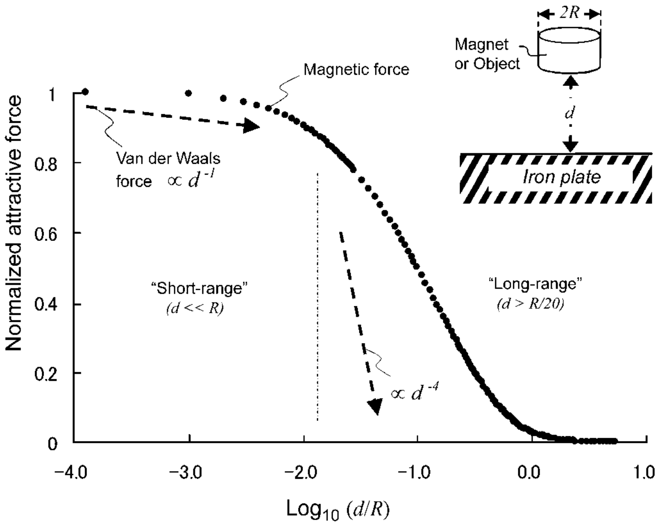

Figure 1. Two forces with similar behaviors; d is the plate-cylindrical object gap. R is the radius of object. Dots: measurement of attraction force between a cylindrical magnet and an iron plate. (height of object $\leqslant R$) Dashed arrows are the theoretical prediction of van der Waals interaction. Qualitative trend only.

magnet or object experiments when suspended over a plate (or iron plate).

The dots are experimental data for a magnet–iron plate system. Figure 1 dots correspond to a cylindrical rare earth magnet of diameter 5 mm and height 2 mm. The pull force has been normalized by the maximum force that acts on the magnet (when $d \to 0$). This maximum force is also known as the breakaway force. (By normalizing the distance by radius and the force by the breakaway value, figure 1 can be applied to any cylindrical magnet whose $R >$ height).

The dashed arrows are the (theoretically predicted) van der Waals force according to [28]. (Qualitative trend only.) Behaviors in common are (i) slow decay in 'short-range' ($d \ll R$) and (ii) a steep decay the moment d becomes comparable to R ($d > R/20$). Though the decay rates are different, let us note the sudden 'switch' of behaviors present in both cases.

2.4. Force substitution hypothesis

Since the forces behave similarly, it should be possible to substitute one for the other in a real system. For example, if we substitute the van der Waals force that acts on the gecko's spatulae by magnetic force, the mechanical principles that allow geckos to walk smoothly and energy efficiently [3] should also work in our 'magnetic' version of a gecko foot. Of course, we should take into account scale factors, and that such a gecko would have to walk on a ferromagnetic substrate. We can build such a device by making a structure similar to a gecko foot and by attaching a magnet to each spatula (hair). The van der Waals interaction becomes negligible by scaling the spatulas by a factor of 100 or bigger. We call this hypothesis the force substitution hypothesis. The rest of the text is based on the validity of this hypothesis. Based on this, we mimicked the shapes of a gecko foot-hair (seta) such as those seen in figure 2, and built several cm-sized magnetic versions.

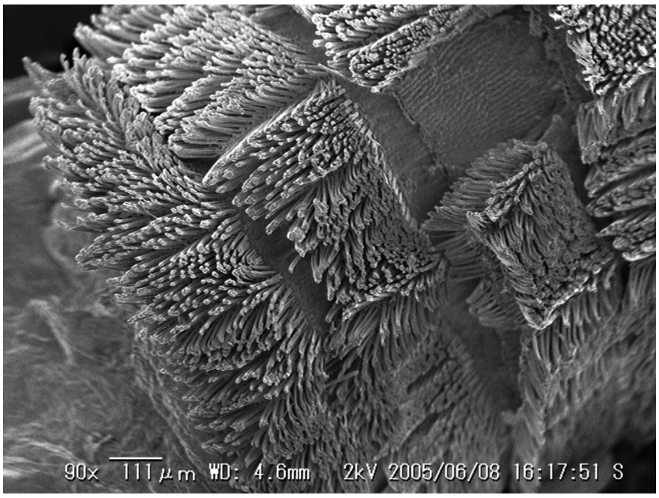

Figure 2. Setae of a Gecko Grossmannir. The characteristic shapes of the hairs seem related to functions for energy efficient walk.

