

Spiderman gloves

Theoretical van der Waals gloves could generate an adhesion force comparable to the body weight of ~500 men. Even if such a strength remains practically unrealistic (and undesired, in order to achieve an easy detachment), due to the presence of contact defects, e.g. roughness and dust particles, its huge value suggests the feasibility of Spiderman gloves. The scaling-up procedure, from a spider to a man, is expected to decrease the safety factor (body weight over adhesion force) and adhesion strength, that however could remain sufficient for supporting a man. Scientists are developing new biomimetic materials, e.g. gecko-inspired. Here we complementary face the problem of the structure rather than of the material, designing and preliminary fabricating a first prototype of Spiderman gloves, capable of supporting ~10 kilograms each on vertical walls. New Adhesive Optimization Laws are derived and applied for increasing the capability of the scaling-up.

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The gecko's ability to "run up and down a tree in any way", was firstly observed by Aristotle in his *Historia Animalium*, almost 25 centuries ago. A comparable adhesive system is found in spiders and in several insects. In general, when two solid (rough) surfaces are brought into contact with each other, physical/chemical/mechanical attraction occurs¹. The developed force that holds the two surfaces together is known as adhesion. A simple example is suction. Suction cups operate under the principle of air evacuation, i.e., when they come into contact with a surface, air is forced out of the contact

area, creating a pressure difference. The adhesive force generated is simply the pressure difference multiplied by the cup area. Thus, in our (sea level) atmosphere the achievable suction strength is coincident with the atmospheric pressure, i.e. about 0.1MPa. Such an adhesive strength is of the same order of magnitude of those observed in geckos and spiders, even if their adhesive mechanisms are different, mainly due to van der Waals attraction^{2,3} and also capillarity⁴. Thus, although several insects and frogs rely on sticky fluids to adhere to surfaces, gecko and spider adhesion is fully dry.

