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Gecko inspired suit could have you climbing the wall

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Abstract. Theoretical van der Walls 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 fascinating new biomimetic materials, e.g. gecko-inspired. Here we complementary face the problem of the structure rather than of the material, designing and fabricating a first prototype of Spiderman gloves, capable of supporting ~10 kilograms each, thanks to new Adhesive Optimization Laws.

Introduction

The gecko's ability to "run up and down a tree in any way, even with the head downwards" 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 attractions occur [1]. The force developed that holds the two surfaces together is known as adhesion. The most 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 differential. The adhesive force generated is simply the pressure differential multiplied by the cup area. Thus, in our (sea level) atmosphere the achievable suction strength is coincident with the atmospheric pressure, i.e. $\sigma_{suction} \approx 0.1\text{MPa}$. 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 capillary [4]. Thus, although several insects and frogs rely on sticky fluids to adhere to surfaces, geckos and spiders use pure dry adhesion.

Hierarchical miniaturized hairs (without adhesive secretions) are characteristic features of both spiders and geckos. In jumping spider *evarcha arcuata*, in addition to the tarsal claws (hooks with radius of ~50μm), a scopula (with surface area of 37000μm^2) is found at the tip of the foot [2]; the scopula is differentiated in setae, each of them covered with numerous setules (with an average density of $\sim 2.1\mu\text{m}^{-2}$), terminating in a triangular contact (with surface area of $\sim 0.17\mu\text{m}^2$). 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 contacts. 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, a tokay gecko (*gecko gecko*) foot consists of lamellae (soft ridges ~1mm in length), from which tiny curved setae (~10μm in diameter, density of $\sim 0.014\mu\text{m}^{-2}$) extend, each of them composed by numerous terminal contact units or spatulae (100-1000 per seta, nearly triangular surface area of $\sim 0.1\mu\text{m}^2$) [5,6]. The adhesive force of a single seta and even of a single spatula has recently been measured to be respectively ~194µN [7] or ~11nN [8]. 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 spiders [2] (~173), cocktail ants [10] (>100) or knotgrass leaf beetles [11] (~50). Note that, according to the previous values, we have estimated [9] for a gecko a total number of points of contacts of ~3 billions, thus much larger than in spiders (~1 million), as required by their larger mass (the number of contacts per unit area scales as the mass to 2/3) [12].

In Fig. 1 "force-displacement" curves on living geckos demonstrate a safety factor of ~10 thus one order of magnitude smaller than its theoretical value, even preferable in order to achieve an easier detachment but still safe attachment. Thus, defects and related size-effects could be even beneficial, again suggesting that Spiderman gloves are not in the domain of science fiction but rather a challenge of the current bio-inspired nanotechnology.

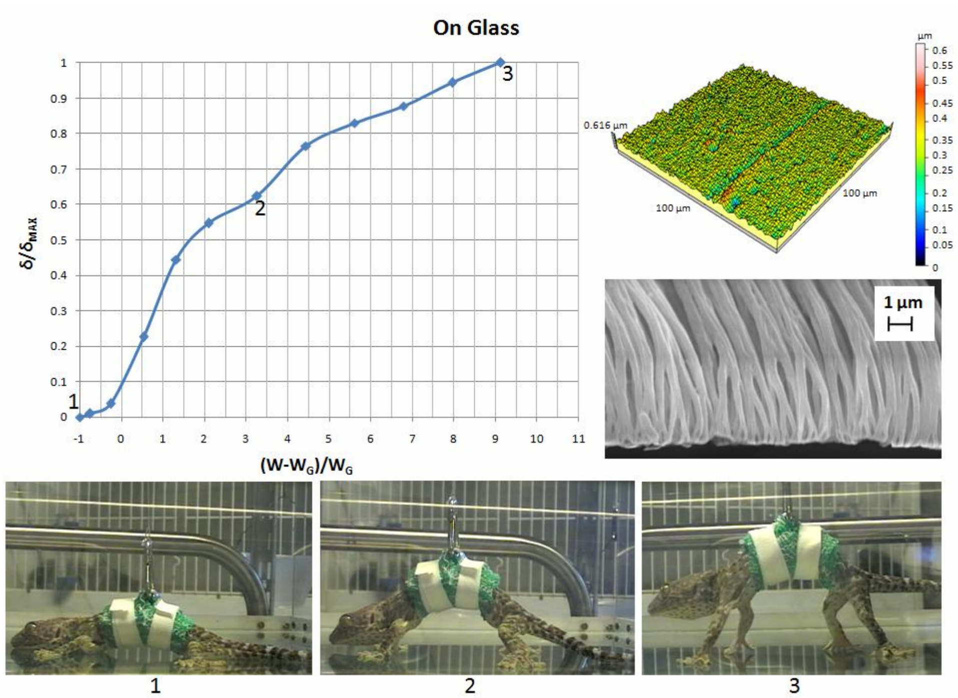


Figure 1: Force-displacement curves on the adhesion of living geckos (on glass). W is the applied force, W_G is the gecko's weight, δ is the gecko's displacement and δ_{MAX} is its maximum value. Thus, the safety factor is here ~9.2 (a similar behaviour has been observed on PMMA, with a safety factor of ~10.5); N. M. Pugno & E. Lepore, work in progress.