2.5. The present study

In the following sections we report the experimental setting for measurements of force, moment and instant stiffness on magnetic 'hair' prototypes (from now on simply referred to as 'hairs'). In the results section we relate the experimental evidence with shapes found in the hairs.

3. Making of a magnetic cm-scale gecko hair and methods

A fishing nylon rod was rolled into an aluminum piece machined with the desired profile and submerged in 98 °C water for 4 min. After cooling, the desired section of the nylon with the desired profile was cut. A magnet (nickel coated rare earth magnet supplied by Magna Trade KK) was attached to the footprint end with Loctite. Other hair prototypes where manufactured by CAD through a Stratasys' Prodigy Rapid Prototyping, in ABS400 plastic. The magnet-iron substrate force curve was measured by means of fixing with glue the magnet to the tip of a force gauge (N&D KK) and by fixing the gauge to a motorized stage (Suruga Seik KK). The motors of the stage seem to electrically interfere the reading of the gauge. This was solved by connecting the gauge to a dry battery cell. Magnetic fields do not seem to interfere with the gauge.

The hairs used to measure the stiffness asymmetry have the following characteristics: length 20 mm, diameter 0.9 mm, material: nylon, magnet diameter 5 mm height: 1 mm, and length 2 mm, diameter 0.5 mm material nylon magnet diameter 20 mm height 0.5 mm. The shape is modeled after Gecko Grossmannir spatula. One extreme of the hair is fixed to a load cell. The magnet-end is placed in contact with a substrate that is fixed to a sliding motorized stage with submicron resolution (Suruga Seiki KK). The whole system is inside a transparent plastic box to minimize external influence. The whole system is placed on an anti-vibration table (air cushion). A layer of non-ferromagnetic material is placed between the magnet and

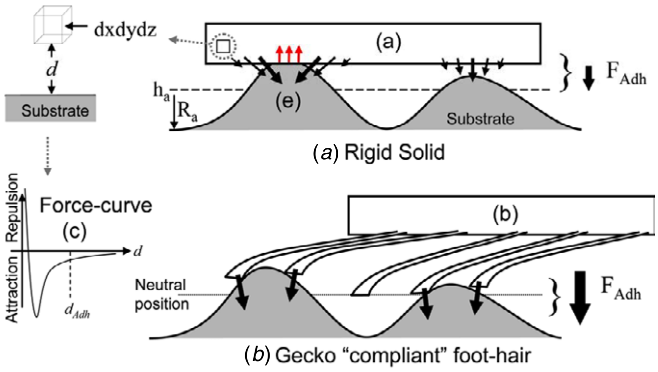

Figure 3. Principle of gecko adhesion. The cantilever shaped hairs are compliant: a key to produce robust grip on irregular surfaces. Comparison between two adhesion systems: (*a*) section view of a rigid solid–rough surface interface. (*b*) Section view of gecko foot-hair–substrate interface. h_a is the average height of the substrate's surface. R_a represents the equivalent roughness. The doted line in (*b*) represents the height at which a foot-hair remains if no force is applied. (*c*) Force-curve (from a Lennard-Jones model), d_{Adh} is the force range threshold. In (*a*) cancellation effects and the non-compliance with the surface roughness prevents a large adhesion force.

the stage in order to decrease the breakaway value so that the magnet detaches by rotation non-brusquely.

4. Results: shape effects of gecko hair structure

After studying the mechanical properties of the cm-sized magnetic hair, we have identified six mechanical properties (or shape effects) that seem useful for attaching to surfaces effectively and detaching effortlessly in an energy efficient way. Such six properties match, obviating scale factors, those of previously identified in living geckos and can be summarized as follows.

4.1. *Cantilever effect*

Compliance is one of the keys of gecko adhesion. Figure 3 reviews the importance of compliance when the adhesion range is short as compared to the average surface roughness in an adhesion system. The cantilever effect in living geckos has been addressed in [7–9]. Figure 4 shows surface roughness adaptability of cm-size magnetic hair prototypes.

