BioSystems 94 (2008) 218–222

Contents lists available at ScienceDirect

BioSystems

journal homepage: www.elsevier.com/locate/biosystems

Observation of optimal gecko's adhesion on nanorough surfaces

Nicola M. Pugno[a,b,*], Emiliano Lepore

[a] Department of Structural Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] National Institute of Nuclear Physics, National Laboratories of Frascati, Via E. Fermi 40, 00044 Frascati, Italy

ARTICLE INFO

Article history:
Received 23 April 2008
Accepted 3 June 2008

Keywords:
Geckos
Adhesion
Roughness
Optimal
Time
Weibull
Statistics

ABSTRACT

In this letter we report experimental observations on the times of adhesion of living Tokay geckos (*Gekko geckos*) on polymethylmethacrylate (PMMA) inverted surfaces. Two different geckos (male and female) and three surfaces with different root mean square (RMS) roughness (RMS = 42, 618 and 931 nm) have been considered, for a total of 72 observations. The measured data are proved to be statistically significant, following the Weibull Statistics with coefficients of correlation between 0.781 and 0.955. The unexpected result is the observation of a maximal gecko adhesion on the surface with intermediate roughness of RMS = 618 nm, that we note has waviness comparable to the seta size.

The Tokay gecko's (*Gekko geckos*) ability to "run up and down a tree in any way, even with the head downwards" was first observed by Aristotle, almost 25 centuries ago, in his *Historia Animalium*. However, the pioneer study on gecko adhesion has been done by Hiller (1968), who first provided scanning electron microscope (SEM) pictures of the setae, showing their hierarchical ultrastructure and high density of terminal spatulae; he first did a very careful experiment on living geckos, showing adhesion dependence on surface energy of the substrate. Ruibal and Ernst (1965) also discussed the structure of the digital setae of lizards. In spite of this, only recently, the adhesive force of a single gecko foot-hair has been measured (Autumn et al., 2000). Like geckos, a comparable adhesive mechanism and adhesive ability, resulting in an extraordinary ability to move on vertical surfaces and ceilings, can be found in other creatures, such as beetles, flies and spiders. A comparison between the gecko and spider nanostructured feet is reported in Fig. 1 (see Kesel et al., 2003; Pugno, 2007).

Surface roughness strongly influences the animal adhesion strength and ability. Its role was shown in different measurements on flies and beetles, walking on surfaces with well defined roughness (Dai et al., 2002; Persson and Gorb, 2003; Peressadko and Gorb, 2004), on the chrysomelid beetle *Gastrophysa viridula* (Gorb, 2001), on the fly *Musca domestica* (Peressadko and Gorb, 2004) as well as on the Tokay geckos (Huber et al., 2007). Peressadko and Gorb (2004) and Gorb (2001) report a minimum of the adhesive/frictional force, spanning surface roughness from 0.3 to 3 μm. The experiments on the reptile Tokay gecko (Huber et al., 2007) showed a minimum in the adhesive force of a single spatula at an intermediate root mean square (RMS) surface roughness around 100–300 nm, and a monotonic increase of adhesion times of living geckos by increasing the RMS, from 90 to 3000 nm.

There are several observations and models in the literature, starting with the pioneer paper by Fuller and Tabor (1975), in which roughness was seen to decrease adhesion monotonically. But there is also experimental evidence in the literature, starting with the pioneer paper by Briggs and Briscoe (1977), which suggests that roughness need not always reduce adhesion. For example, Persson and Tosatti (2001) and Persson (2002), in the framework of a reversible model, have shown that for certain ranges of roughness parameters, it is possible for the effective surface energy to first increase with roughness amplitude and then eventually decrease. Including irreversible processes, due to mechanical instabilities, Guduru (2007) has demonstrated, under certain hypotheses, that the pull-out force must increase by increasing the surface wave amplitude.

Here we suggest that roughness alone could not be sufficient to describe the three-dimensional topology of a complex surface and additional parameters have to be considered for formulating a well-posed problem. Accordingly, we have machined and characterized three different polymethylmethacrylate surfaces (PMMA 1–3; surface energy of ~41 mN/m) with a full set of roughness parameters, as reported in Table 1 (see Lepore et al., 2008 for details): Sa repre-

* Corresponding author at: Department of Structural Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy. Tel.: +39 0115644902; fax: +39 0115644899.
E-mail address: nicola.pugno@polito.it (N.M. Pugno).