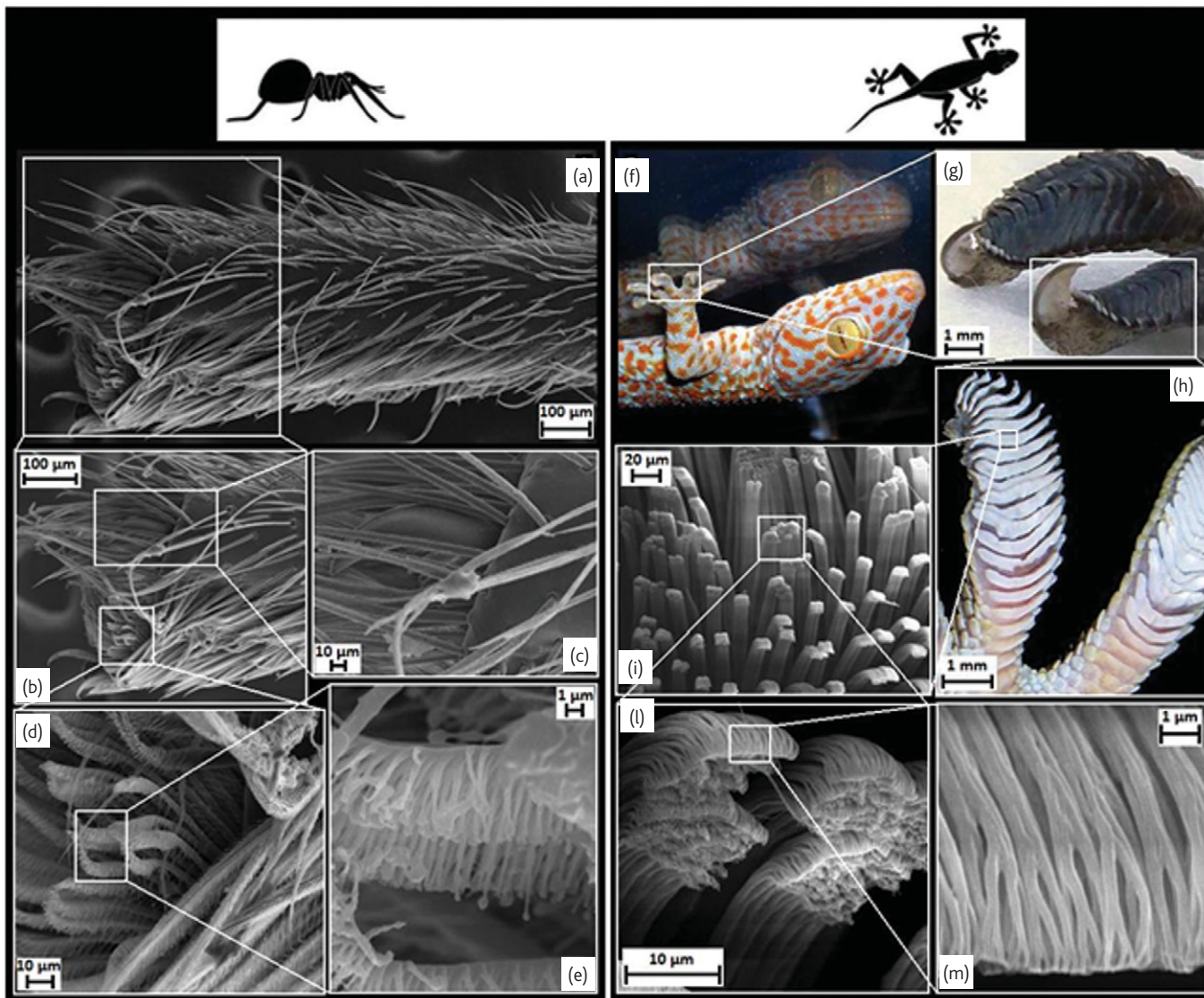


Fig. 1 Spider and gecko feet showed by SEM. In the Tokay gecko (Fig. 1f) the attachment system is characterized by a hierarchical hairy structures, which starts with macroscopic lamellae (soft ridges ~1mm in length, Fig. 1h), composed by setae (30-130μm in length and 5-10μm in diameter, Fig. 1i,l). Each setae branches in (Fig. 1m) 100-1000 substructures called spatulae, the contact tips (0.1-0.2μm wide and 15-20nm thick) responsible for the gecko's adhesion⁵. Terminal claws are located at the top of each singular toe (Fig. 1g). Van der Waals and capillary forces are responsible for the generated adhesive forces³, whereas claws guarantee an efficient attachment system on surfaces with very large roughness. Similarly, in spiders an analogous ultrastructure is found². Thus, in addition to the tarsal claws, which are present on the tarsus of all spiders (Fig. 1c), adhesive hairs can be distinguished in many species (Fig. 1d,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. 1a,b). In jumping spider *Evarcha arcuata*, in addition to the tarsal claws (hooks with radius of ~50μm), a scopula (with surface area of 37000μm²) is found at the tip of the foot²; the scopula is differentiated in setae, each of them covered with numerous setules (with an average density of ~2.1μm⁻²), terminating in a triangular contact (with surface area of ~0.17μm²).

Hierarchical miniaturized hairs (without adhesive secretions) are characteristic features of both spiders² and geckos^{5,6}, see Figure 1. In jumping spider *Evarcha arcuata*, the total number of setules per foot can be calculated at 78000 and thus all 8 feet are provided with a total of ~0.6 million points of contact. The average adhesion force per setule was measured to be ~41nN, corresponding for the 8 feet or scopulae to $\sigma_{spider} \approx 0.24\text{MPa}$ and to a safety factor (that is the adhesive force over the body weight, ~15.1mg)

of $\lambda_{spider} \approx 173$. Similarly, for a tokay gecko (*Gekko gekko*), the adhesive force of a single seta and even of a single spatula has recently been measured to be respectively ~194μN⁷ or ~11nN⁸. This corresponds to an adhesive strength of $\sigma_{gecko} \approx 0.58\text{MPa}$ ⁷ and a safety factor of $\lambda_{gecko} \approx 102$ ⁹, comparable only with those of spiders² (~173), cocktail ants¹⁰ (>100) or knotgrass leaf beetles¹¹ (~50). Note that, according to the previous values, we have estimated⁹ for a gecko a total number of points of contact of ~3 billions, thus