4.2. *The lever effect*

In living gecko foot-hair, this effect is described by [2, 29]. After observing various attachment–detachment sequences of magnetic hair models we found out that there always seems to be a preferred path for detachment: a path of least effort. This path seems to start always with a rotation of the hair followed by a detachment by peeling. (The direction of the peeling wave in living gecko has opposite direction but both are equivalent in terms of energy efficiency). Figure 5 shows the detachment condition when the hair, originally adhered to a substrate, rotates over an axis. A hair subject to an external force (for example an actuator) rotates if $M_R > M_{Adh}$, where M_{Adh} is the moment over the rotation axis due to adhesion forces and M_R is the moment due to an external force applied on the hair. By the lever principle, the longer the hair the lesser the force needed. However, a too long hair might have other drawbacks, such as increased matting [30]. Fortunately, magnetic force, in contrast to van der Waals force, can be shielded. Industry standard shielding cups and cylindrical

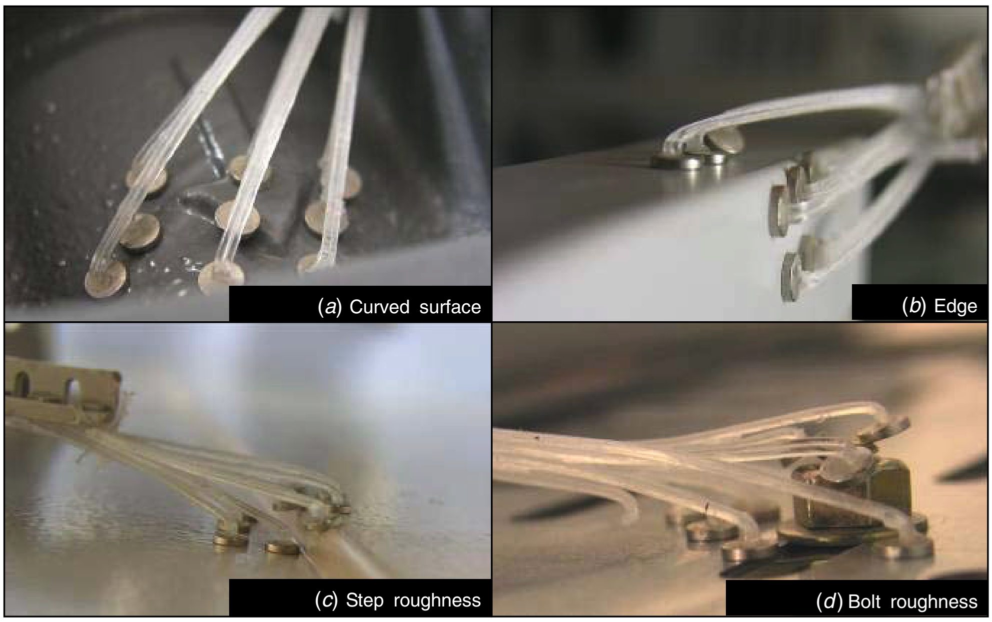

Figure 4. Compliance of gecko-inspired magnetic hair. The van der Waals force has been substituted by magnets. The hair has surface roughness adaptability: a key factor for effective adhesion. (*a*) Adaptability to a curved surface: gas a pipe. (*b*) Adaptability to an edgy surface: a table leg. (*c*) Adaptability to a step: a junction of a door. (*d*) Adaptability to extreme roughness: a bolt.

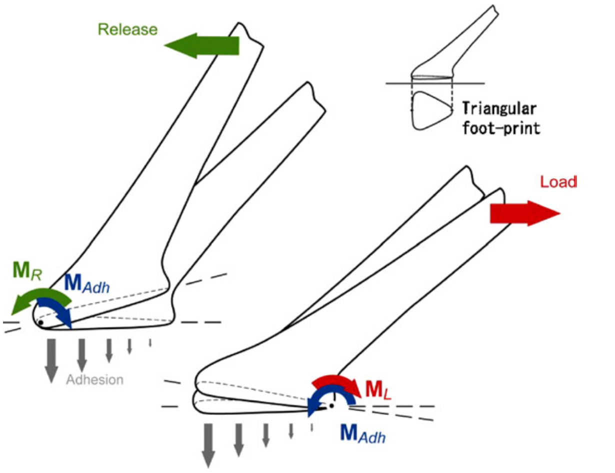

Figure 5. Moments and forces acting on a triangular footprint 'hair' (seta, spatula). The force necessary for successful detachment (release) and the maximum load the system can support depend on the length of the hair and the shape of the footprint. M_R is the moment due to a release force. M_L is the moment due to a load. M_{Adh} is the moment due to adhesion forces between the substrate and the footprint. Detachment condition (non-sliding situation): the hair detaches in a release motion when $M_R > M_{Adh}$. The hair will fail to support a load if $M_L > M_{Adh}$.