The necessary 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 be [9]:

$$\sigma_C^{(N)} \approx \sigma_C^{(0)}(\varphi n)^{N/2} \tag{1}$$

were 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). The necessity of having nanosized contacts suggested [9] that carbon nanotubes could be one of the most promising candidates for our applications: on a small scale a carbon nanotube surface was able to achieve adhesive forces ~200 times greater than those of gecko foot hairs [13], even if it could not replicate large scale gecko adhesion, perhaps due to a lack of compliance, hierarchy and the reasons that we are going to discuss in the next section. Thus, we have proposed [9] the use of hierarchical branched long (to have the sufficient compliance) nanotubes [14] as a good candidate for a Spideman suit and in general for realizing gecko/spider-inspired materials. Today a group is working exactly on this proposal [15]. 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 stress [18], 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 once [19], e.g. by controlling the pulling angle. The ratio between the attachment (longitudinal) and detachment (anti-longitudinal) forces is predicted to be [9]:

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

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

A man (palm surfaces of ~200cm^2) with gecko-material gloves ($\sigma_{gecko} \approx 0.58\mathrm{MPa}$) could support a mass of ~1160Kg (safety factor ~14), or with spider-material gloves ($\sigma_{spider} \approx 0.24\mathrm{MPa}$) a mass of ~480Kg (safety factor ~6). Note that theoretical van der Waals gloves ($\sigma_{vdW}^{(th)} \approx 20\mathrm{MPa}$) would allow one to support a mass of ~40000Kg (safety factor of ~500). Obviously, the challenge is the scaling-up procedure, that will imply both a larger surface over volume ratio and contact imperfections, thus lower safety factor and adhesion strength. Consequently, not only the material but also the structure itself has to be optimized. Accordingly, we use a new material in order to design and fabricate a first prototype of Spiderman gloves, capable of supporting ~10 kilograms each, by developing a proper structural design for optimized adhesion on vertical walls (for uniform interface shear stresses).

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. 2: 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.

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); we accordingly find that the following equations must hold:

$$\sum_{j=1}^{i} x_j + c_i x_i - \lambda_i c_i x_{i+1} = 1, \quad x_i = \frac{X_i}{F}, \quad c_i = \frac{E_i A_i}{z_i k_i}, \quad \lambda_i = \frac{k_i}{k_{i+1}}, \quad i = 1,\ldots,N-1 \tag{3}$$

in addition to that imposing the equilibrium of the system:

$$\sum_{j=1}^{N} x_j = 1 \tag{4}$$

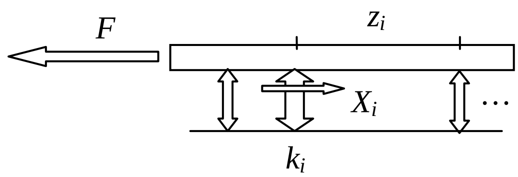
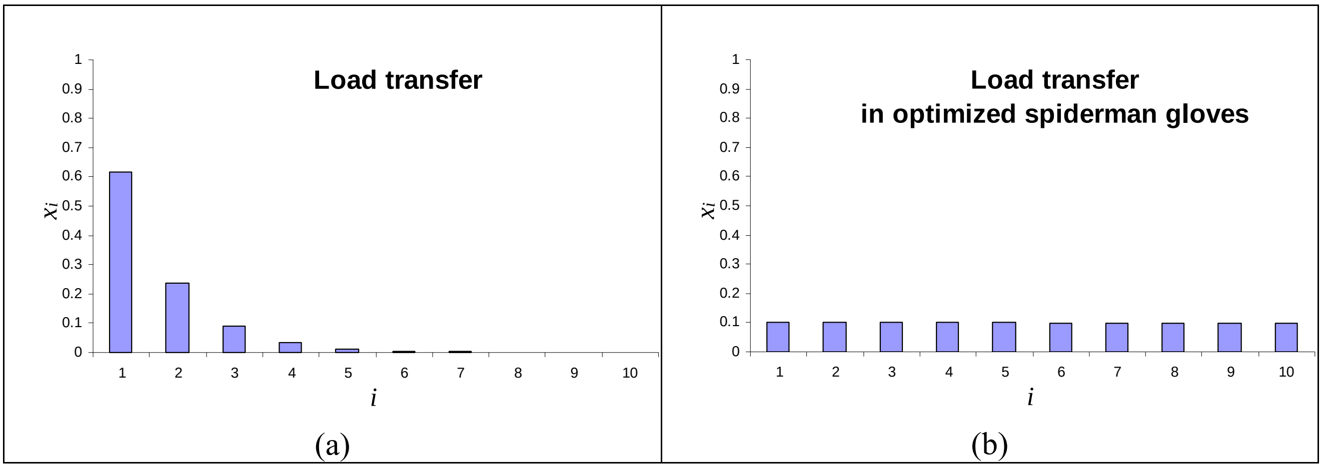


Figure 2: Shear adhesion: distribution of the contact forces X_i.

