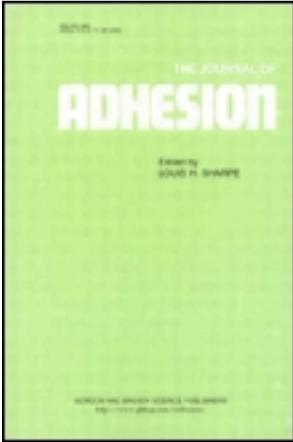


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Optimal Angles for Maximal Adhesion in Living Tokay Geckos

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*In this paper, we report experimental measurements of the adhesive angles of living Tokay geckos (*Gekko gecko*) at the two different characteristic sizes of the feet and toes. In particular, we have determined the adhesive angles between the opposing front and rear feet and between the first and fifth toe of each foot on different inverted surfaces [steel, aluminium, copper, poly(methyl methacrylate), and glass]. We rationalize the experimental results with the multiple peeling theory, recently derived, finding an interesting agreement; previous reported observations on the architecture of the gecko adhesive system, even at the size scale of the single seta, suggest the validity of the approach at different hierarchical levels.*

KEYWORDS *Geckos; Hierarchical levels; Living; Maximal adhesion; Optimal angles*

1. INTRODUCTION

Geckos, and more, in general, lizards, usually climb in complex three-dimensional habitats and this is what determines the development of such a sophisticated dry adhesive system on their pads. During the last century, many of the secrets of the gecko adhesion have been explained [1–30], although some crucial problems still remain not completely solved

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[14,19,21,31–34]. Such open questions include function, molecular mechanism, morphological characteristics of the nano-hierarchical structures, mechanism of frictional adhesion, tail function during climbing or aerial descent, and interactive effects of size and loading on kinematics. The milli seconds controllable attachment/detachment mechanism in geckos with negligible forces assumed a huge importance also from a technological point of view, *e.g.*, fabrication of dry adhesives, robotics systems, artificial adhesive suits, and gloves for astronauts [21,23,30,35–41]; this is achieved thanks to the uniqueness of the gecko adhesive system in terms of repeatable strong foot contacts combined with temporary and reversible weak bonds, basically intermolecular van der Waals forces [14,30,33,42–44]. In order to maintain the necessary shear/frictional adhesive [12] forces and to avoid toe detachment, the gecko adhesive mechanism is based on the use of opposing feet and toes making a V-shaped geometry and the gecko attachment being achieved only proximally along the toe axis of the gecko, which pulls its feet inwards towards the center of mass (COM) and its toes inwards towards the foot to engage adhesion [14,21,30,31,34,45,46], as schematically reported in Fig. 1A.

The key factor that governs the gecko mechanism of attachment/detachment is the adhesion angle, α , between the terminal structure attached to the surface and the surface itself. Several scientific studies have been developed to establish the value of the angle α from an experimental [12,21,31,32], computational [14,19,31,41,47], or theoretical [19,29,34,41,46, 48–58] point of view and at different characteristic sizes of the hierarchical adhesive system. From the literature, the angle α of Tokay geckos (*Gekko gecko*) is equal to $\sim 25.5^\circ$ for a single toe, $\sim 24.6^\circ$ (or $\sim 30^\circ$) for isolated setae arrays, and $\sim 30.0^\circ$ (or $\sim 31^\circ$) for a single seta [21] (or [31]).

In this paper, we evaluated experimentally the adhesive angles of living Tokay geckos at the two different hierarchical characteristic sizes of the feet and toes. We measured the angles between the opposing front and rear feet and between the first and fifth toe of each foot on five different surfaces [steel, aluminium, copper, poly(methyl meth-acrylate), *i.e.*, PMMA, and glass] and compared them with the new theory of multiple peeling [48], and other previous published experimental results, finding an interesting agreement with theoretical results. This finding could be useful for the industrial fabrication of dry adhesives, robotics systems, artificial adhesive suits, and gloves for astronauts or redesigning bio-inspired smart adhesive nanomaterials, in general.