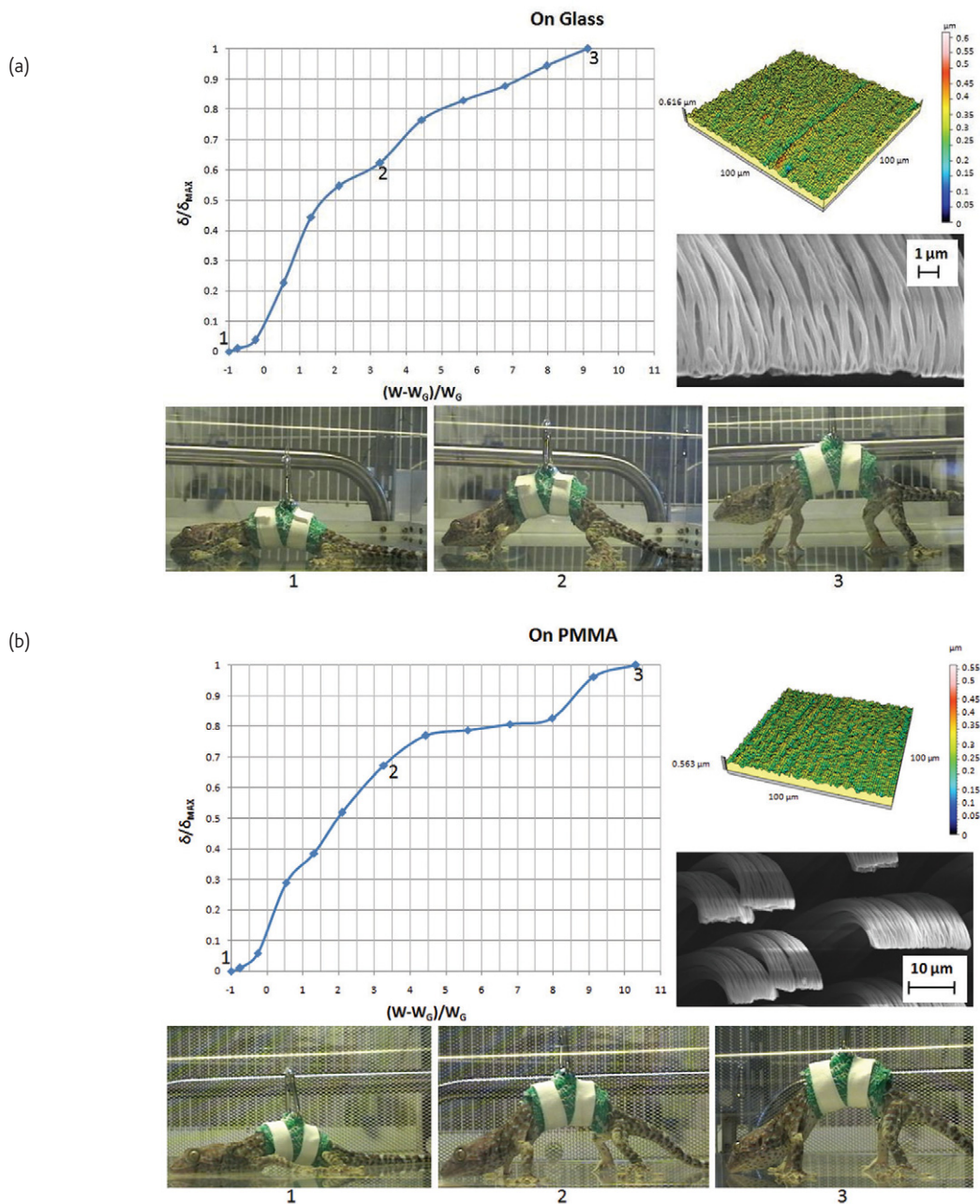


Fig. 2 Force-displacement curves on the adhesion of living geckos, on glass (a) or on polymethylmethacrylate (PMMA, b). W is the applied weight, W_G is the gecko's weight, δ is the gecko's displacement and δ_{MAX} is its maximum value. The safety factor on glass is ~ 9.2 and on PMMA is ~ 10.5 ; thus, it is reduced by one order of magnitude with respect to the theoretical value.

much larger than in spiders (~ 0.6 million), as required by their larger mass (the number of contacts per unit area scales as the mass to $2/3$)¹².

In Fig. 2 the first adhesive force-displacement (Pugno and Lepore, work in progress) curves on living geckos, on glass or polymethylmethacrylate (PMMA) nanorough surfaces, are reported; these reveal a safety factor of ~ 10 , thus one order of magnitude smaller than its theoretical value. Note that, as an exception, this strength reduction is here beneficial in order to achieve an easier detachment but still safe attachment. Thus, contact imperfections and related size-

effects could be, at least partially, smartly controlled, suggesting that Spiderman gloves are not in the domain of science fiction but rather a challenge of the current bio-inspired nanotechnology. Understanding the size-effect on gecko adhesion is the reason why we are focusing on "large" scale (in vivo) *ad hoc* new experiments. The pioneer study on the adhesion of living geckos is reported in ref. 5.