0303-2647/$ – see front matter © 2008 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.biosystems.2008.06.009

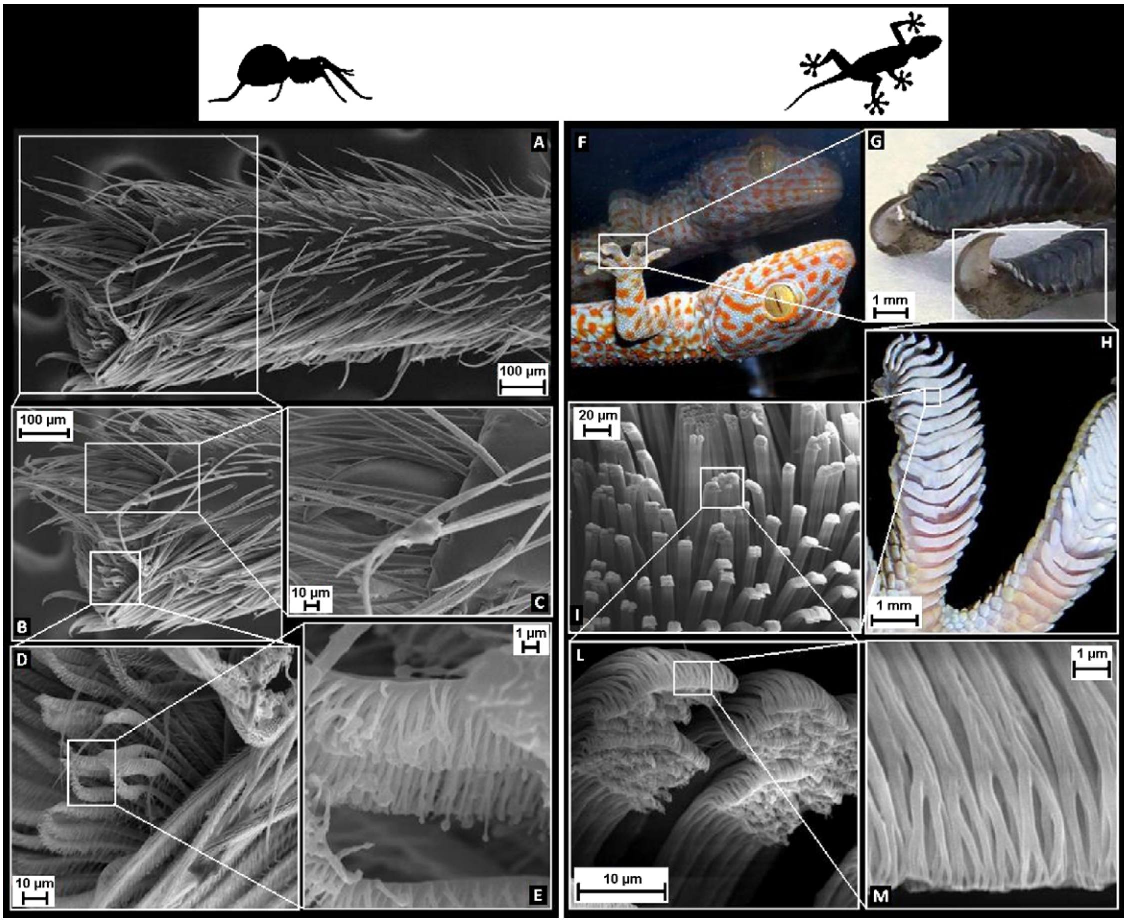

Fig. 1. Spider and gecko feet showed by SEM. In the Tokay gecko (F) the attachment system is characterized by a hierarchical hairy structures, which starts with macroscopic lamellae (soft ridges ~1 mm in length, H), branching in setae (30–130 μm in length and 5–10 μm in diameter, I and L; Ruibal and Ernst, 1965; Hiller, 1968; Russell, 1975; Williams and Peterson, 1982). Each seta consists of 100–1000 substructures called spatulae (Ruibal and Ernst, 1965; Hiller, 1968), the contact tips (0.1–0.2 μm wide and 15–20 nm thick, M; Ruibal and Ernst, 1965; Hiller, 1968) responsible for the gecko's adhesion. Terminal claws are located at the top of each singular toe (G). Van der Waals and capillary forces are responsible for the generated adhesive forces (Autumn and Peattie, 2002; Sun et al., 2005), whereas claws guarantee an efficient attachment system on surfaces with very large roughness. Similarly, in spiders (e.g. *Evarcha arcuata*, Kesel et al., 2003) an analogous ultrastructure is found. Thus, in addition to the tarsal claws, which are present on the tarsus of all spiders (C), adhesive hairs can be distinguished in many species (D and E). Like for insects, these adhesive hairs are specialised structures that are not restricted only to one particular area of the leg, but may be found either distributed over the entire tarsus, as for lycosid spiders, or concentrated on the pretarsus as a tuft (scopula) situated ventral to the claws (A and B), as in the jumping spider *Evarcha arcuata* (Kesel et al., 2003).

sents the surface arithmetical average roughness; Sq = RMS is the classical mean square roughness; Sp and Sv are respectively the height of the highest peak and the deepness of the deepest valley (absolute value); Sz is the average distance between the five highest peaks and the five deepest valleys (detected in the analyzed area); Ssk indicates the surface skewness; Sdr is the effective surface area minus the nominal one and divided by the last one.

