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Adhesion Without Adhesives: Gecko-Like Adhesives

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(biography and contact information for author can be found at the end of this paper)

Abstract

Research into adhesive mechanisms used by living organisms has resulted in innovative improvements in medical, architectural, and underwater adhesion. For museums, there are promising developments arising from the study of gecko feet.

The underside of gecko toes has layered ridges with very fine keratinous hairs (setae) that provide intimate contact with virtually any surface, enabling the gecko to hang upside down supported only by a few toe pads. Even more impressive is the gecko's ability to detach and reattach itself within milliseconds.

During the last decade, international research has been carried out to study the degrees of adhesion provided by different shapes and arrangements of nanofibre arrays and to mimic the setae in synthetic materials. Many of these materials are chemically suitable for direct contact with museum artifacts.

Gecko adhesion is dry and mechanically activated, which offers a solution for some problems (e.g. solvent damage and inadequate reversibility) with existing museum adhesives.

Titre et Résumé

L'adhérence sans adhésifs : les adhésifs de type gecko

Les travaux de recherche portant sur les mécanismes d'adhérence chez les organismes vivants ont entraîné des améliorations de pointe dans les applications médicales, architecturales et sous-marines. Dans le cas des musées, des progrès prometteurs peuvent être réalisés grâce à l'étude des pattes du lézard gecko.

Le dessous des doigts du gecko comporte des couches de stries recouvertes de poils kératiniques très fins (des soies ou sétules) qui assurent un contact très étroit avec pratiquement toutes les surfaces, ce qui permet au lézard de se tenir à l'envers sur un plafond en ayant uniquement comme appui quelques coussinets des doigts. La capacité qu'a le gecko de se détacher d'une surface et de s'y fixer de nouveau en quelques millisecondes est encore plus étonnante.

Au cours de la dernière décennie, des travaux de recherche ont été réalisés à l'échelle internationale afin d'étudier le degré d'adhérence que permettent les réseaux de nanofibres présentant divers motifs et différentes formes, et d'élaborer des moyens d'imiter les soies dans les matériaux synthétiques. La composition chimique de bon nombre de ces matériaux permet d'assurer un contact direct avec les objets de musée.

Le processus d'adhérence de type gecko est exécuté par voie sèche et activé mécaniquement, ce qui offre une solution pratique à certains problèmes que posent les

adhésifs actuellement utilisés en restauration (par exemple les dommages causés par les solvants et une réversibilité inadéquate).

Introduction

Developments in nanotechnology and the study of biological mechanisms and functions (biomimetics) are creating vast new possibilities in many fields, including adhesion. One enticing direction which seems to hold great promise for museum collections care is the development of adhesive systems based on the study of gecko feet. Gecko-like synthetic adhesives (GSAs) are currently under development in several countries and commercial production of gecko tapes appears to be imminent.

Geckos can run swiftly upside down across dusty, crumbling plaster ceilings or polished glass skylights. Their feet are able to attach and release many times per second adapting to widely differing conditions with little apparent difficulty.

Studies of their feet have shown that gecko toes have layered ridges of fine bristles (setae) further divided and subdivided into branches which culminate in thickened tips (spatulae). Figure 1.