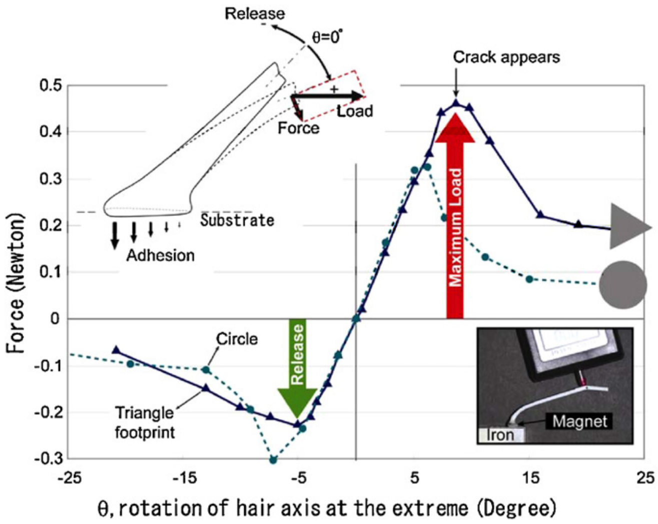

Figure 6. Comparison of two footprints by the minimum energy path. The X-axis is the detachment path of two hairs with different (magnetic) footprints measured as the angle θ. The Y-axis is the force applied to the hair extreme. Solid line: hair with an equilateral triangle footprint. Dash line: hair with a circular foot-print. The big arrows indicate the maximum load and peak release force in the case of a triangle footprint.

magnets are usually sold in sets. Cups reduce lateral magnetic mating dramatically, while they double the breakaway value (payload) of the bare magnet.

4.3. The foot-print effect

From lever effect analysis we can derivate the following. Assuming that the maximum load a hair can support is determined by the moment M_L, then, since M_R and M_L depend on the footprint shape, and different footprint shapes yield different M_L/M_R ratios, a hair with a high ratio means that it can support a big load while it needs a low release force for a successful detachment. This would be an efficient design because it minimizes the forces (peak forces) needed for release while maximizing load capacity. For a constant area, same length footprint and uniform adhesion pressure, experiments (figure 6) show that a triangle-shaped footprint yields a higher M_L/M_R ratio than a circular or square footprint. The foot-print effect might explain why some species (gecko, insects) hair tips end in triangularly, rhomboid foot-prints. Related spatula shape effects of living creatures are described in [31].

4.4. The peeling effect

A third function at work is the peeling effect, identified in living gecko foot-hair by [32]. Peeling refers to very same action as when one peels an adhesive tape from a substrate. Figure 7(*a*) shows a 'magnetic' pad comprised of eight hairs. When a load acts on the lower extreme of the structure, the eight hairs pull coordinated from the substrate. Figure 7(*b*) shows the initial stage of a detachment motion. Figures 7(*b*)–(*h*) show the peeling motion: one-at-time successive detachment of each