Two different Tokay gecko's, female (G1, weight of ~46 g) and male (G2, weight of ~72 g), have been considered. The gecko is first placed in its natural position on the horizontal bottom of a box (50 cm × 50 cm × 50 cm). Then, slowly, we rotated the box up to the gecko reaches a natural downwards position and, at that time, we start the measurement of the time of adhesion. We excluded any trial in which the gecko walks on the inverted surface. The time measurement was stopped when gecko breaks loose from the inverted surface and falls on the bottom of the box (for G1) or at the first detachment movement of the gecko's foot (for G2). The time between one measurement and the following, pertaining to the same set, is only that needed to rotate the box and place the gecko again on the upper inverted surface (~14 s). The experiments were performed at ambient temperature (~22 °C) and humidity (~75%). The measured adhesion times are summarized in Table 2 and confirmed to be statistically significant by applying Weibull Statistics, see Fig. 2.

We have observed a maximum in the gecko's adhesion times on PMMA 2, having an intermediate roughness of RMS = 618 nm. An oversimplified explanation could be the following. For PMMA 1 (Sq = 42 nm, waviness of $\lambda \approx 3$–4 μm, amplitude of $h \approx 0.1$ μm), the gecko's seta (diameter of ~10 μm, represented in blue in Fig. 3, that must not be confused with the terminal nearly two-dimensional spatualae) cannot penetrate in the characteristic valleys and adhere on their side (Fig. 3A), thus cannot optimally adapt to the surface

Table 1
Roughness parameters for the three different polymethylmethacrylate (PMMA 1–3) surfaces

	PMMA1	PMMA2	PMMA3
Sa (μm)	0.033 ± 0.0034	0.481 ± 0.0216	0.731 ± 0.0365
Sq (μm)	0.042 ± 0.0038	0.618 ± 0.0180	0.934 ± 0.0382
Sp (μm)	0.252 ± 0.0562	2.993 ± 0.1845	4.620 ± 0.8550
Sv (μm)	0.277 ± 0.1055	2.837 ± 0.5105	3.753 ± 0.5445
Ssk	−0.122 ± 0.1103	0.171 ± 0.1217	0.192 ± 0.1511
Sz (μm)	0.432 ± 0.1082	4.847 ± 0.2223	6.977 ± 0.2294
Sdr (%)	0.490 ± 0.0214	15.100 ± 1.6093	28.367 ± 2.2546

Table 2
Gecko adhesion times on PMMA 1–3 surfaces

Test no.	PMMA 1	PMMA 2	PMMA 3
1	8	137	15
2	13	215	22
3	36	243	22
4	37	280	25
5	48	498	27
6	62	610	29
7	67	699	32
8	87	900	35
9	88	945	48
10	93	1194	51
11	116	1239	53
12	134	1320	91
13	145	2275	97
14	160	2740	102
15	197		109
16	212		114
17	215		148
18	221		207
19	228		424
20	292		645
21	323		
22	369		
23	474		
24	550		
25	568		
26	642		
27	660		
28	700		
29	707		
30	936		
31	1268		
32	1412		
33	1648		
34	1699		
35	2123		
36	2703		
37	2899		
Scale parameter t_0 (s)	800	1251.7	108.4
Sq (μm)	0.042 ± 0.0038	0.618 ± 0.0180	0.934 ± 0.0382