2. MATERIAL AND METHODS

We used a single male adult Tokay gecko maintained in its terrarium at $\sim 28^\circ\text{C}$. The gecko was provided with food (moths and crickets with

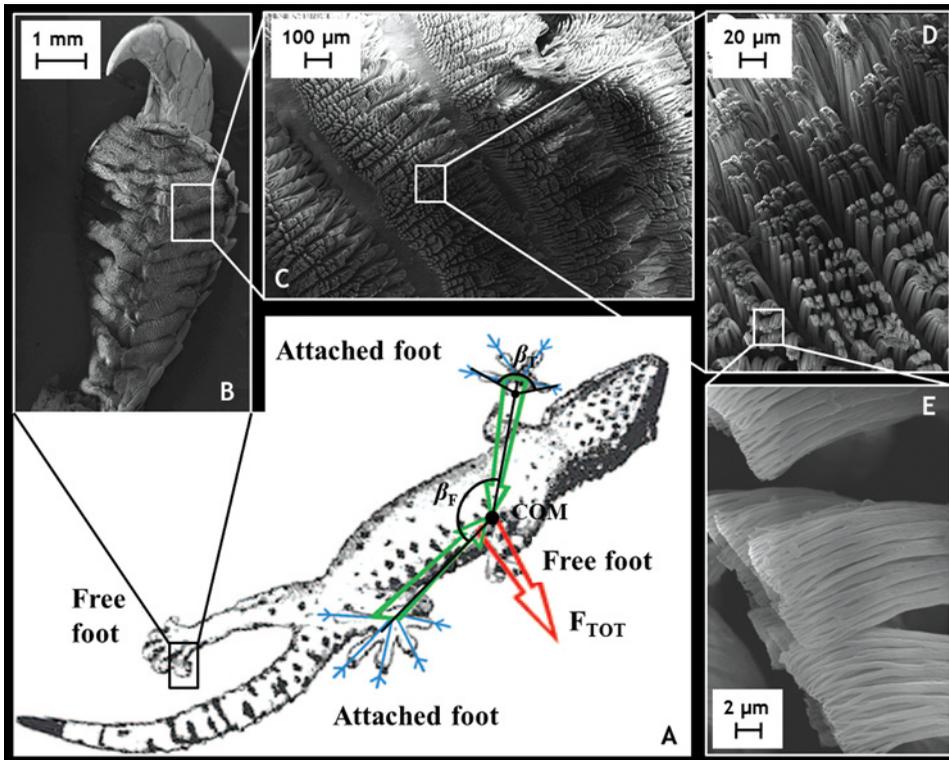


FIGURE 1 (A) A schematic 3D representation of the measured angle between both the opposed front-rear feet (β_F) and the first-fifth toe (β_T) of each foot on inverted surfaces; inset adapted from Y. Tian, N. Pesika, H. Zeng, K. Rosenberg, B. Zhao, P. M., K. Autumn, and J. Israelachvili, Adhesion and friction in gecko toe attachment and detachment. 19320–19325, PNAS, December 19, 2006, vol. 103, no. 51; Copyright (2006) National Academy of Science, U.S.A. Gecko adhesion system showed by (B, C, D) FESEM (ZEISS SUPRA 40) and by (E) SEM (ZEISS EVO 50). (B) Tokay gecko toe, (C) FESEM micrograph of the setae array, (D) SEM micrograph of several setae, and (E) nanoscale array of hundreds of spatula tips (color figure available online).

calcium supplement) and water *ad libitum*. The animal and all experimental procedures were authorized by Ministerial Decree n° 73/2010-B.

The animal was placed in its natural position on the horizontal bottom of a box ($50 \times 50 \times 50 \text{ cm}^3$) composed of the tested surfaces. Then, slowly, we rotated the box, so that the gecko reached its downwards position under only its weight ($\sim 88 \text{ g}$). At this time, we recorded the adhesive angle between the opposing front and rear feet (β_F) and between the first and fifth toe (β_T) of each foot on inverted surfaces (steel, aluminium, copper, PMMA, and glass; Vetronova, Varese, Italy) at every new attachment. Each leg is named as follows: front right (FR), front left (FL), rear right (RR), rear left (RL). All experiments were performed at an ambient (experimental box) temperature of $\sim 21^\circ\text{C}$ ($\sim 25^\circ\text{C}$) and humidity of $\sim 50\%$ ($\sim 30\%$). Figures 2 and 3 report, as