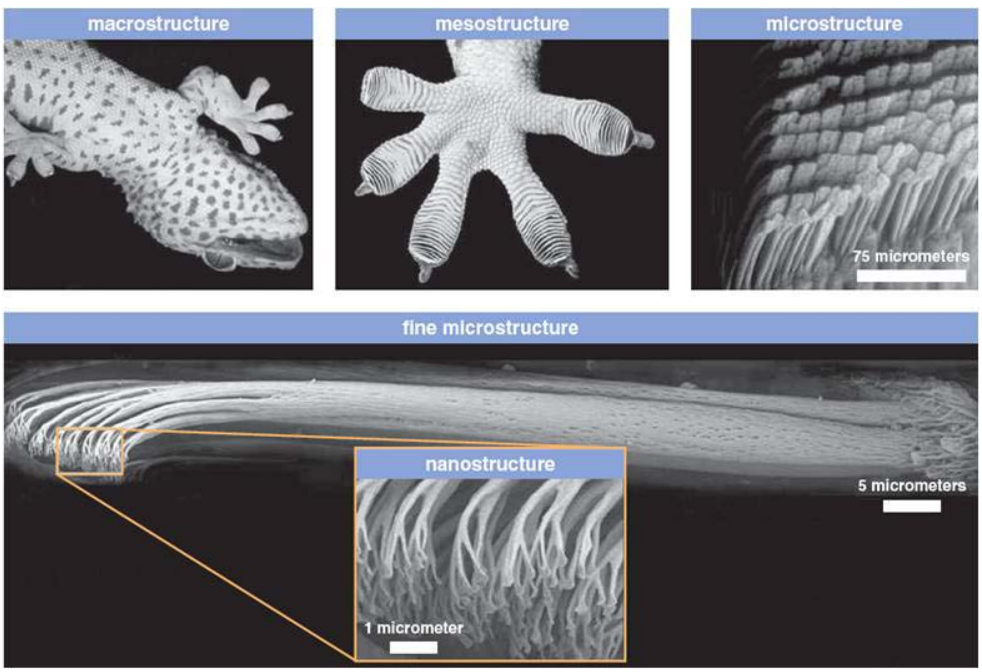

Figure 1 Macro, micro and nano view of gecko toe setae. Courtesy of Dr. Kellar Autumn, Lewis and Clarke Institute.

Intimate contact with different surfaces is made possible by the fineness of the divisions at the tips of the setae and the lamellar arrangement which permits close conformity with underlying textures. The gecko slides its toes until enough spatulae are engaged with the surface. The accumulation of weak intermolecular forces of attraction (van der Waals forces) at these numerous points of contact, are more than enough to support the weight of the lizard. The numerous setae on each gecko toe allows for an enormous safety margin to accommodate the fact that not all of them are orientated in the same direction or will make contact at any one time. As a result, an eight to ten ounce Tokay gecko can easily suspend its entire body weight from a single toe attached to polished glass.

Gecko toes bend in the opposite direction to human toes so, to release its hold, the gecko curls its toes upwards until the angle between the setal stalk(s) increases to more than 30 degrees which releases the bond, i.e. it slides its feet to bond and peels back its toes to let go. On horizontal surfaces, geckos do not need gecko adhesion and can be seen to run with their toes curled up so the setae do not make contact with the ground.

There have been other theories to explain gecko adhesion, for example micro suction. However, despite the spatulate thickening at the tips of the branched setae, micro suction has been discounted (Autumn 2006). Suction would not only interfere with the gecko's demonstrated ability to detach itself within microseconds but since gecko adhesion can be proved to work under vacuum, it clearly does not rely on adhesion due to air pressure differential.

Other possible explanations for gecko adhesion that have been investigated and disproved (Autumn 2006) include secretions, friction, electrostatic attraction and micro interlocking of the setae tips. It has also been postulated that capillary forces between spatulae and the thin film of water present on many surfaces may play some role in gecko adhesion (Sun 2005), and there are still many adherents to this theory since gecko adhesion is demonstrably stronger at higher humidities. However Autumn (2006) discounts capillary forces having found that gecko adhesion was not measurably lower on a polished hydrophobic wafer of gallium arsenide than it was on a polished hydrophilic wafer of silicon dioxide. Capillary forces may nevertheless be a factor with some species of gecko, since the shape of the spatula and the arrangement of the lamellae seem to be species specific, possibly resulting from adaptations to different environments. Until now most of the information on gecko adhesion is based on studies of the Tokay gecko (Gekko gecko). Figure 2

Figure 2 Tokay gecko. Courtesy of Dr. Robert Murphy, Royal Ontario Museum.

Characteristics of Gecko Adhesion

Geckos adhere well to most surfaces, even molecularly smooth surfaces, but they do not bond well to Teflon. This is supposedly because Teflon is not easily polarisable, suggesting that it is the chemical nature of the surface rather than its texture which affects gecko adhesion (Autumn 2006). Many geckos also do not adhere well to wet surfaces and some herpetologists take advantage of this by spraying the terrarium glass with water to make it easier to detach geckos for study.