Note that, as an index of the gecko adhesion ability, here we use the Weibull scale parameter t_0 (in seconds) of the distribution of the detachment/failure F (closely related to its mean value).

roughness. For PMMA 2 (Sq = 618 nm, $\lambda \approx 7$–$8\,\mu$m, $h \approx 1\,\mu$m) the gecko's setae are able to adapt better to the roughness: thus the effective number of setae in contact increases and, as a direct consequence, also the adhesion ability of the gecko increases (Fig. 3B). On PMMA 3 (Sq = 931 nm, $\lambda \approx 10$–$12\,\mu$m and $h \approx 2\,\mu$m) the waviness characterizing the roughness is larger than the seta's size: as a consequence, a decreasing in the number of setae in contact is expected (Fig. 3C). As a result, on PMMA 2 an adhesion increment, of about 45%, is observed.

According to Briggs and Briscoe (1977) an increment of 40%, thus close to our observation, is expected for an adhesion parameter α equal to 1/3. Such a parameter was introduced as the key parameter in governing adhesion by Fuller and Tabor (1975) as:

$$\alpha = \frac{4\sigma}{3}\left(\frac{4E}{3\pi\sqrt{\beta}\gamma}\right)^{2/3} \qquad (1)$$

where σ is the standard deviation of the asperity height distribution (assumed to be Gaussian), β is the mean radius of curvature of the asperity, γ is the surface energy and E is the Young modulus of the soft solid (gecko foot). Even if the value of E of the entire foot cannot be simply defined, as a consequence of its non-compact structure, we note that considering it to be of the order of 10 MPa (thus much smaller than that of the keratin material), with γ = 0.05 N/m (Autumn et al., 2000), $\sigma \approx$ Sq, $\beta \approx \lambda$ would correspond to values of α close to 0.5.

The reported maximal adhesion was not observed by Huber et al. (2007). Note that their tested polished surfaces were of five different types, with a nominal asperity size of 0.3, 1, 3, 9 and 12 μm, which correspond to RMS values of 90, 238, 1157, 2454 and 3060 nm, respectively. Huber et al. (2007) have observed sliding of geckos on polishing paper with a RMS value of 90 nm for slopes larger than 135°. On a rougher substrate, with a RMS value of 238 nm, two individual geckos were able to cling to the ceiling for a while, but the foot-surface contact had to be continuously renewed because gecko toes slowly tend to slid off the substrate. Finally, on the remaining tested rougher substrates, animals were able to adhere stably to the ceiling for more than 5 min.

These different observations (assuming that the influences of claws and moult were minimized also by Huber et al., 2007) suggest that the RMS parameter is not sufficient alone to describe all the aspects of the surface roughness. The use of a "complete" set of roughness parameters, as we have here proposed, could help in better understanding the animal adhesion.

The authors would like to thank M. Buono and S. Toscano, DVM and SIVAE member, for the technical and veterinary aid and also for the support on the experimental measurements. We gratefully acknowledge the "2I3T Scarl-Incubatore dell'Università di Torino" for SEM imaging instruments and M.G. Faga, CNR-ISTEC member, Chemical Department IFM and NIS Centre of Excellence, University of Torino for the fundamental help in performing the

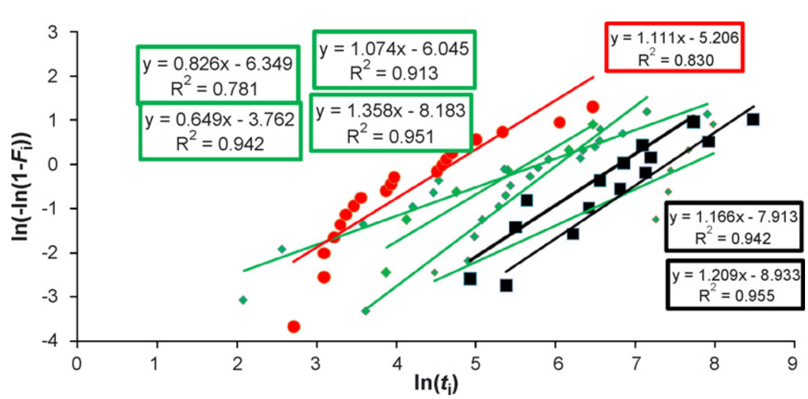

Fig. 2. Weibull Statistics (F is the cumulative probability of detachment/failure and t_i are the measured adhesion times) applied to the measured adesion times on PMMA surfaces. PMMA 1 (green, for which we made the measurements in four different days and with both geckos G1 and G2), PMMA 2 (black, for which we made the measurements in 2 different days, one with gecko G1 and one with gecko G2) and PMMA 3 (red, for which we made the measurements in a single day with gecko G2).