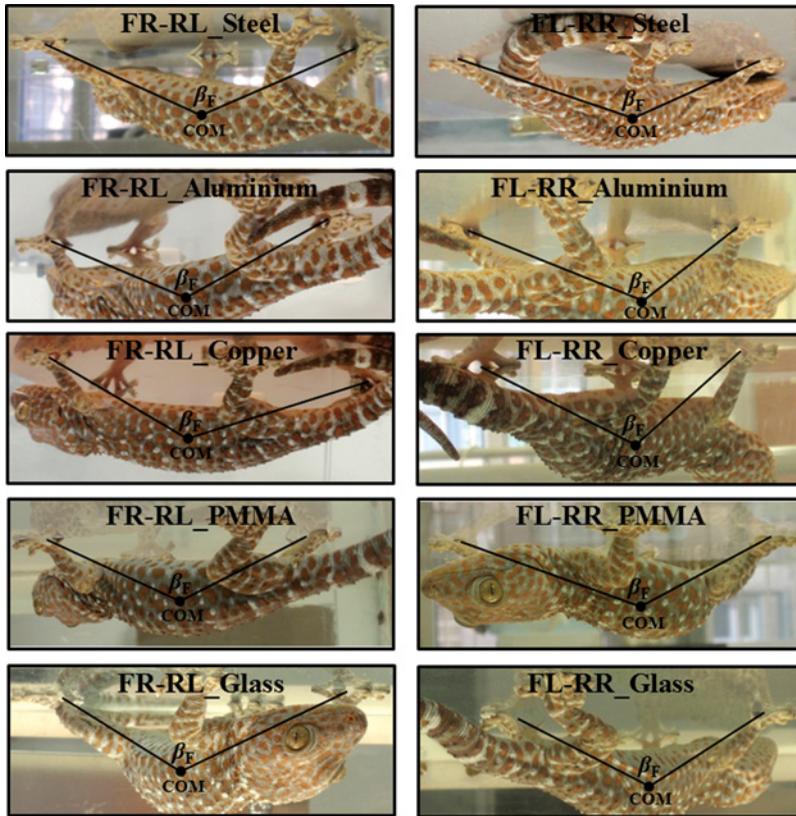


FIGURE 2 The measured angle, β_F between the opposed front-rear feet on different surfaces (steel, aluminium, copper, PMMA, and glass) (color figure available online).

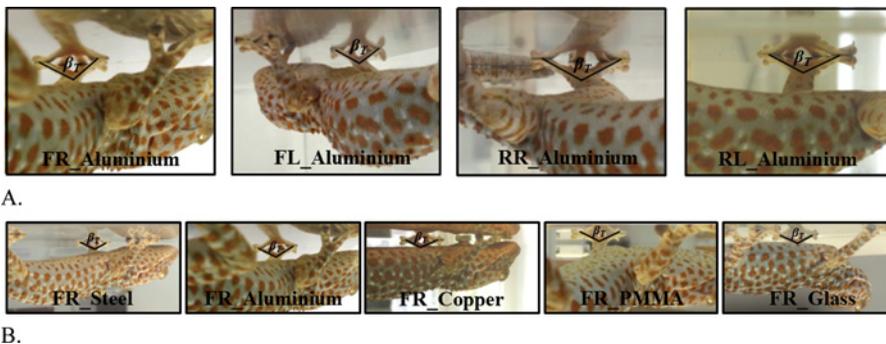


FIGURE 3 The measured angle, β_T between the gecko first and fifth toe: (A) on the aluminium surface for all legs, or (B) for the FR leg on different surface (steel, aluminium, copper, PMMA, and glass) (color figure available online).

examples, the images used to calculate the adhesion angles for the opposed front-rear (Fig. 2), on the same substratum (Fig. 3A), or for the same leg (Fig. 3B). The angle β_T was determined by taking the foot-forearm joint as the vertex of the resulting triangle. Analogously, the angle β_F was determined by using the COM located between the front and the opposed rear foot, as defined in [21]. The resulting angle α was computed as $\alpha = (180^\circ - \beta)/2$.

3. RESULTS

The experimental measurements of the adhesion angles are summarized in Table 1.

We note that the FR value of α_T is lower than the FL one for each surface and, similarly, the RL leg shows a lower value of α_T than the RR one, with the exception of the copper surface. Moreover, the opposed FR and RL legs show the smallest values of α_T if compared with the opposed ones (FL and RR). The values of α_F and α_T in Tokay geckos here determined are in agreement with previously obtained results, indicating both the 25° to 30° values of α in toes, arrays, and single setae, as reported by Autumn *et al.* [21], suggesting a maximum of the attachment force when α reaches values around 30° [36,41].

4. DISCUSSION

We have found an interesting agreement of the experimental results with the theory of multiple peeling [48]. According to the theory of multiple peeling, the dimensionless detachment force of a V-shaped system is:

$$f = \frac{F_C(\alpha)}{F_C(\alpha/2)} = \frac{\sin \alpha \left(\cos \alpha - 1 + \sqrt{(1 - \cos \alpha)^2 + 4\lambda} \right)}{-1 + \sqrt{1 + 4\lambda}}, \quad (1)$$

where α is the adhesion angle and

$$\lambda = \frac{\gamma}{tE}, \quad (2)$$

where γ is the surface energy, t is the tape thickness, and E is the Young's modulus. Thus, we fit our data (so the mean values of α_F and α_T obtained for each surface) with Eq. (1). The corresponding dimensionless adhesion strength, λ , was thus determined for the five surfaces at each hierarchical level (of foot and toe), as graphically shown in Fig. 4 and reported in the right columns of Table 1A and 1B for α_F and α_T , respectively. Note that λ_T is smaller than λ_F (except for the steel surface). Thus, according to the multiple peeling theory, the smaller the parameter λ ($\lambda_T < \lambda_F$), the smaller the

