THE USE OF BIOMIMETIC SYNTHETIC SETAE IN ADHESIVES

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Abstract— Biomimicry involves the enhancement of mechanical processes by adopting the technology of phenomena occurring in the natural world. Biomimicry advocates that we stop "seeing nature as a source of raw materials" and start seeing "nature as a source of ideas, as a mentor." Engineers value this field of study as inspiration for modern design because of the natural ingenuity that billions of years of evolution offers to emerging design problems. In the realm of biomimicry, there has been recent interest in a gecko's ability to climb in nearly inverted environments; this phenomenon has piqued the interests of scientists because of its potential to be applied to improving adhesive technology. Until recently, it was difficult for scientists to study the nature of geckos' feet due to its microscopic scale. However, recent advancements in nanoimaging have revealed the tiny secret underneath these geckos' feet: setae.

The idea of synthetic setae- the microscopic "hairs" found at the bottom of gecko feet- originated from the observation of the mechanics and chemistry of geckos' feet when they climbed. When these nanohairs come into contact with a surface, molecular attractions, caused by Van der Waal's forces, allow the gecko to adhere to the surface. Modeling the nanostructure of these setae has allowed engineers to create an adhesive that can be used in more diverse conditions, with greater structural stability, than preceding adhesives. Since the nature of how the setae surface adheres to another surface is different from most adhesives, this gecko-adhesive can be used where you would normally expect adhesives to fail, such as underwater or within human tissues.

Key Words—Adhesives, Biocompatibility, Biomimicry, Carbon Nanotubes, Gecko adhesion, Gecko-Like Synthetic Adhesive, Setae

PROBLEM WITH CONVENTIONAL PRESSURE SENSITIVE ADHESIVES

Traditional tapes, such as duct tape, are classified as pressure-sensitive adhesives (PSA) and rely on viscoelastic materials for their adhesive abilities [1]. This means that the materials on the bottom of the tape are somewhere in between the solid and liquid states. Most are familiar with this viscoelastic material since it is what leaves a sticky residue behind when peeling off duct tape or barcode labels. PSA's take advantage of the physical phenomena of cohesion and adhesion [2]. Cohesion is the molecular attraction between molecules of the same structure, the viscoelastic molecules in this case; while adhesion is the molecular attraction between molecules of a different structure [2]. These phenomena are due to Van der Waal's forces [2]. Traditional tapes are very useful in simple household applications; however, they have their flaws.

Traditional tapes are generally weak and are poor choices for binding more massive objects. Their viscoelastic materials do not accrue a large enough sum of Van der Waal's forces to allow them to be strong. There are some stronger viscoelastic tapes like duct tape; however, they are not easily removed and leave behind a sticky residue upon removal. Another issue is that these tapes wear out with a few uses. Since these traditional tapes rely on creating a sandwich of the viscoelastic material in between the polymer backing of the tape and the surface, each surface tends to retain roughly half of the viscoelastic material after the two are peeled apart [2]. This means that the tape quickly loses its "stickiness" after just a few applications. Additionally, if the surface is dirty, the viscoelastic material sticks to the dirt. This not only means that the bond between the tape and the surface is not as strong as it could be, but when the tape is removed, the "half" of the viscoelastic materials that the tape retains is tainted. So, after traditional tape is applied to a dirty surface and removed, the tape has less than half of its original adhesive potential. Lastly, viscoelastic material dependent tapes are time dependent [2]. These tapes gradually lose their adhesive ability with time, regardless of the number of uses.

BIOMIMICRY

Biomimicry utilizes designs of nature, perfected by billions of years of evolution, as inspiration for man-made technology [3]. Geckos, in particular, have evolved into expert climbers, able to climb vertical and inverted surfaces with ease. Their feet act as tiny tape-pads that repeatedly attach and detach to scale smooth, rough, wet, and dry surfaces. The environment in which they climb is certainly not the most sterile one either. Aside from the rough-textured bark on the trees they climb, rain, pollen, and other particles cover the bark. How, then, are the gecko's tape-like feet able to stay

sticky enough to fully support their weight in vertical and inverted circumstances despite adverse environments for adhesion?

Until recent nano-imaging breakthroughs, the secret behind geckos' climbing ability was not fully understood. It appears that geckos' feet use no such viscoelastic material as found in traditional tapes [1]. Scientists now understand that their ability rests within the nanostructure of their feet. Thousands of microscopic hairs, called "setae", cover the bottom of a gecko's foot [1]. Each of these setal hairs branch off to form "spatulae", similar in scale and structure to the split ends of human hair [1]. The number and structure of these hairs allow for intermolecular attractions to occur between the gecko's feet and the climbing surface [1]. From this discovery, researchers have attempted to replicate these hairs with the interest of creating an adhesive technology, superior in strength and versatility, to the viscoelastic technology used in traditional tapes today. This new gecko-inspired adhesive has potential for diverse applications in industry and medical fields.

