Experimental analysis on the adhesion of living tokay geckos on nanorough surfaces

Emiliano Lepore[1], Nicola Pugno[2]

[1,2]*Department of Structural Engineering, Politecnico di Torino, Torino, Italy*

[1]*emiliano.lepore@polito.it; presenting author*

[2]*nicola.pugno@polito.it; corresponding author*

Keywords: Geckos, Adhesion, Nanoroughness.

SUMMARY. With *in vivo* observations and time measurements, we have demonstrated that living geckos display adhesion times following Weibull statistics and the Weibull shape and scale parameters can be used to describe quantitatively the statistics of the adhesion times of different geckos (male or female), materials (glass or PMMA), and interfaces (virgin or machined PMMA surfaces).

1 INTRODUCTION

The Tokay gecko's (*Gekko gecko*) ability to "run up and down a tree in anyway, even with the head downwards" was first observed by Aristotle, almost 25 centuries ago [1]. However, the pioneer study on gecko adhesion has been done by Hiller [2], who first provided 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. The structure of the digital setae of lizards was discussed [3]. In spite of this, only recently, the adhesive force of a single gecko foot-hair has been measured [4]. 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 [5, 6].

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 [11, 12, 13], on the chrysomelid beetle *Gastrophysa viridula* [14], on the fly *Musca domestica* [13] as well as on the Tokay geckos [15]. A minimum of the adhesive/frictional force, spanning surface roughness from 0.3 to 3 μm, was reported [13, 14].

The experiments on the reptile Tokay gecko [15] 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 [16], 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 [17], which suggests that roughness need not always reduce adhesion. For example, in the framework of a reversible model [18, 19], it was 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, it was demonstrated, under certain hypotheses, that the pull-out force must increase by increasing the surface wave amplitude [20].