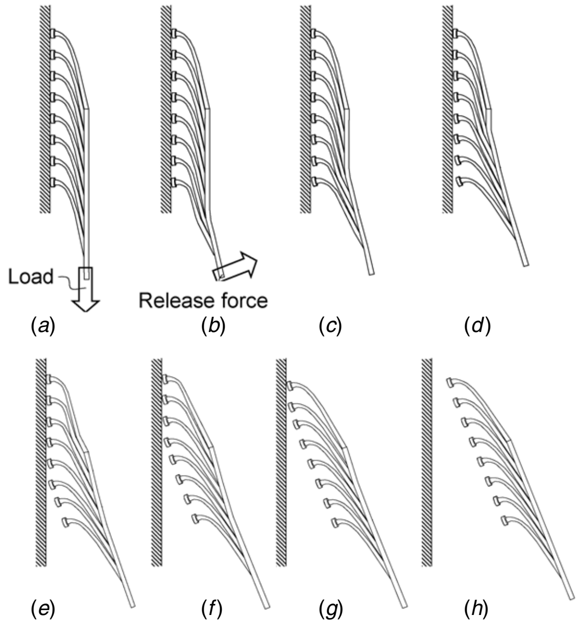

Figure 7. Detachment motion of a group of 8 hairs. (*a*) Loaded hairs. The hairs pull coordinatedly. (*b*)–(*h*) Peeling stages of the same.

magnet. From figure 7 we conclude that the more contact points (N) there are the more efficient the system is,

$$\text{(peak detachment force/system max load capacity)} \propto N^{-1}, \tag{1}$$

where we assume that the detachment of hairs is one at a time. On the other hand, if the hair pad detaches like an adhesive tape (by peeling through a line fracture), as is the case with the magnetic pads used in figure 8. In such a case if the aspect ratio of the pad is fixed then the widest peeling line width

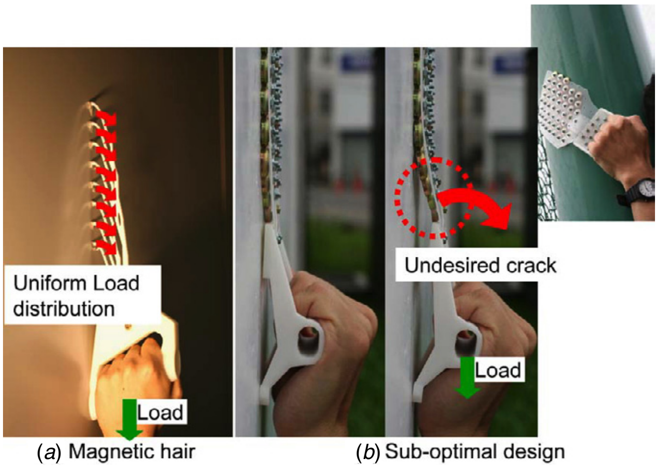

Figure 8. Holder + magnets on flexible support. (*a*) Holder and fractal hair structure. The branching structure ensures a uniform load distribution. (*b*) The non-uniform load distribution causes the load to concentrate on the lower line of magnets. In this case an undesired (fatal) peeling crack has started (dotted circle).

during detachment = maximum pad width $\propto$ area$^{1/2}$. If the area $\propto N$, then

$$(\text{peak detachment force/system max load capacity}) \propto N^{1/2}/N = N^{-1/2}. \quad (2)$$

Note that an increase in N implies an increase of the adhesion area, making the pads potentially cumbersome to use. But this is not a critical constraint in magnetic hair pads for two reasons: (i) neodymium magnets pack enough adhesion power in the cm scale for climbing applications and (ii) they can be arranged in a close packed way (because magnetic force can be shielded).

4.5. The stiffness asymmetry effect

A fifth effect at work is what we call stiffness asymmetry, as described in living geckos by [33, 34]. This effect is due to the characteristic curvature of the hairs. Stiffer hairs are easier to detach from a non-ideally-flat surface than softer ones [35], for the same reason that a chewing gum adhered to a surface is easier to detach the stiffer (usually, the colder) it is. That is, softer hairs are tackier. (The 'tack' term is borrowed from pressure sensitive adhesives context [36]). Figure 9 shows a stiffness–displacement relation of a mm-size magnetic hair prototype. The x-axis represents relative displacement between a load cell (which is fixed) and a sliding stage (to which the magnet is in contact). $\Delta x = 0$ represents the displacement at which the load cells measures no force. $\Delta x > 0$ corresponds to a decrease of the distance between the load cell and the stage (hair compression). $\Delta x < 0$ corresponds to an increase of the distance between the load cell and the stage. The Y-axis represents the reading of the load cell: $y > 0$ indicates tension on the hair; $y < 0$ indicates that the hair is under a compression. Dots represent the reading of the load cell. The tangential stiffness of a hair is not constant but changes abruptly depending on whether (i) the hair is under compression or (ii) the hair is under a tension. The instant the hair switches from tension to compression, the tangential stiffness increases almost three times. (Other geometries and materials lead to other values. We have measured changes in stiffness up to 5). One thing in common is that the abrupt change is always present. From figure 9 we conclude that hairs under tension (load) are softer and therefore can 'stick' better. Hairs under compression (as in a peeling motion, figure 7) are stiffer and thus are easier to release. This effect is strong enough to be felt by a human detaching device such as the one shown in figure 8(*a*).