Table 1 Experimental values (and number, N, of measurements) for different adhesion angles (A) α_F and (B) α_T on different surfaces

A		FR-RL	FL-RR	MEAN \pm st.dev.	λ_F		
α_F (°)							
Steel	28 ± 4.7 (N = 21)	29 ± 4.6 (N = 39)	29 ± 0.6	0.013			
Aluminium	31 ± 4.5 (N = 33)	31 ± 4.2 (N = 57)	31 ± 0.3	0.018			
Copper	31 ± 8.0 (N = 25)	33 ± 3.8 (N = 37)	32 ± 0.8	0.023			
PMMA	22 ± 4.5 (N = 19)	26 ± 6.9 (N = 33)	24 ± 2.8	0.007			
Glass	28 ± 3.7 (N = 22)	31 ± 3.8 (N = 28)	30 ± 1.6	0.016			
MEAN \pm st.dev.	28 ± 3.7	30 ± 2.4					
B		FR	FL	RR	RL	MEAN \pm st.dev.	λ_T
α_T (°)							
Steel	28 ± 2.9 (N = 24)	31 ± 4.3 (N = 22)	31 ± 4.8 (N = 44)	28 ± 4.4 (N = 40)	30 ± 1.7	0.016	
Aluminium	28 ± 3.9 (N = 39)	30 ± 4.1 (N = 50)	29 ± 4.3 (N = 14)	28 ± 4.8 (N = 28)	29 ± 0.8	0.013	
Copper	24 ± 3.4 (N = 30)	32 ± 6.1 (N = 35)	28 ± 4.5 (N = 43)	29 ± 4.7 (N = 45)	28 ± 3.4	0.013	
PMMA	21 ± 2.4 (N = 24)	23 ± 2.7 (N = 23)	21 ± 3.5 (N = 27)	19 ± 2.0 (N = 27)	21 ± 1.8	0.003	
Glass	27 ± 3.7 (N = 56)	32 ± 2.5 (N = 37)	30 ± 3.3 (N = 33)	27 ± 5.7 (N = 18)	29 ± 2.5	0.015	
MEAN \pm st.dev.	26 ± 3.0	29 ± 3.8	28 ± 4.3	26 ± 4.3			

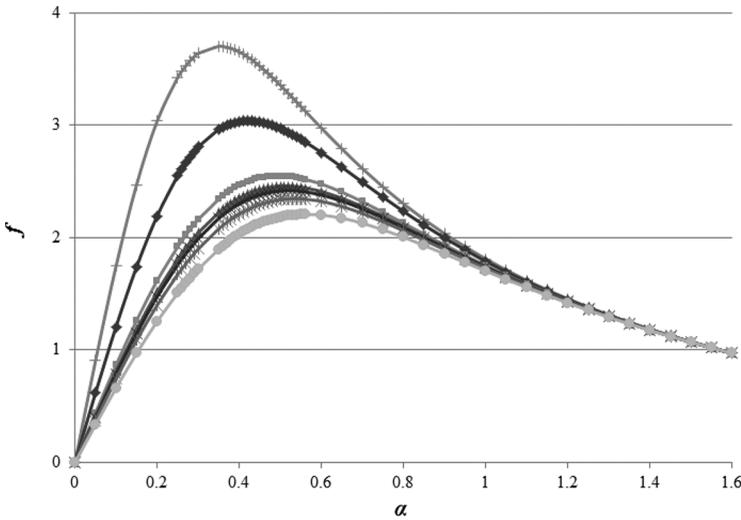


FIGURE 4 From the multiple peeling theory [48], dimensionless force, versus adhesion angle, α , by fitting the experimental mean value α_F and α_T (fitting parameters λ reported in Table 1).

optimal adhesion angle ($\alpha_T < \alpha_F$), which corresponds to the peak value of the function f in Fig. 4.