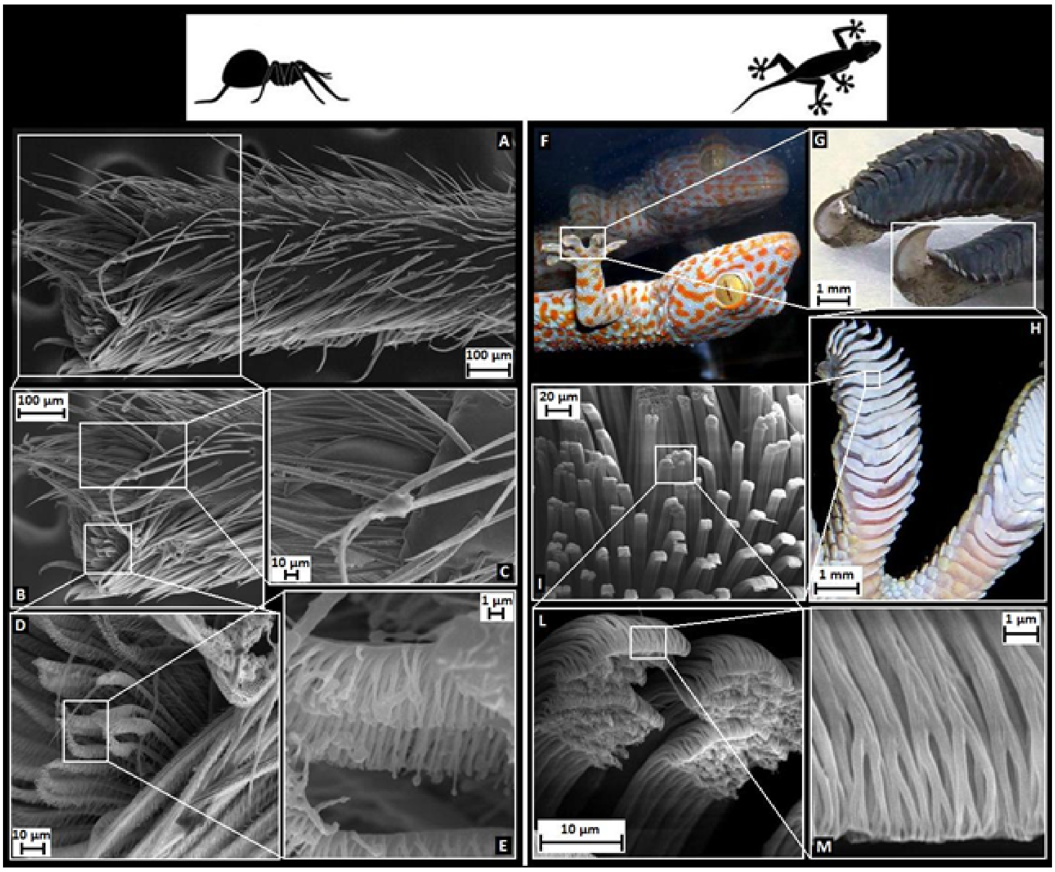

Figure 1. Spider and gecko feet showed by SEM. In the Tokay gecko (Fig. 1 F) the attachment system is characterized by a hierarchical hairy structures, which starts with macroscopic lamellae (soft ridges ~1 mm in length, Fig. 1 H), branching in setae (30-130 µm in length and 5-10 µm in diameter, Fig. 1 I, L) [2, 3, 7, 8]. Each seta consists of 100-1000 substructures called spatulae [2, 3], the contact tips (0.1-0.2 µm wide and 15-20 nm thick, Fig. 1 M) responsible for the gecko's adhesion [2, 3]. Terminal claws are located at the top of each singular toe (Fig. 1 G). Van der Waals and capillary forces are responsible for the generated adhesive forces [9, 10], whereas claws guarantee an efficient attachment system on surfaces with very large roughness. Similarly, in spiders (e.g. *Evarcha arcuata*) an analogous ultrastructure is found [5]. Thus, in addition to the tarsal claws, which are present on the tarsus of all spiders (Fig. 1 C), adhesive hairs can be distinguished in many species (Fig. 1 D, 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 (Fig. 1 A, B), as in the jumping spider *Evarcha arcuata* [5].

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 [21] for details): Sa represents 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.

	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 1. Roughness parameters for the three different Polymethylmethacrylate (PMMA 1, 2, 3) surfaces.

In addition, we demonstrate that living tokay geckos display adhesion times on PMMA and glass surfaces following Weibull Statistics. Considering all the analyzed PMMA surfaces, both virgin and machined ones, we have found a value of the Weibull modulus in the restricted range m_{PMMA}=1–1.2, suggesting that this value could be a characteristic of the PMMA-gecko interaction. Similarly, for glass the Weibull modulus is m_{Glass}=2.0.

2 MATERIAL AND METHODS

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 stoppedwhen 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 confirmed to be statistically significant by applying Weibull Statistics (Fig. 2 summarized the results of adhesion times on PMMA surfaces and Figure 3 shows the results of adhesion times on glass surfaces).