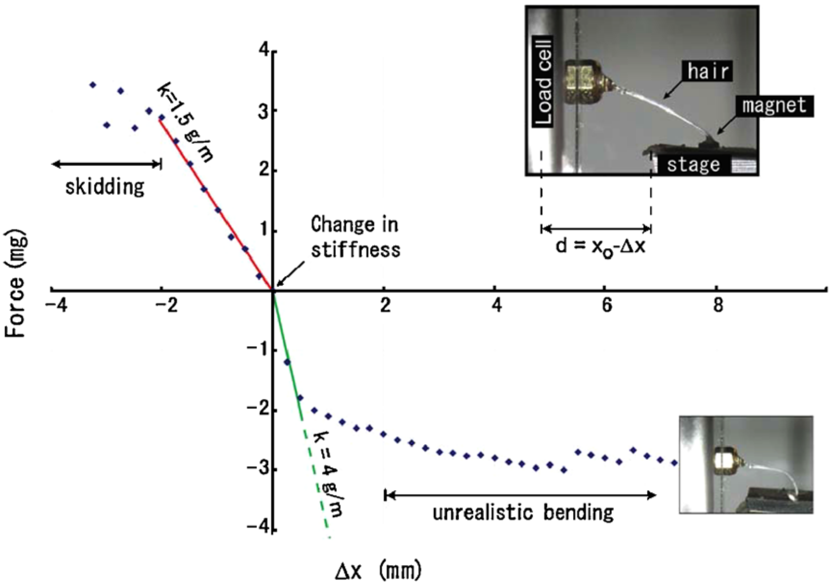

Figure 9. Tangential force-displacement relation of magnetic-hair. Dots: force measurement. Line: estimated instantaneous tangential stiffness of the system. Nylon hair diameter is 0.5 mm, modeled after a Gecko Grossmannir seta.

Figure 10. A 63 kg man climbing a round iron wall. The magnetic pads used (figure 7(*b*)) achieve a climbing efficiency that nears that of gecko by virtue of the peeling effect. The maximum load capacity of each hand pad is 70 kgf but each requires less than 3 kgf to detach by peeling motion.

4.6. Moment distribution

Another effect of the characteristic curvature of the hairs is the ability to distribute economically (in the sense of [37]) a big load, as seen in figure 8(*a*), into smaller loads to each hair (M_{Adh} of figure 5). This effect is described in the context of biomimetic fiber interfaces in [38, 39]. The importance of this function (the complement of the peeling effect) can be understood best when we try to climb a wall with a system that does not ensure uniform load distribution. In figure 8(*b*) a load of 63 kg on a semi-rigid pad (a gecko-inspired sub-optimal but cheaper design) causes a momentum that is not distributed uniformly into the magnets. If this momentum causes an unwanted detachment (peeling crack) of the inferior part, the crack might propagate ensuing a spiraling loss of adhesion of the system as a whole. A gecko structure does not have this problem (figure 8(*a*)). The characteristic curved shape gecko hair seems naturally fitted to avoid this drawback by conveying loads and tensions acting in one end of the hairs to the substrate in a homogeneous manner.

5. Prototype evaluation

Figure 10 shows a man climbing an iron wall by means of four magnetic pads such as those shown in figure 8(*b*). The pads can be considered a particular case of a hair-pad where the length of the hair is 0. Still, the pads have enough compliance to operate on round surfaces (something not possible for the IB-magnet). Though, their use is limited to ferromagnetic substrates, the climbing efficiency (thanks to the peeling effect) approaches that of geckos. By using the measure of efficiency proposed in section 1 (*peak detachment force*/*max load*) the hand pads rates $\sim 5\%$ ($N = 49$), the foot pads rate $\sim 3\%$ ($N = 100$).