The necessity of having a large number of small contacts can be evinced noting that the scaling of the adhesion strength $\sigma_c^{(N)}$ is predicted to be⁹:

$$\sigma_c^{(N)} \approx \sigma_c^{(0)} (\varphi n)^{N/2} \quad (1)$$

where N is the number of hierarchical levels and φ, n are the area fraction and number of sub-contacts into a single contact (e.g. for $\varphi \approx 0.5$ and $n \approx 200$ the strength is increased by a factor of 10 per each hierarchical level). Thus, we have suggested⁹ that carbon nanotubes could be one of the most promising candidates for our application: at small size-scale a carbon nanotube surface was able to achieve adhesive forces ~ 200 times greater than those of gecko foot hairs¹³, even if it could not replicate large scale gecko adhesion, perhaps due to a lack of compliance, hierarchy and/or the reasons that we are going to discuss in the next section. Thus, we have proposed⁹ the use of hierarchical branched long (to have a sufficient compliance) nanotubes¹⁴ as a good candidate for a Spiderman suit and in general for realizing gecko/spider-inspired materials. Some researchers are today working on this proposal¹⁵. The nanotube aspect ratio must not be too large, to avoid bunching^{16,17} and elastic self-collapse under their own weight, but sufficiently large to conform to a rough surface by buckling under the applied stress¹⁸, similar to the optimization done by nature in spiders and geckos.

The total adhesive force could “easily” be overcome by subsequently detaching single setules and not the whole foot at once¹⁹, e.g. by controlling the pulling angle. The ratio between the attachment (longitudinal) and detachment (anti-longitudinal) forces is predicted to be⁹:

$$\frac{F_a}{F_d} \approx \frac{1 + \sqrt{\chi + 1}}{\sqrt{\chi}}, \quad \chi \equiv \gamma / (hE) \quad (2)$$

where γ is the adhesion energy, h is the thickness (/diameter) of the hair and E is its Young modulus (e.g. for $\gamma = 0.05\text{N/m}$, $h = 100\text{nm}$, $E = 10\text{GPa}$ we find $F_a/F_d \approx 283$, i.e. for a man with adhesive gloves capable of longitudinally supporting 300Kg, only $\sim 1\text{Kg}$ applied in the opposite direction would be necessary to detach them).

A man (palm surfaces of $\sim 200\text{cm}^2$) with gecko-material gloves ($\sigma_{\text{gecko}} \approx 0.58\text{MPa}$) could support a mass of $\sim 1160\text{Kg}$ (safety factor ~ 14), or with spider-material gloves ($\sigma_{\text{spider}} \approx 0.24\text{MPa}$) a mass of $\sim 480\text{Kg}$ (safety factor ~ 6). Note that theoretical van der Waals gloves ($\sigma_{\text{vdw}}^{(th)} \approx 20\text{MPa}$) would allow one to support a mass of $\sim 40000\text{Kg}$ (safety factor of ~ 500). Obviously, the challenge is the scaling-up procedure, that will imply both larger surface over volume ratios

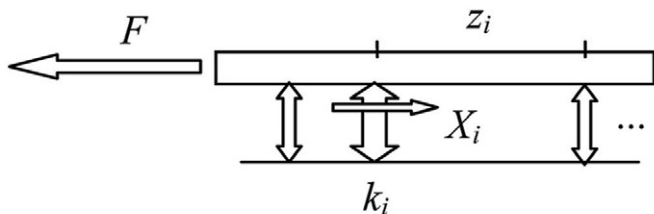


Fig. 3 Shear adhesion: distribution of the contact forces.

and contact imperfections, thus lower safety factor and adhesion strength. In other words, fixing the adhesion strength, the safety factor is expected to be inversely proportional to the animal size, but the adhesion strength itself is expected to decrease by increasing the size. We thus have to counterbalance both these size-effects. Consequently, not only the material but also the structure itself has to be optimized.