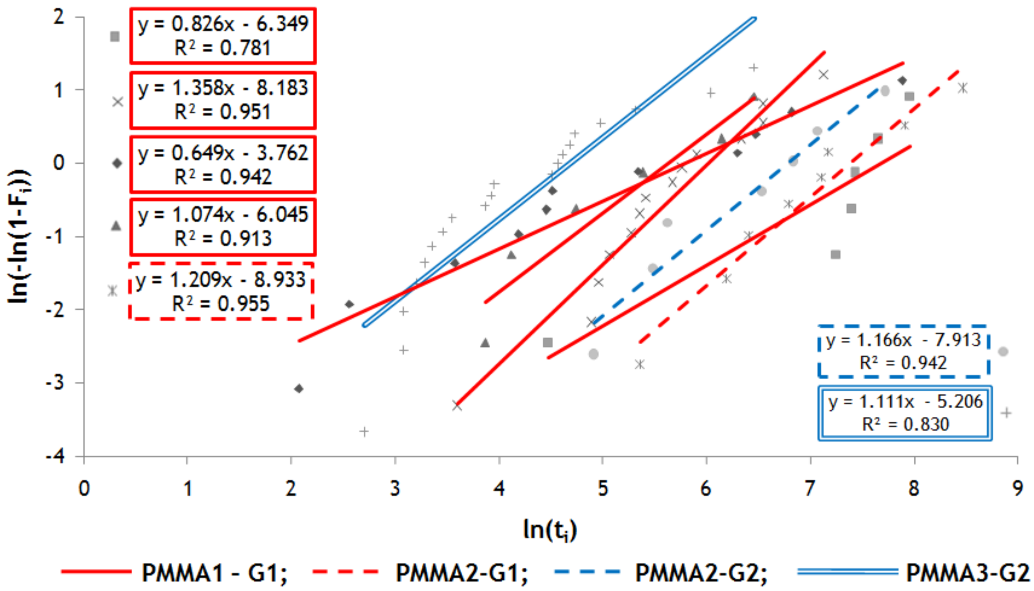

Figure 2. Weibull Statistics (F is the cumulative probability of detachment/failure and t_i are the measured adhesion times) applied to the measured adhesion times on PMMA surfaces. PMMA 1 (red lines, for which we made the 4 sets of measurements in four different days with gecko G1), PMMA 2 (dotted lines, for which we made the 2 sets of measurements in two different days, one with gecko G1 (red) and one with gecko G2 (blue)) and PMMA 3 (blue double-line, for which we made the measurements in a single day with gecko G2).

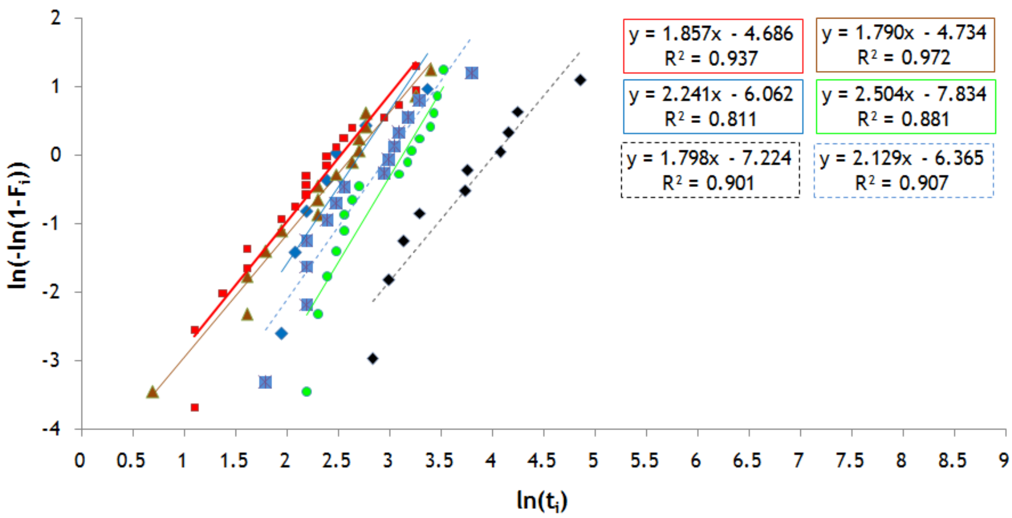

Figure 3. The standard Weibull statistics applied to the results of 4 sets of measurements of the first gecko (G1) and 2 sets of measurements of the second gecko (G2) (dotted line) on the glass surface.

3 RESULTS

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. 4, that must not be confused with the terminal nearly two-dimensional spatualae) cannot penetrate in the characteristic valleys and adhere on their side (Fig. 4A), thus cannot optimally adapt to the surface roughness. For PMMA 2 (Sq = 618 nm, $\lambda \approx 7$–8 μm, $h \approx 1$ μm) 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. 4B). On PMMA 3 (Sq = 931 nm, $\lambda \approx 10$–12 μm and $h \approx 2$ μm) 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. 4C). As a result, on PMMA 2 an adhesion increment, of about 45%, is observed.

According to paper [17] 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 as [16]:

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

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 $\gamma = 0.05$ N/m [4], $\sigma \approx$ Sq, $\beta \approx \gamma$ would correspond to values of α close to 0.5.

The reported maximal adhesion was not observed by Huber et al. [15]. 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. In paper [15], Huber et al. 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.