6. Concluding remarks

Mechanical experiments with ‘magnetic’ hair models performed in the mm$\sim$cm range seem to indicate that a relation between characteristic shapes and functions (mechanical properties) useful for an energy efficient detachment–attachment operation in gecko scaled foot-hair structures exist. These properties seem to match those of living gecko. The adhesion performance and effectiveness of the various prototypes examined seem to indicate that

(i) Gecko foot-hair properties are scalable.
(ii) The energy efficiency of gecko-shaped foot-hair as an adhesion device is independent of the adhesion force at work.

7. Future directions

Based on the conclusions of this work we are developing a version of gecko foot-hair based on the same force principle of electrostatic chucks. We expect that such a device will have a wider range of application as opposed to magnet based devices.

Acknowledgments

This work was supported by the Venture Business Initiative at the Tokyo Institute of Technology, 2006. The authors are grateful to Masataka Urago for fruitful discussions, and to Hirose Lab members who helped machine the foot-pads.

References

[1] Autumn K, Chang W P, Fearing R, Hsieh T, Kenny T, Liang L, Zesch W and Full R J 2000 Adhesive force of a single gecko foot-hair *Nature* **405** 681–5
[2] Autumn K, Sitti M, Peattie A, Hansen W, Sponberg S, Liang Y A, Kenny T, Fearing R, Israelachvili J and Full R J 2002 Evidence for van der Waals adhesion in gecko setae *Proc. Natl Acad. Sci. USA* **99** 12252–6
[3] Sitti M and Fearing R S 2003 Synthetic Gecko Foot-Hair Micro/Nanostructures for Future Wall- Climbing Robots *Proc. IEEE Robotics and Aut. Conf.*
[4] Geim A K, Dubonos S V, Grigorieva I V, Novoselov K S, Zhukov A A, Shapoval and S.Yu 2003 Microfabricated adhesive mimicking gecko foot-hair *Nat. Mater.* **2** 461–3
[5] Northen M T and Turner K L 2005 A batch fabricated biomimetic dry adhesive *Nanotechnology* **16** 1159–66
[6] Moon W, Kim S, Lee H S, Kim D S, Lee J, Lee K H and Kwon T H 2006 Replication of high-aspect-ratio nanopillar array for biomimetic gecko foot-hair prototype by UV nano embossing with anodic aluminum oxide mold *Microsyst. Technol.*
[7] Campolo D, Jones S D and Fearing R S 2003 Fabrication of gecko foot-hair like nano structures and adhesion to random rough surfaces *IEEE Nano 2003 (August 12–14)* vol 2 pp 856–9
[8] Majidi C, Groff R and Fearing R 1995 Attachment of fiber array adhesive through side contact *J. Appl. Phys.* **98** 103521
[9] Persson B N J and Gorb S 2003 The effect of surface roughness on the adhesion of elastic plates with application to biological systems *J. Chem. Phys.* **119** 11437
[10] Williams E E and Peterson J A 1982 Convergent and alternative designs in the digital adhesive pads of scincid lizards *Science* **215** 1509–11
[11] Hansen W R and Autumn K 2005 Evidence for self-cleaning in gecko setae *Proc. Natl Acad. Sci. USA* **102** 385–9
[12] Spolenak R, Gorb S, Gao H J and Arzt E 2004 Effects of contact shape on the scaling of biological attachments *Proc. R. Soc.* A **461** 305–19
[13] Huber G, Mantz H, Spolenak R, Mecke K, Jacobs K, Gorb S and Arzt E 2005 Evidence for capillarity contributions to gecko adhesion from single spatula nanomechanical measurements *Proc. Natl Acad. Sci. USA* **102** 16293–6
[14] Maderson P F A 1964 Keratinized epidermal derivatives as an aid to climbing gekkonid lizards *Nature* **203** 780–1