Adhesive Optimization Laws

To make a complex problem simple, let us consider a sheet (glove) with cross-sectional area A and Young’s modulus E , adhering over a surface thanks to N discrete contact points, as schematized in Fig. 3: the adhesive force F is applied at one end and is supported by the action of the points in contact; each of them is characterized by the relative position z_i , the distance from the next contact point, and by a stiffness k_i . To be more general, we assume different values of the Young’s modulus E_i and cross-sectional area A_i in the different segments, of length z_i . The unknown forces X_i carried by each contact point can be deduced invoking the compatibility of the relative interface displacements (in the absence of relative sliding; see the Appendix for the mathematical formulation).

A plausible example of force distribution along the contact points is computed in Fig. 4a, demonstrating that in general only a few of them are active. This, we believe, is the main reason of the frustration encountered during our scaling-up attempts for producing large adhesive surfaces: the failure of the chain takes place for an external force $F = F_c \ll Nf$, where f is the mean contact strength.

The optimal solution $X_i = F/N$ is ensured if the following Adhesive Optimization Laws (AOL) are satisfied (see the Appendix):

$$(1 - \lambda_i)c_i = N - i, \quad \lambda_i = \frac{k_i}{k_{i+1}}, \quad c_i = \frac{E_i A_i}{z_i k_i}, \quad i = 1, \dots, N - 1 \quad (3)$$

which physically correspond, for identical contact points ($\lambda_i = 1$), to have infinitely large relative compliances c_i ; or, equivalently, for constant relative compliances ($c_i = c$) to have increasing stiffness (by increasing the distance from the point of load application) or, in general, to a mixed functionally graded architecture. Imposing the AOL implies the optimal force distribution depicted in Figure 4b.

For realizing a preliminary prototype of Spiderman gloves, we have used a new viscoelastic ultra-soft material (“gecko skifell”, worldwide patent pending, washable with water at $\sim 30^\circ\text{C}$, active in a wide range of temperatures, from -70°C to $+250^\circ\text{C}$ and based on “molecular fusion”, i.e. microscopic suction), shown in Figure 5. A wavy surface can be recognized; due to the extreme softness of the material, each crest acts as a single contact point and each valley as a suction cup, resembling the scheme reported in Fig. 3. Even if the AOL suggest more complex and sophisticated strategies, their solutions also include the case of perfectly compliant identical contact points ($\lambda_i = 1, c_i = \infty$). This condition is roughly satisfied by the discrete ultra-soft microstructure of the considered material.

