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

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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-

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doi:10.1016/j.biosystems.2008.06.009

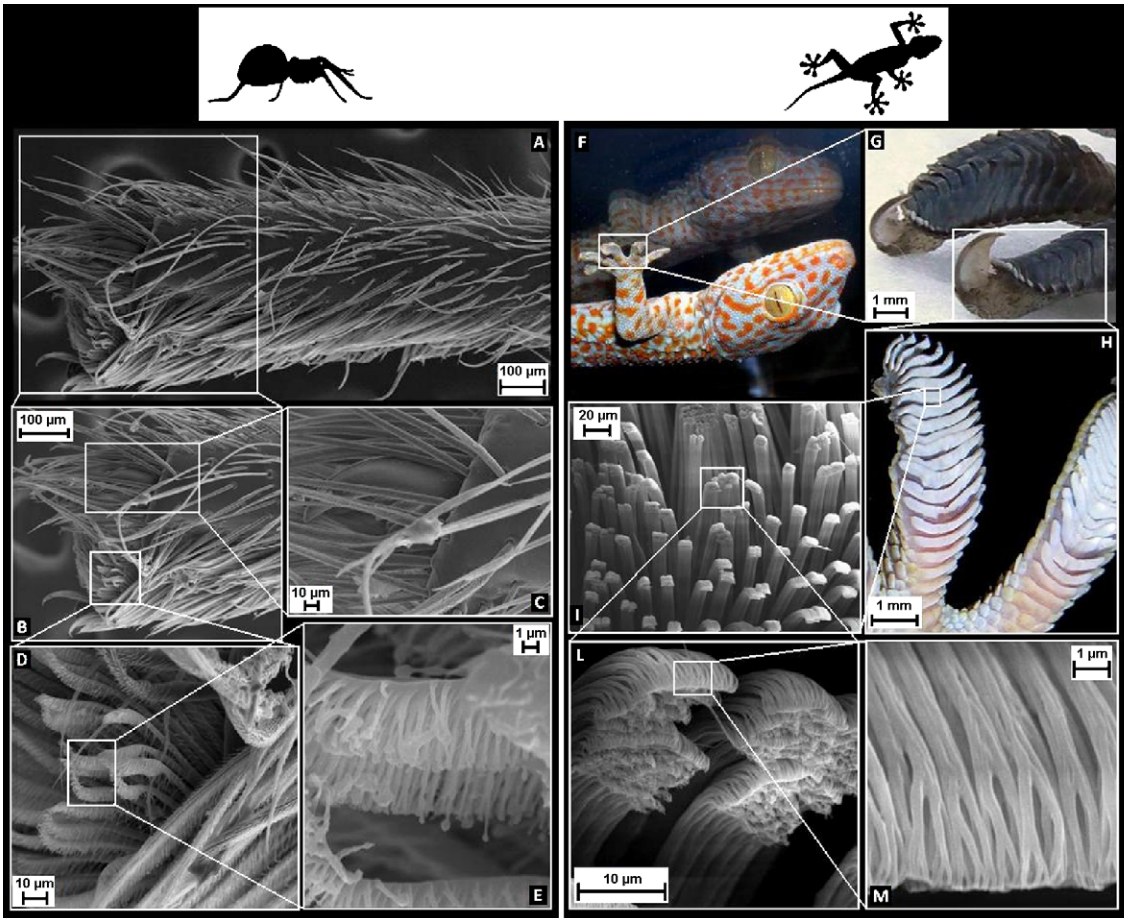

Fig. 1. Spider and gecko feet showed by SEM. In the Tokay gecko (F) the attachment system is characterized by a hierarchical hairy structures, which starts with macroscopic lamellae (soft ridges ~1 mm in length, H), branching in setae (30–130 μm in length and 5–10 μm in diameter, I and L; Ruibal and 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