Gecko setae are formed from stiff beta-keratin similar to that found in feathers. Because of their intrinsic stiffness, the hairs themselves are not inherently tacky so are not prone to clump, tangle or self adhere.

Geckos do not groom or deliberately wet their feet; nevertheless their toes do not become permanently clogged with dirt between moults that occur about every two months. The setae appear to self clean, shedding particles as the gecko walks. It is believed that this is an intrinsic chemical and physical property of the setal array which allows self cleaning in the dry state (Hansen 2005). The premise is that very few spatulae will attach to any one particle of dirt so the intermolecular forces attaching that particle to the gecko are very weak, whereas the energy attracting the dirt particle to the substrate is greater; consequently dirt particles detach as the gecko moves. This premise has been borne out by mimicking setal arrays in stiff, non-adhesive, hydrophobic polypropylene microfibers (Lee 2008). These also self cleaned when “walked” along glass. The degree of cleaning would not have been sufficient for any gecko’s exacting requirements but would be quite adequate for a modest amount of positioning and repositioning if such materials were used for mounting or clamping during museum conservation treatments.

The lotus leaf is known for its ability to self clean in a wet environment. It has a superhydrophobic surface which causes water droplets to bead up and to roll off the surface carrying away particles of dirt from the surface. Although gecko feet are self cleaning in the dry state they, like the lotus leaf, exhibit superhydrophobicity. This is inherent in their structure because innumerable, tiny nanohairs create a very hydrophobic surface. As a result, gecko toes have self cleaning properties in both wet and dry conditions. It should therefore theoretically be possible for conservators to rinse soiled, synthetic GSAs for limited reuse.

To sumarize, geckos have a dry, mechanical, solvent-free, plasticiser-free, directional adhesive system which is instantly effective on a variety of polarisable surfaces even in a vacuum. It is reversible, reusable, resilient, self cleaning, without creep or deformation, non-matting and non-self-adhesive leaving no (bonded) residues. Some choice in the degree of adhesive force also seems to be possible. It is less effective on wet surfaces and does not bond to non-polarisable surfaces such as smooth Teflon.

Gecko Synthetic Adhesive Tapes

Such an adhesive system could be very useful for museum artefacts given the possibility of quick, stress-free, reversibility with no harmful interactions or residues - an ideal embraced, but rarely achieved, by conservators. However it seemed to be no more than an interesting theoretical concept since the actual production of gecko-like adhesive surfaces is far beyond the means, the expertise or the equipment in the average conservation laboratory.

Fortunately, interest from well-funded groups involved in space research (an alternative to magnetic attraction in the dry, cold, vacuum of space); sports (better grip for running shoes and baseball bats); and robotics (scaling dangerous heights or entering toxic environments (Unver 2005; Kim 2011)) have stimulated international research into the production of gecko adhesives.

During the last decade, gecko setae have been artificially reproduced and modified in research institutions throughout the world using a variety of synthetic materials. Among the many materials under scrutiny are carbon nanotubes (Ge 2007) and various polymer formulations. Several of these are polymers which museums consider chemically acceptable for direct contact with artefacts, for example silicones, polypropylene, polyesters and acrylics. It should not be long before museums can take advantage of the products arising from this research.

Different physical configurations have also been studied for their adhesive effect. For example the hair-like setal structures have been compared with bumps, tubes and pillars arranged in various flat, angled and layered structures. These nanostructures have been attached to inert, flexible backings to create “gecko tapes”. Many individual patents have been taken out and companies have been formed to exploit GSA tapes having properties suitable for different uses in areas such as electronics, medicine and clothing manufacture. The remaining barrier to wholesale production seems to be the difficulty and expense of actually making the tapes. Fortunately improved methods based on vapour deposition, nanomoulding, plasma etching, etc. are in continual development. (Davis 2008, Jeong 2009). No double-sided tapes, i.e. tapes with a GSA surface on both sides, have yet been produced.