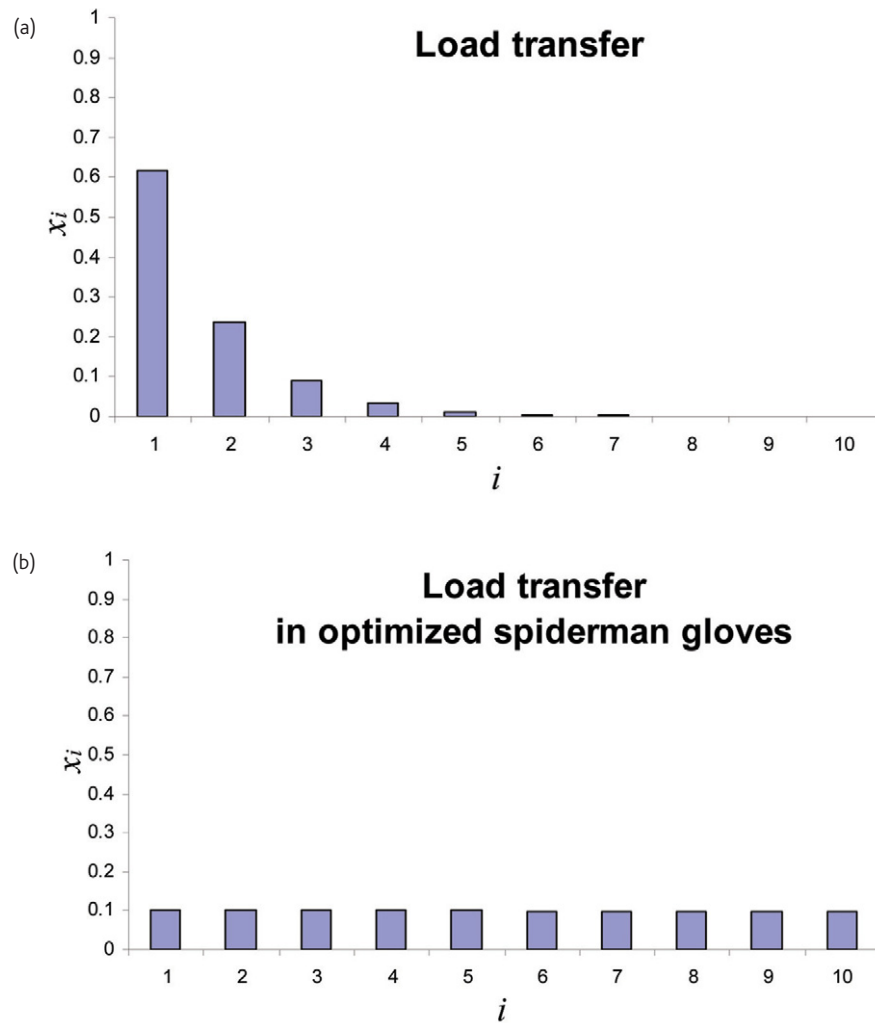


Fig. 4 (a) Dimensionless forces x_i ($x_i = X_i/F$) carried by $N=10$ identical contact points, for $\lambda_i = 1$ and $c_i = 1$. The maximum adhesive force is $F_c \approx f/0.6$ (increasing the number of contacts, i.e. the surface area, the force cannot increase and its scaling-up is thus impossible). At this value of the external force the first contact ($n. 1$) is broken and a new force distribution takes place: it can be easily computed setting the relative stiffness of the broken contact point to zero ($k_1 = 0$). Basically, the force distribution is shifted by one contact point, and so on (here for three times) up to the activation of the last contact ($n. 10$); at this time the contact points become even more solicited, up to the failure of the last contact point, taking place for an external load $F = f$. Thus the "chain unfolding" is here basically metastable and finally unstable. (b) Dimensionless forces x_i carried by $N=10$ optimized (eq. (3)) contact points. The transmissible adhesive force is maximized, i.e. $F_c = 10f$ (increasing the number of contacts, i.e. the surface area, the force is proportionally increased and its scaling-up is optimized).

In order to test the validity of this hypothesis we have performed adhesion tests on macroscopic strips, up to 1 meter long and 1 cm wide, following the scheme reported in Figure 3. For a 5 cm long strip the breaking mass was of 0.9 Kg, becoming 1.3 Kg for 10 cm, 1.5 Kg for 15 cm, 1.8 Kg for 20-30 cm, 2 Kg for 40-60 cm, but still increasing up to 2.6 Kg for the strip with length of 1 meter. The observed behaviour is intermediate between those depicted in Figs. 4, suggesting the existence of a preliminary form of optimization in the tested adhesive material.

Moreover, for better satisfying the AOL not only at the micro (material) but also at the macro (structural) size-scale, an optimal geometry could be invoked. For the sake of simplicity let us consider

as a variable in $c_i = E_i A_i / (z k_i)$ only the cross-sectional area A_i of the sheet; satisfying the AOL would imply a discrete linear tapering (see the Appendix). Is it interesting to note that the spatulae of spiders and geckos show a tapering of the thickness that closely resembles our theoretical prediction (S. Gorb, private communication).

The optimized geometries A_i are, strictly speaking, not free and functions also of the properties of the interface/substrate; moreover, the variation of the area should be due to a variation of thickness t rather than of width w , since we expect k_i to be proportional to w . We have deliberately ignored these considerations and fabricated a triangular surface with width $w(0) \approx 6$ cm and height $L \approx 5$ cm ($t=1$ mm). Under three different tests, the breaking masses, acting at the middle