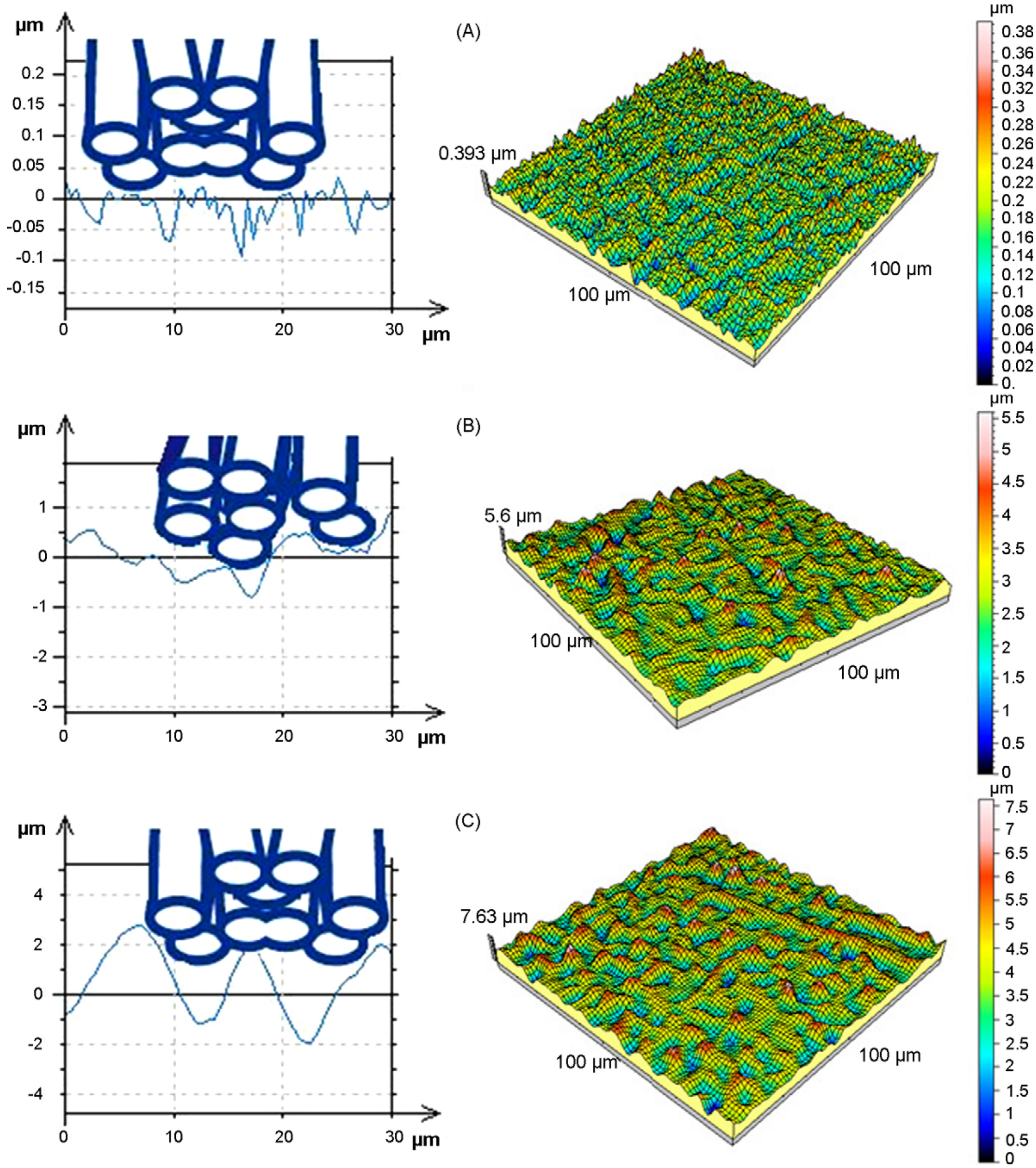

Fig. 3. A simple interpretation of our experimental results on the adhesion tests of living geckos on PMMA surfaces having different roughness. (A) Setae cannot adapt well on PMMA 1; (B) on PMMA 2 the adhesion is enhanced thanks to the higher compatibility in size between setae and roughness; (C) on PMMA 3 only partial contact is achieved. On the right, we report the analyzed three-dimensional profiles of the roughness for all the three investigated surfaces (from the top: PMMA 1–3).

SEM micrographs. NMP is supported by the "Bando Ricerca Scientifica Piemonte 2006", BIADS: Novel biomaterials for intraoperative adjustable devices for fine tuning of prostheses shape and performance in surgery.

References

Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R., Full, R.J., 2000. Adhesive force of a single gecko foot-hair. Nature 405, 681–685.

Autumn, K., Peattie, A.M., 2002. Mechanism of adhesion in geckos. Integr. Comp. Biol. 42, 1081–1090.

Briggs, G.A.D., Briscoe, B.J., 1977. The effect of surface topography on the adhesion of elastic solids. J. Phys. D: Appl. Phys. 10, 2453–2466.

Dai, Z., Gorb, S.N., Schwarz, U., 2002. Roughness-dependent friction force of the tarsal claw system in the beetle *Pachnoda marginata* (Coleoptera Scarabaeidae). J. Exp. Biol. 205, 2479–2485.

Fuller, K.N.G., Tabor, D., 1975. The effect of surface roughness on the adhesion of elastic solids. Proc. R. Soc. Lond. A vol. 345, 327–342.

Gorb, S.N., 2001. Attachment Devices of Insect Cuticle. Dordrecht: Kluwer Academic Publishers.

Guduru, P.R., 2007. Detachment of a rigid solid from an elastic wavy surface: theory. J. Mech. Phys. Solids 55, 445–472.

Hiller, U., 1968. Untersuchungen zum Feinbau und zur Funktion der Haftborsten von Reptilien. Z. Morphol. Tiere 62, 307–362.