In equation (3) we have assumed, to be more general, different values of the Young modulus and cross-section area in different segments (of length z_i).

A plausible example of force distribution along the contact points is computed in Fig. 3a, 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 $F = F_C << Nf$, where f is the (mean) contact strength.



Figures 3. (a) Dimensionless forces x_i carried by N=10 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 contact 1 is broken and a new force distribution takes place: it can be easily computed setting the 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 (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 unstable. (b) Dimensionless forces x_i carried by N=10 optimized cross-links, eq. (5). 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).

Nevertheless we observe the existence of the optimal solution $x_i = const$ (same force supported by each contact point, Fig. 3b, 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):

$$(1-\lambda_i)c_i = N - i, \quad i = 1,\ldots,N-1 \tag{5}$$

which physically correspond, for identical contact points ($\lambda_i = 1$), to have infinitely large relative compliances c_i or, equivalently, for identical relative compliances ($c_i = c$) to have increasing stiffness ($\lambda_i \equiv \frac{k_i}{k_{i+1}} = 1 - \frac{N-i}{c} < 1$), or to a mixed functionally graded solution (see also the optimization proposed for the continuum in [20]).

In order to realize a first prototype of Spiderman gloves, we have used a new material ("gecko skifell", worldwide patent pending, washable with water at ~30°C, active in a wide range of temperatures, from –70°C to +250°C and based on "molecular fusion", i.e. microscopic suction), shown in Fig. 4. 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. 2. Even if the AOL suggest more complex and sophisticated strategies, their solutions also include the case of perfectly compliant identical contact points ($c_i(\lambda_i = 1) = \infty$). This condition is roughly satisfied by the discrete ultra-soft microstructure of the considered material.

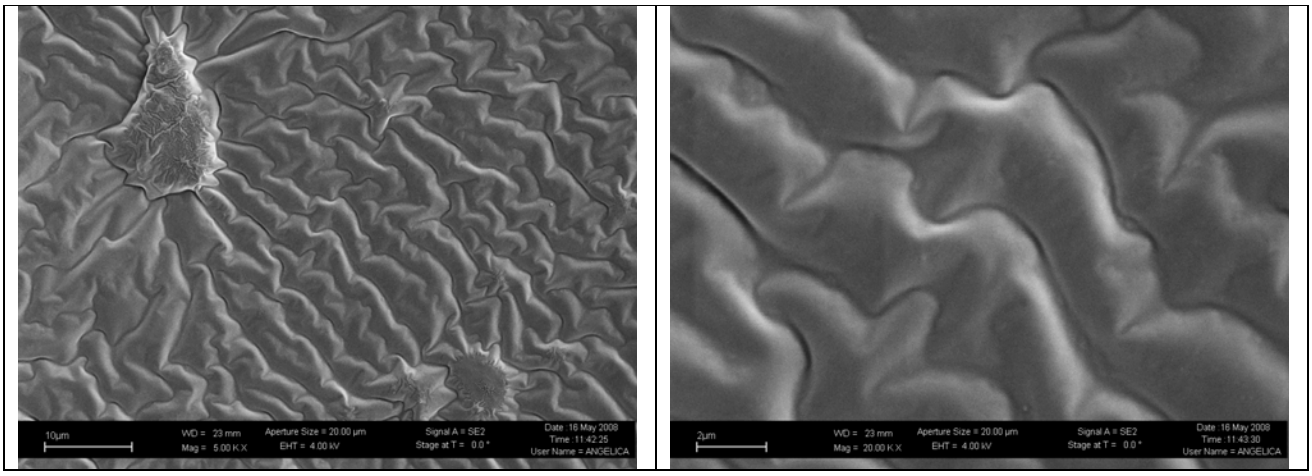


Figure 4. SEM images of the "gecko skifell" material, used for producing the first prototype of Spiderman gloves.

Fabricating the gloves with the "gecko skifell", thus roughly forcing, by imposing the AOL, a nearly uniform shear stress distribution, we were able to suspend ~10Kg on each glove (with a detachment force nearly two orders of magnitude smaller), adhering on flat surfaces made by glass or wood. Such a value corresponds to a macroscopic shear strength of only ~1 N/cm^2, thus much lower than ~37.5 N/cm^2 reached by patterned gecko tapes [15]. The last shear strength is about three times larger than that of geckos and, even if obtained only on a very small surface area (0.16 cm^2, corresponding to a force of ~5.8 N), suggests that there is room for improvements in the near future.

Conclusions

The paper tries to scale-up the amazing 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. Obviously, rather than mimicking Nature we must be inspired by Nature (an airplane is not a big bird). The project is in fact feasible, as here preliminary demonstrated, since for Spiderman gloves we need an adhesive strength that is much lower than the theoretical van der Waals strength and the size-effect of the adhesion strength can be mitigated by imposing the AOL. Perhaps geckos use AOL for reaching a strong attachment and 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.

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