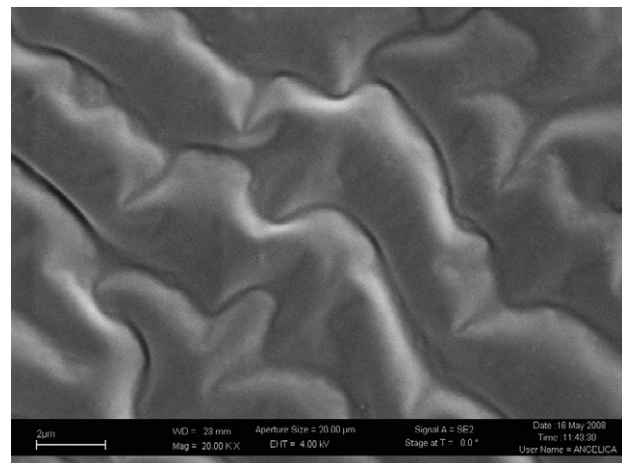
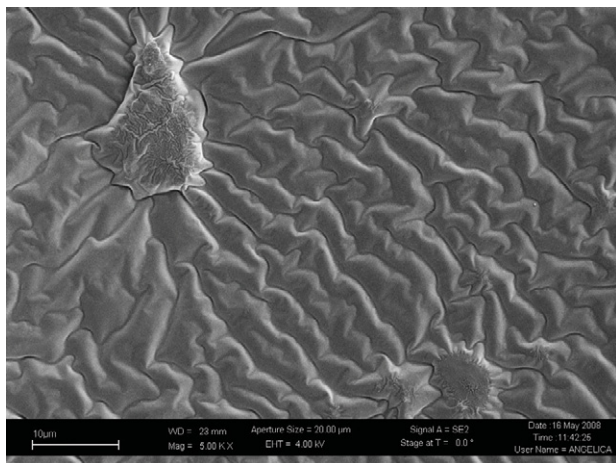


Fig. 5 SEM images of the “gecko skifell” material, used for producing the first prototype of Spiderman gloves.

of the cross-section of width $w(0)$, were of 1.1 Kg, 1.1 Kg and 1.2 Kg. Even larger breaking masses are expected distributing their action along the entire length $w(0)$. We have conducted the same experiments inverting the orientation of the surface, thus maintaining the same contact area, finding breaking masses (applied at the tip) of 0.8 Kg, 0.9 Kg and 1.0 Kg. The observed behaviour may suggest the existence of a very preliminary form of optimization in the tested adhesive structure (note that the spatulae shape is more similar to the inverted geometry, but this is due to the imposed different boundary conditions; here we basically optimize the structure removing the inefficient material, as in classical evolutionary structural optimization).

Fabricating the gloves with the discussed material and structure, thus forcing by imposing the AOL a nearly uniform shear stress distribution, we were able to suspend $\sim 10\text{Kg}$ on each glove (with a detachment force nearly two orders of magnitude smaller), adhering

on flat surfaces of glass or wood. Such a value corresponds to a macroscopic shear strength of only $\sim 1\text{ N/cm}^2$, thus much lower than $\sim 37.5\text{ N/cm}^2$ reached by patterned gecko tapes¹⁵. The last shear strength is about three times larger than that of geckos and, even if obtained only on a very small surface area (0.16cm^2 , corresponding to a mass of $\sim 0.6\text{ Kg}$) suggests that there is plenty of room also at the top.

We have also performed a simple home-made experiment. Using classical USA adhesive tape we have generated a multi-layered profile possessing the derived linear tapering of the thickness. With a surface comparable to that of a human palm we were able to suspend a man of $\sim 70\text{ Kg}$ on a horizontal iron bar having a diameter of $\sim 3\text{ cm}$. Even if the role of friction in the adhesion is still a controversial issue, this home-made experiment suggests that friction has a tremendous effect.