So far the surface area of most of the experimental sample tapes is extremely small; less than a square inch. Because of their directional nature, and the need for conformity, increasing the area of the gecko-like surface is not necessarily effective in magnifying adhesion force or contact area. A British company (B.A.E. Systems Advanced Technology Centre) claims to have overcome this problem and to be able to produce sheets approximately one metre square in polyimide (Acker 2007). They have named the product “Synthetic Gecko.”

An interesting variant on gecko tape, patented under the name “Geckel,” coats the GSA with mussel adhesive. Mussels attach themselves to rocks in tidal pools by secreting a very tough, proteinaceous material which withstands very onerous wet and dry conditions. It is both reversible and self-healing. As yet, only very small amounts of Geckel have been made, using a silicone GSA coated with synthetic mussel protein poly(dopamine methacrylamide-co-methoxyethyl acrylate) (Lee 2007). Geckel reputedly combines a reversible, pH sensitive chemical reaction with mechanical gecko adhesion. It is versatile in that it adheres well to both wet and dry surfaces (including Teflon) and has proved to be reusable over 1000 times before its adhesive properties were significantly reduced. It is being developed for medical and electronic purposes but could conceivably be of use as an archaeological first response treatment for wet material, for example keeping broken sherds from underwater sites together during lifting. Similarly, damp, recently excavated material or flood-damaged artefact fragments could be held in the correct alignment to counteract differential warping while drying.

With the exception of Geckel, most GSA tapes do not seem to have nearly the same degree of reusability as real gecko feet. This is hardly surprising since geckos replenish the setae on their toes by periodic moulting and regrowth so it is unfair to expect non-renewable, nanoscale polymer fibres to show indefinite resilience. Some reusability in terms of repositioning would be quite adequate for most museum purposes.

Gecko adhesion has been so well publicized in populist science during the past decade that the trade name “Gecko” has begun to appear on several tapes and adhesive systems which are actually traditional pressure-sensitive adhesives (PSAs) and have no connection with dry, mechanical, directional adhesion.

Potential Uses for Gecko Tapes in Museums

As an alternative to traditional PSAs

PSA tapes are undeniably useful especially as temporary clamping systems during the alignment and repair of breaks. However, museum staff are rightly wary about using such tapes in direct contact with artefacts, because of recurrent problems with staining, creep, chemical instability, unpredictable adhesion and persistent residues.

GSA tapes, when made from stable, artefact-friendly polymers, should have better chemical stability and be safer than traditional PSAs given that they have no plasticizers, solvents or viscoelastic adhesive to migrate, harden or interact with the substrate. Indeed, they could potentially outperform PSAs, for example when used to hold joins in place while glue is setting, because they would not have the same tendency to stretch, release unexpectedly or discolor as a result of reactions with the repair adhesive or its solvents.

In theory GSAs leave no residues but it is to be expected that some nanohairs will break or become detached from GSA tapes during use. Any such loose fibres should be easy to brush, vacuum or blow away but even if some tiny, transparent hairs remain unnoticed in contact with the artefact, they will probably be more inert and harmless than most museum dust.

In addition, GSAs should offer less risk of physical damage. PSAs flow (or are pushed) into surfaces, greatly increasing the probability that weak areas will be detached when the tape is pulled off. GSA adhesion is the result of an overall accumulation of myriad tiny points of contact, so the adhesive force at each of the individual contact points is extremely weak. This should significantly reduce the risk of damage to delicate surfaces as the tape is peeled back.

Safe contact with artefact surfaces could open up a whole range of uses for GSA tapes. For example, in close-up photography of vertical surfaces (e.g. paintings) tiny, temporary GSA labels containing the registration number and the treatment stage could be used directly on the object so that all the necessary information could be actually incorporated into the photograph itself. Barcode labels could be attached directly to artefacts as has been proposed for upgraded registration systems

Mounting

Gecko tapes can be used as pressure-sensitive mounting systems as in the illustration of a U.S. quarter mounted onto a steeply angled Plexiglas support (Figure 3). However there are already perfectly adequate support systems for such small rigid objects, so this example is an alternative rather than an improvement.