[15] Saunders A, Goldman D I, Full R J and Buehler M 2006 The RiSE climbing robot: Body and leg design *SPIE Proc.* **6230** 623017
[16] Ruibal R and Ernst V 1965 The structure of the digital setae in lizards *J. Morphol.* **117** 271–94
[17] Ruibal R and Ernst V 1967 The structure and development of the digital lamellae of lizards *J. Morphol.* **120** 233–66
[18] Russell A P 1975 A contribution to the functional analysis of the foot of the tokay, Gekko gecko (Reptilia: Gekkonidae) *J. Zool. Lond.* **176** 437–76
[19] Williams E E and Peterson J A 1982 Convergent and alternative designs in the digital adhesive pads of scincid lizards *Science* **215** 1509–11
[20] Huber G, Mantz H, Spolenak R, Mecke K, Jacobs K, Gorb S N and Arzt E 2005 *Proc. Natl Acad. Sci. USA* **99** 16293–6 102-45
[21] Rizzo N W, Gardner K H, Walls D J, Keiper-Hrynko N M, Ganzke T S and Hallahan D L 2006 *J. R. Soc. Interface* **3** 441–51
[22] Autumn K, Hsieh S T, Dudek D M, Chen J, Chitaphan C and Full R J 2006 The dynamics of vertical running in geckos *J. Exp. Biol.* **209** 260–72
[23] Gorb S, Niederegger S, Hayashi C Y, Summers A P, Votsch W and Walther P 2006 Biomaterials: silk-like secretion from tarantula feet *Nature* **443** 407–7
[24] Hirose S, Nagakubo A and Toyama R 1991 Machine that can walk and climb on floors, walls and ceilings *Proc. 5th Int. Conf. Advanced Robotics* pp 753–8
[25] Daltorio K A, Horchler A D, Gorb S, Ritzmann R E and Quinn R D 2005 A small wall-walking robot with compliant, adhesive feet *Proc. IROS 2005* pp 3648–53
[26] Xiao Z, Sadegh A, Elliot M, Calle A, Persad A and Chiu H M 2005 Design of mobile robots with wall climbing capability *Proc. of the 2005 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics* pp 438–43
[27] Hirose S, Imazato M, Kudo Y and Umetani Y 1986 Internally-balanced magnetic unit *Adv. Robot.* **3** 225–42
[28] Stokes R J 1997 *Fundamentals of Interfacial Engineering* (New York: Wiley-VCH) pp 17–38
[29] Autumn K, Dittmore A, Santos D, Spenko M and Cutkosky M 2006 Frictional adhesion: a new angle on gecko attachment *J. Exp. Biol.* **209** 3569–79
[30] Shah G J and Sitti M 2004 Modeling and design of biomimetic climbing robots *IEEE Int. Conf. Robotics*
[31] Spolenak R, Gorb S, Gao H J and Arzt E 2004 Effects of contact shape on the scaling of biological attachments *Proc. R. Soc.* **461** 305–19
[32] Gao H J, Wang X, Yao H M, Gorb S and Arzt E 2005 Mechanics of hierarchical adhesion structures of geckos *Mech. Mater.* **37** 275–85
[33] Yao H and Gao H 2006 Mechanics of robust and releasable adhesion in biology: bottom-up designed hierarchical structures of gecko *J. Mech. Phys. Solids* **54** 1120–46
[34] Autumn K, Majidi C, Groff R, Dittmore A and Fearing R 2006 Effective elastic modulus of isolated gecko setal arrays *J. Exp. Biol.* **209** 3558–68
[35] Takahashi K, Berengueres J, Saito S and Obata K J 2006 Gecko foot hair structure seems designed to control normal adhesion to take a quick step *Int. J. Adhes. Adhes* **26-8** 639–43
[36] Allen K W 1977 *ADHESION* (London: Applied Science) pp 185–90
[37] Inou N, Uesugi T and Ujihashi S 1995 Autonomous Formation of Biomimetic Structures by Cellular Automaton *Proc. 4th Japan Int. SAMPE Symp.* pp 621–6
[38] Glassmaker N J, Jagota A, Hui C Y and Kim J 2004 Design of biomimetic fibrillar interfaces: 1. Making contact. *J. R. Soc. Lond. Interface* **1** 1–11
[39] Hui C Y, Glassmaker N J, Tang T and Jagota A 2004 Design of biomimetic fibrillar interfaces: 2. Mechanics of enhanced adhesion *J. R. Soc. Lond. Interface* **1** 12–26