Following [53], we expect at each hierarchical level, n , the validity of the following equation:

$$\frac{8}{(1 - \nu_f^2)} \frac{\gamma_n (E_n / \phi_{n-1})}{\pi (\sigma_{tb} \phi_{n-1})^2 R_n} = 1, \quad (3)$$

where $\gamma_n = W_n^{ad}$ is the work of adhesion, $E_n / \phi_{n-1} = E_f$ is the elastic modulus of a fiber, ν_f is the Poisson's ratio of the fiber, $\sigma_{tb} \phi_{n-1} = S_n = E_n \varepsilon$ is the effective adhesion strength, and $\phi_{n-1} = \prod_{i=1}^{n-1} \phi_i$, where ϕ_i is the area fraction. Thus, according to Eq. (3), Eq. (2) can be rewritten for each hierarchical level as:

$$\lambda_n = \phi_{n-1}, \quad (4)$$

finding a weak dependence of the parameter λ on the number n of hierarchical levels, since the parameter λ decreases as n increases.

Defining the hierarchical level n and the thickness t of the feet ($n_F = 4$ (four feet per gecko), $t_F = 10$ mm) and toes ($n_T = 5$ (five toes per each foot), $t_T = 4$ mm), the Young modulus $E_T = E_F = 1$ GPa, and, using the work of adhesion, γ , of [53] (varying in the range $10^3 - 10^6$ J/m²), we have found the theoretical range of λ ($10^{-4} - 10^{-1}$), which confirms the values of the parameter λ ($10^{-2} - 10^{-1}$), computed in [53], and also the experimental range of λ ($10^{-3} - 10^{-2}$) determined here.

A further consideration concerns the critical angle α_c , which corresponds to the inclination of the force vector (F_{TOT} in Fig. 1) just before animal detachment and is governed by the normal (F_n) and shear (F_s) adhesive forces, physically defined as follows:

$$\alpha_c = \arctg\left(\frac{F_n}{F_s}\right) \leq \alpha. \quad (5)$$

The experimental value of the critical angle α_c is equal to $\sim 11.3^\circ$ for the whole *Hemidactylus garnotii* gecko (calculated with $F_n = 0.006$ N and $F_s = 0.03$ N [21]) and for the Tokay gecko at the level of the whole animal it is $\sim 9.5^\circ$ (calculated with $F_n = 6.7$ N [42] and $F_s = 40.2$ N [2]) or at the characteristic size of setae it assumes the value of $\sim 11.3^\circ$ (calculated with $F_n = 40$ μ N [15] and $F_s = 200$ μ N [12]). Note that these experimental values of the critical angle α_c confirm the range of 5.2° – 11.3° , for whole insects, previously reported in [21], and, according with Eq. (5), are coherently smaller than the optimal adhesion angle, α , experimentally determined here.

A final consideration refers to the linear relation which fits the experimental data of the perpendicular adhesive force, F_n , of gecko seta and the adhesion angle, α , reported in [12],

$$\alpha = \frac{0.22}{1N} \cdot F_n + 28.2. \quad (6)$$

Interestingly, using the normal adhesive force $F_n = 6.7$ N for the entire Tokay gecko [42] in Eq. (6), we obtain the value α of 28.6° or 28.9° for feet or opposed front-rear feet, respectively (roughly dividing F_n by 4, as the number of gecko feet, or by 2, as the number of gecko opposed front-rear feet), in agreement with the experimental results of the gecko adhesive angles reported here.

5. CONCLUSIONS

Summarizing, the angles α were estimated for a single gecko toe ($\sim 25.5^\circ$ [21]), for isolated setae arrays ($\sim 24.6^\circ$ [21], $\sim 30^\circ$ [31]), for a single seta ($\sim 30.0^\circ$ [21], $\sim 31^\circ$ [12]), and we have calculated the angles between the opposing front and rear feet ($\alpha_{F-FR-RL} = 28^\circ$, $\alpha_{F-FL-RR} = 30^\circ$) and between the first and fifth toe of each foot ($\alpha_{T-FR} = 26^\circ$, $\alpha_{T-FL} = 29^\circ$, $\alpha_{T-RR} = 28^\circ$, $\alpha_{T-RL} = 26^\circ$), directly for the whole gecko [48]. Thus, such angles in the range from $\sim 26^\circ$ to $\sim 30^\circ$ seems to be optimized to maximize the adhesion of living Tokay geckos. The agreement between theoretical calculations of the multiple peeling theory and the experimental results at the level of foot and toe extracted here, also with those already reported in the literature about the gecko adhesive system (single toe, isolated setae arrays, and single seta),

support the validity of the approach at different hierarchical levels and provides an important contribution to the literature. In general, the presented findings could be useful for the industrial fabrication of bioinspired dry adhesives, robotics systems, artificial adhesive suits, and gloves for astronauts or in designing bio-inspired smart adhesive nanomaterials, and, especially, they can have significant biomedical applications.

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