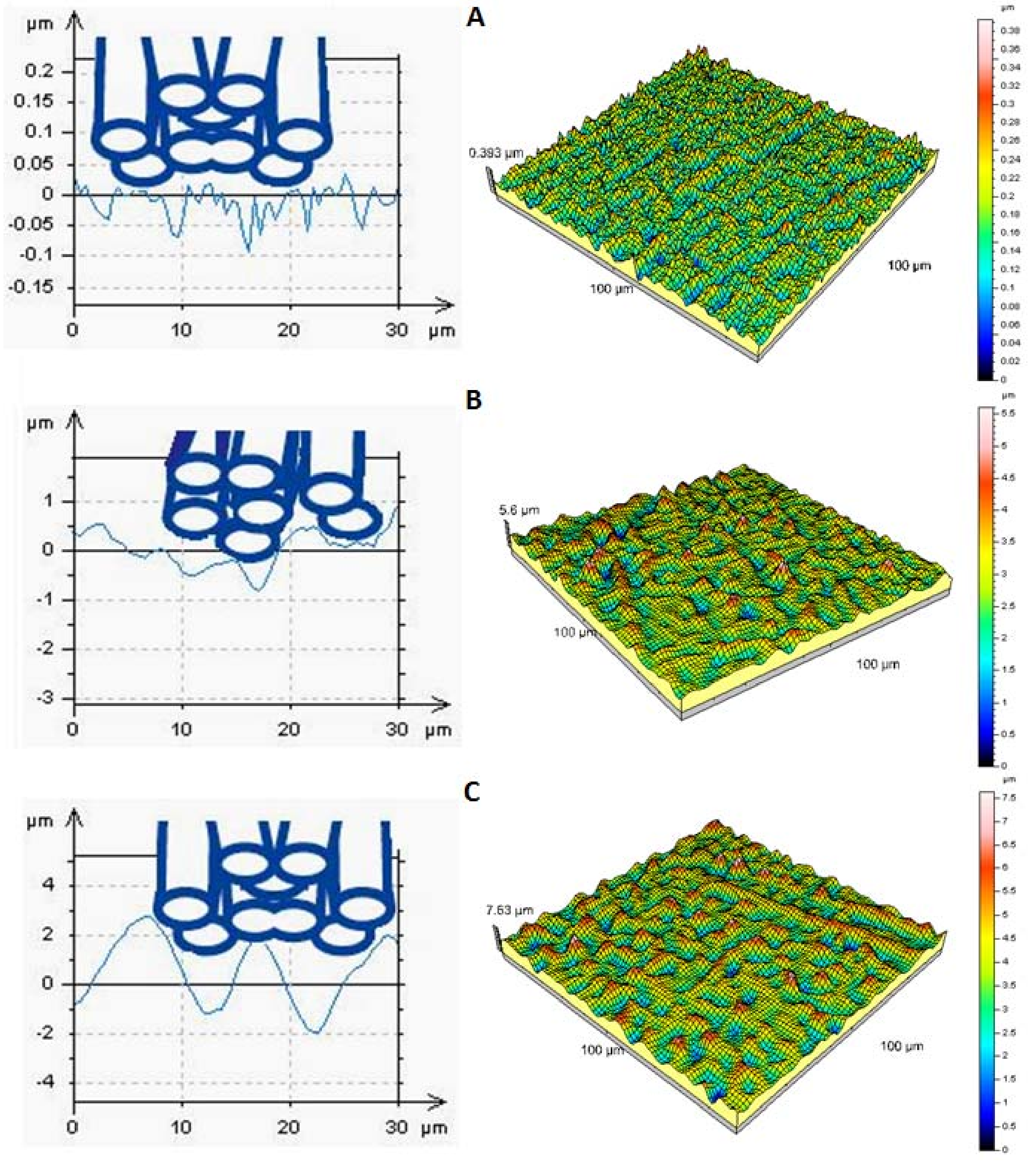

Figure 4. A simple interpretation of our experimental results on the adhesion tests of living geckos on PMMA surfaces having different roughness. (A) Setae cannot adapt well on PMMA 1; (B) on PMMA 2 the adhesion is enhanced thanks to the higher compatibility in size between setae and roughness; (C) on 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, 2 and 3).