However, GSAs may be able to address some unresolved mounting problems. GSA tapes "breathe" i.e. they do not create an airtight seal as they bond because gases can diffuse between the nanofibres whereas PSAs or elastomeric clamping systems form tight seals against the underlying surface. "Diffusability" could be very helpful when mounting artefacts which are emitting corrosive volatiles such as Vulcanite, cellulose acetate, cellulose propionate and some urea formaldehydes. Such artefacts are extremely difficult to support without inhibiting the emissions - which accelerates deterioration. These plastics can show noticeable changes in colour, translucency, texture and strength after volatiles have been trapped for a relatively short time.

Cellulose nitrate plastics also emit corrosive volatiles but they are so aggressive that the GSA filaments would probably degrade too rapidly to be useful.

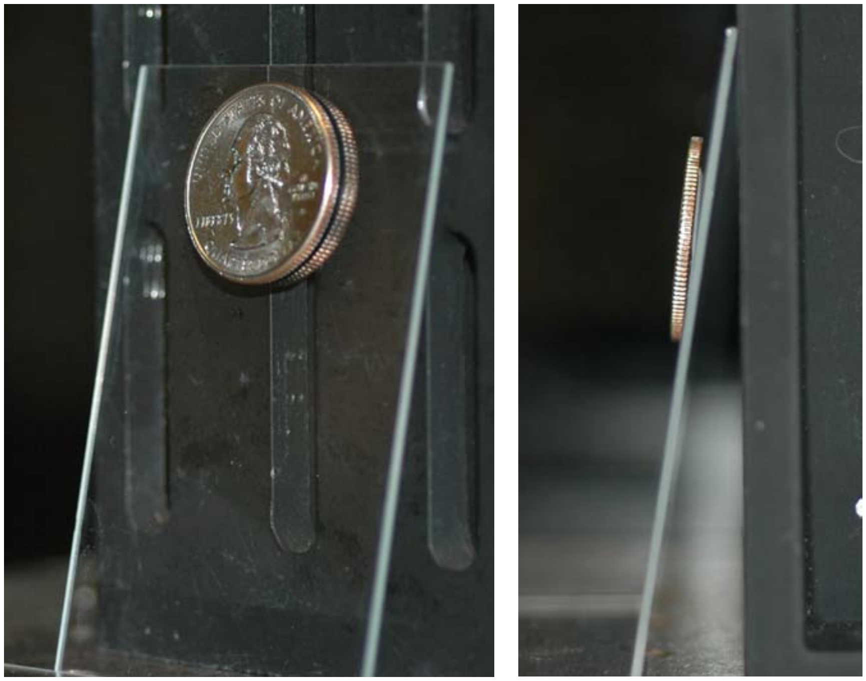

Figure 3 Gecko tape holding coin onto Plexiglas. Courtesy of C. Majidi and Professor R. S. Fearing, University of California at Berkeley.

Temporary first aid for damage

As a completely reversible system with no side effects, GSA tapes could be useful as an easily applied, interim adhesion system for museums and collectors who lack ready access to affordable conservation services. GSA tapes do not need ventilation, training or any specialized equipment which would prevent them from being used for quick emergency repairs in the storeroom or the home.

Even in museums with trained conservators, loss of staff and recession economics has altered conservation priorities. As a result there is an accumulation of "non-priority" damage which is not scheduled for repair in the foreseeable future. In the interim, loss of fragments, soiling, or crumbling edges can make the eventual repair so difficult or so expensive that it will never be done. A "quick–fix" could keep the artifact together in reasonable shape for future repairs and would be particularly useful for humidity-sensitive, anisotropic materials such as carved ivories which often distort after fracturing and can be very difficult to reassemble once the warp has set.

Vibration resistance

Even museums which are not in earthquake zones can be affected by significant vibration from HVAC systems, traffic, or exuberant school groups. Current methods of preventing artefacts from "walking" or "jittering" on display such as museum gels, silicone sheet and quake waxes sometimes creep or leave unacceptable stains on porous materials. Given the structure of GSAs, they should be able to counteract vibration and could be mechanically fastened to the support (e.g. by sewing) then the artefact could be slid onto the GSA surface until firmly held. In this way GSA tapes could be used on both vertical and horizontal surfaces to reduce vibration damage while on display and in storage.