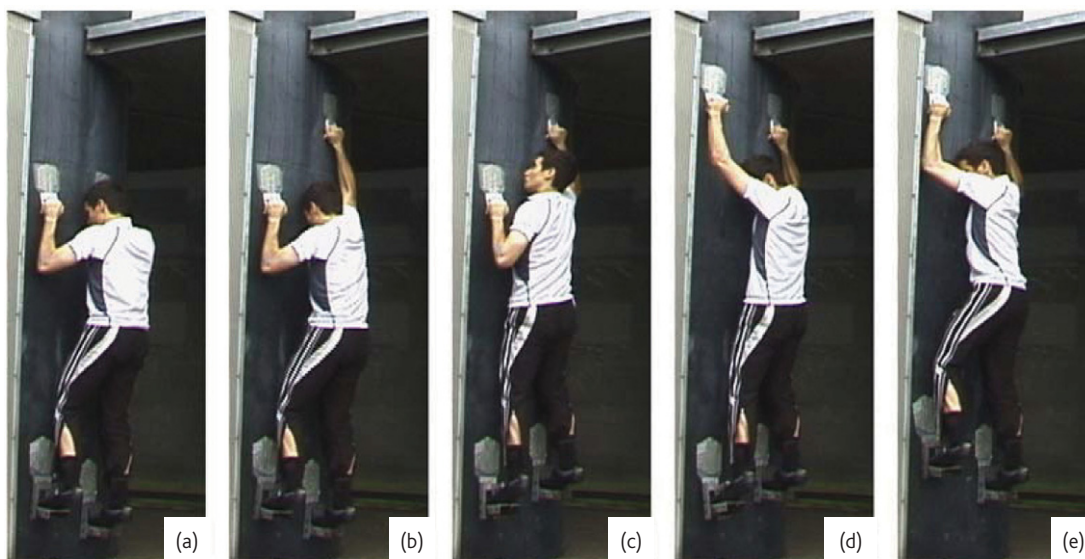


Fig. 6 A 63 Kg man climbing a round iron wall thanks to magnets, adapted from ref. 20. Fully Spiderman gloves would similarly permit to climb walls made by any kind of material. Large scale applications in different fields are expected.

Thus, in a near future, not only magnets for climbing ferromagnetic walls²⁰ but fully Spiderman gloves, possibly also based on electrostatic adhesion (<http://www.technologyreview.com/Infotech/20831/>), could become available, Fig. 6.

Conclusions

The paper tries to scale-up the adhesion properties of a spider to the size of a man. Strong attachment, easy detachment (and self-cleaning) are all properties that must be achieved simultaneously. One could deduce that fabricating Spiderman gloves is unfeasible, since no adhesive-based animals larger than geckos exist in nature. This is not fully right: nature has often different scopes with respect to ours, for example animals are not interested in going into space, as we are. Moreover, rather than mimicking nature we must be inspired by nature (an airplane is not a big bird). The project is in fact feasible, as we have here preliminary demonstrated, and as *a priori* suggested by the fact that for Spiderman gloves an adhesive strength that is much lower than the theoretical van der Waals strength is needed. Perhaps spiders and geckos use AOL for reaching a strong attachment and alternatively their violation for facilitating the detachment (in addition to the peeling mechanism), e.g. controlling the stiffness of their feet. Smart adhesive materials could control adhesion by imposing or violating AOL. **nt**

Acknowledgements

The author 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. The author thanks Ing. E. Lepore for the realization of the SEM pictures.

Appendix: Mathematical derivation of the AOL

In the segment i , of length z_i , cross-sectional area A_i and Young's modulus E_i , the axial force $N = F - X_1 - \dots - X_i$ imposes an elongation $N z_i / (E_i A_i)$ that must be equal (compatible) to the relative displacement between the contact points i and $i+1$, namely

$X_i/k_i - X_{i+1}/k_{i+1}$. We accordingly find that the following equations must hold:

$$\sum_{j=1}^i X_j + c_i X_i - c_i \lambda_i X_{i+1} = 1, \quad X_i = \frac{X_i}{F}, \quad (A1)$$

$$c_i = \frac{E_i A_i}{z_i k_i}, \quad \lambda_i = \frac{k_i}{k_{i+1}}, \quad i = 1, \dots, N-1$$

In addition, the equilibrium of the forces requires $F = X_1 + \dots + X_N$, i.e.:

$$\sum_{j=1}^N X_j = 1 \quad (A2)$$

Solving the N equations (A1,2) gives the N unknowns X_i .

Nevertheless we observe the existence of the optimal solution $x_i = \text{const}$ (same force supported by each contact point, thus $x_i = 1/N$ from the equilibrium equation) if the following Adhesive Optimization Laws (AOL) are satisfied (inserting $x_i = 1/N$ in the compatibility equations):

$$(1 - \lambda_i) c_i = N - i, \quad i = 1, \dots, N-1 \quad (A3)$$

For the sake of simplicity let us consider as a variable in $c_i = E_i A_i / (z_i k_i)$ only the cross-sectional area A_i of the sheet; satisfying the AOL would imply a discrete linear tapering, i.e.:

$$A_i = A_0 \left(1 - \frac{i}{N} \right), \quad i = 1, \dots, N-1 \quad (A4)$$

In the continuum limit, eq. (A4) leads to:

$$A(z) = A(0) \left(\frac{L-z}{L} \right) \quad (A5)$$

where L is the length of the contact zone, starting at $z=0$.

Note that the continuum limit of eq. (A3) is similar²¹ but singular in $z=0$:

$$A(z) = A(L/2) \frac{L-z}{z} \quad (A6)$$

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