4 CONCLUSION

Our observations (assuming that the influences of claws and moult were minimized also by Huber et al., [15]) 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.

References

[1] Aristotele, *Historia Animalium*, translated by D’Arcy Wentworth Thompson (see http://etext.library.adelaide.edu.au/a/aristotle/history/).

[2] Hiller, U., “Untersuchungen zum Feinbau und zur Funktion der Haftborsten von Reptilien”, *Z. Morphol. Tiere* **62**, 307–362 (1968).

[3] Ruibal, R. and Ernst, V., “The structure of the digital setae of lizards”, *J. Morphol.* **117**, 271–294 (1965).

[4] Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch,W., Chan,W.P., Kenny, T.W., Fearing, R. and Full, R.J., “Adhesive force of a single gecko foot-hair”, *Nature* **405**, 681–685 (2000).

[5] Kesel, A.B., Martin, A. and Seidl, T., “Adhesion measurements on the attachment devices of the jumping spider *Evarcha arcuata*”, *J. Exp. Biol.* **206**, 2733–2738 (2003).

[6] Pugno, N.M., “Towards a Spiderman suit: large invisible cables and self-cleaning releasable superadhesive materials”, *J. Phys.: Condens. Matter* **19**, 17 (395001) (2007).

[7] Russell, A.P., “A contribution to the functional morphology of the foot of the tokay, *Gekko gecko”, J. Zool. Lond.* **176**, 437–476 (1975).

[8] Williams, E.E. and Peterson, J.A., “Convergent and alternative designs in the digital adhesive pads of scincid lizards”, *Science* **215**, 1509–1511 (1982).

[9] Autumn, K. and Peattie, A.M., “Mechanism of adhesion in geckos”, *Integr. Comp. Biol.* **42**, 1081–1090 (2002).

[10] Sun,W., Neuzil, P., Kustandi, T.S., Oh, S. and Samper, V.D., “The nature of the gecko lizard adhesive force”, *J. Biophys.* **89**, L14–L17 (2005).

[11] Dai, Z., Gorb, S.N. and Schwarz,U., “Roughness-dependent friction force of the tarsal claw systemin the beetle Pachnoda marginata (*Coleoptera Scarabaeidae*)”, *J. Exp. Biol.* **205**, 2479–2485 (2002).

[12] Persson, B.N.J. and Gorb, S., “The effect of surface roughness on the adhesion of elastic plates with application to biological systems”, *J. Chem. Phys.* **119**, 11437–11444 (2003).

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

[14] Gorb, S.N., *Attachment Devices of Insect Cuticle*, Dordrecht: Kluwer Academic Publishers (2001).

[15] Huber, G., Gorb, S.N., Hosoda, N., Spolenak, R. and Arzt, E., “Influence of surface roughness on gecko adhesion”, *Acta Biomater.* **3**, 607–610 (2007).

[16] Fuller, K.N.G. and Tabor, D., “The effect of surface roughness on the adhesion of elastic solids”, *Proc. R. Soc. Lond.* A Vol. **345**, 327–342 (1975).

[17] Briggs, G.A.D. and Briscoe, B.J., “The effect of surface topography on the adhesion of elastic solids”, *J. Phys. D: Appl. Phys.* **10**, 2453–2466 (1977).

[18] Persson, B.N.J. and Tosatti, E., “The effect of surface roughness on the adhesion of elastic solids”, *J. Chem. Phys.* **115**, 5597–5610 (2001).

[19] Persson, B.N.J., “Adhesion between and elastic body and a randomly hard surface”, *Eur. Phys. J. E* **8**, 385–401 (2002).

[20] Guduru, P.R., "Detachment of a rigid solid from an elastic wavy surface: theory", *J. Mech. Phys. Solids* **55**, 445–472 (2007).
[21] Lepore, E., Antoniolli, F., Brianza, S., Buono, M., Carpinteri, A. and Pugno, N. "Preliminary *in vivo* experiments on adhesion of geckos", *J. Nanomaterials*, Vol. **2008**, Article ID 194524, 5 pages (2008).