Improving grip on fragile fragments

Another use for the tapes might be to improve control when manipulating tiny, friable fragments of rotted silk, crumbs of ethnographic earth pigments or flakes of iridescent, archaeological glass. To pick up and reposition such fragile items is often very risky using traditional tools such as forceps, spatulas, solvent-dampened rods or even mini vacuum tweezers. Fine brushes or rods dampened with solvent, gelatin or methyl cellulose can leave tide-marks or other residues which alter the refractive index, especially of lime pigments, iridescent glass or feather fragments. It seems likely that gluing a very small piece of GSA to a rod with the GSA surface facing outwards would provide a better lifting tool which could work with very light pressure and would not alter the surface appearance of the tiny flake. The rod could be angled for easy release once the fragment was attached in its rightful place.

Discussion

There are many unanswered questions that cannot be resolved until actual samples of gecko tapes are available for testing in real museum situations so that the apparent advantages of using GSA's can be conclusively proved.

For example, it is not clear how long GSA systems can be expected to adhere before failing. Long-term adhesion is not necessary for geckos - they do not need to hang in situ for more than a few hours at any one time so gecko adhesion may have an inherent flaw from a museum perspective. Similarly the GSA tapes may have little chemical durability. Most synthetic gecko tapes are made from multiple polymers - unlike homogenous gecko keratin. It is not yet known how this will affect their long-term durability and toughness under different environments. GSA surfaces consist of microscopic, non-renewable filaments. Such tiny fibres, having narrow diameters but comparatively large surface areas, might be extremely vulnerable to damage from light, aggressive volatiles, metallic catalysts or corrosive artifact surfaces such as those present on corroded metal, rubber, alkaline degraded glass and certain acidic plastics.

Many of the test results on GSAs, for example load bearing properties, effective contact area and peel strength seem to have been based on very short-term measurements (i.e. hours and days). Since one of the major applications for GSA tapes in museums would probably be in support mounts for display and storage, there needs to be evidence of long-term stability, both of the bond and the GSA tape itself. Until this has been clearly demonstrated, perhaps GSA tapes should be considered only for very short-term applications such as clamping and support during treatments where they will be under observation.

GSA tapes may also require a different approach to repairs and supports. Gecko adhesion is attached by sliding but is detached by peeling, so the mount design needs careful forethought. Removing a rigid coin from a rigid mount such as the one in Figure 3 would be very stressful to a fragile archaeological coin although sliding it onto the tape would have been simple and stress-free. Even when a safe plan for freeing the artifact from the mount is incorporated into the design, it will need to be clearly apparent even to a different crew dismounting the exhibit. One misdirected tug on a fragile object is all it takes!

It also remains to be seen what degree of skill will be required to get appropriate adhesion in any given situation. It may require considerable practice on the human scale to achieve what is intuitive for small lizards.

Conclusion

GSA's are not the only exciting new adhesives becoming available. There is a whole range of "smart adhesives" which can be activated or released by non-solvent methods such as pH change or electrical charges. However gecko adhesion does fill gaps in the area of quick, simple, mechanical reversibility with no side effects which is currently not available in most commercial adhesives – not even museum quality adhesives.

Adhesion of this kind would be totally in line with the growing conservation belief that a feasible plan for safe reversibility should be incorporated into any treatment proposal.

Acknowledgments

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Julia Fenn was born in South Africa and obtained a degree in Archaeology at the University of Cape Town. She subsequently qualified in Conservation (archaeological and ethnographic) at the Institute of Archaeology in London (United Kingdom) and was employed for several years at the British Museum Research Laboratory. Following her marriage to a Canadian, she moved to Ontario where she has worked for National Historic Sites, coordinated the Conservation Technician training program at Fleming College in Peterborough, and taught in the Museum Studies program at the University of Toronto. She is currently the Ethnographic Conservator at the Royal Ontario Museum in Toronto.

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