Huber, G., Gorb, S.N., Hosoda, N., Spolenak, R., Arzt, E., 2007. Influence of surface roughness on gecko adhesion. Acta Biomater. 3, 607–610.

Kesel, A.B., Martin, A., Seidl, T., 2003. Adhesion measurements on the attachment devices of the jumping spider *Evarcha arcuata*. J. Exp. Biol. 206, 2733–2738.

Lepore, E., Antoniolli, F., Brianza, S., Buono, M., Carpinteri, A., Pugno, N., 2008. Preliminary in vivo experiments on adhesion of geckos. J. Nanomater., in press.

Peressadko, A.G., Gorb, S.N., 2004. Surface profile and friction force generated by insects. In: Boblan, I., Bannasch, R. (Eds.), Bionik, vol. 15. Hannover, p. 237.

Persson, B.N.J., 2002. Adhesion between and elastic body and a randomly hard surface. Eur. Phys. J. E 8, 385–401.

Persson, B.N.J., Gorb, S., 2003. The effect of surface roughness on the adhesion of elastic plates with application to biological systems. J. Chem. Phys. 119, 11437–11444.
Persson, B.N.J., Tosatti, E., 2001. The effect of surface roughness on the adhesion of elastic solids. J. Chem. Phys. 115, 5597–5610.
Pugno, N.M., 2007. Towards a Spiderman suit: large invisible cables and self-cleaning releasable superadhesive materials. J. Phys.: Condens. Matter 19, 17 (395001).
Ruibal, R., Ernst, V., 1965. The structure of the digital setae of lizards. J. Morphol. 117, 271–294.
Russell, A.P., 1975. A contribution to the functional morphology of the foot of the tokay, Gekko gecko. J. Zool. Lond. 176, 437–476.
Sun, W., Neuzil, P., Kustandi, T.S., Oh, S., Samper, V.D., 2005. The nature of the gecko lizard adhesive force. Biophys. J. 89, L14–L17.
Williams, E.E., Peterson, J.A., 1982. Convergent and alternative designs in the digital adhesive pads of scincid lizards. Science 215, 1509–1511.