The Relation Between PSA Innovations and Sustainability

With the arrival of new inventions in the field of engineering, it is important to consider thier societal and environmental impacts. Specifically, it is the engineer's ethical responsibility to ensure their improvements or inventions are safe and sustainable. To understand what this entails, it is necessary to first define sustainability. "Sustainability is commonly perceived as the capacity to endure some challenges, obstacles, stress, varied conditions, etc., and to continue normal or even improving operation [4]." This concept is currently applied to economies, environments, ecosystems, industries and society as a whole [5]. Evaluating the sustainability of an invention involves considering the lifespan of it, as well as its environmental and societal impacts.

Due to the disposable nature of how PSAs stick to surfaces, they are inherently bad for the environment. These PSAs are generally used once and disposed of in a landfill. What's more is the fact that since these adhesives are generally weaker, people use larger quantities to try to achieve the level of adhesion they need. Since the adhesive strength of gecko tape is stronger than that of most PSAs, less tape is required to achieve the same effect [1]. Not only is less tape needed to achieve adhesion, but the tape is also reusable and cleanable [6]. This means that one could theoretically never buy another roll of gecko tape again and none of the said tape will make it to the landfill.

THE SCIENCE OF GECKO ADHESION

Geckos use adhesive methods that are independent of viscoelastic materials. They take advantage of the natural phenomenon known as Van der Waal's interactions, the weakest of the intermolecular forces [2]. This phenomenon occurs when an atom's electrons temporarily get unevenly distributed. This induces a temporary difference in charge, known as a 'dipole', in the atom [2]. This is due to an excess of electrons forming on one side and an absence of electrons forming on the other. The dipole that occurs in that atom then induces a dipole in neighboring atoms, creating a domino effect of electric dipoles. These interactions occur in a way that the positive dipole of one atom and the negative dipole of the other attract each other, such as to create a weak, attractive intermolecular force, allowing two separate objects to stick.

A single gecko foot has millions of tiny follicle cells. Each of these follicle cells contains a hair, or seta, made out of the hydrophobic protein beta-keratin [7]. These setae usually occur in groups of four to six and have a length of 110 μm and radius of 2.1 μm [7]. Each seta further splits into hundreds of smaller spatulas, with length 800 nanometers and radius of 25 nm, with flat, perpendicular heads 100-200 nm wide and 5 nm thick [7]. These spatulas, which are smaller than the wavelength of visible light, branch off from the setae, bending slightly but aligning themselves in the same general direction as seen in Figure 1 [7].

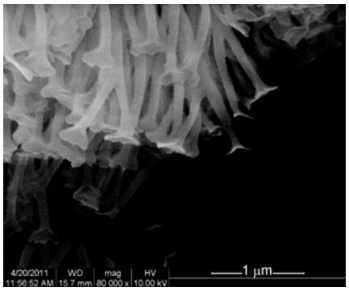

FIGURE 1 [7]
Microscopic Image of Gecko Setae and Spatulae

Geckos' hierarchical structure of fibrillar hairs allows the surface of the foot to have more surface area and more contact with the opposing surface as shown in Figure 2. This is integral to a gecko's sticking ability, as Van der Waal's interactions only occur when the surface of the atom on the setae, and the atom of the opposing surface, are as close as physically possible, when they are the atomic distance apart [7]. In other words, the interactions only occur and produce a force when the two surfaces are as close as possible to each other. When a gecko's foot steps on a surface, the individual setae fit the surface's larger irregularities, the smaller spatulas fit the smaller irregularities, and the heads of the spatulas deform and spread to fully maximize contact between the two surfaces. Figure 2 represents a visual of this on a microscopic scale. In optimal conditions (smooth, dry surface), a single seta has been shown to be able to support about 40 μN in this way [2].

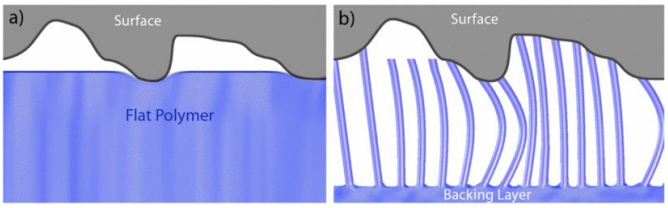

FIGURE 2 [3]
Surface Contact of a Flat Polymer PSA Versus Gecko-Like Setae

Geckos' setae and spatulas can accrue such a large sum of Van Der Waal's forces that it seems as though the gecko shouldn't be able to unstick its feet from a surface once adhered. However, geckos are clearly able to unstick their feet and skirt away easily. Gecko feet contain actins, or proteins that can be contracted by electrical impulses supplied by the abundance of peripheral nerves in the gecko's feet [7]. These proteins can be controlled to produce adduction, bringing the toes closer together; abduction, spreading the toes apart; and rotation, to name a few maneuvers [7].

As a gecko prepares to step onto a surface, it uncurls its toes so that they will contact the surface at a 30.6±1.8° angle, the angle that produces the greatest magnitude of adhesion [8]. This angle is favorable because it ensures that the gecko foot does not impact the surface perpendicularly and allows a certain amount of sliding to occur during contact. Scientists measuring the adhesive force of setae found that a parallel slide is critical to adhesive force. When setae were first preloaded and then pulled parallel to the surface, they "developed over ten times the force (13.6 ± 2.6 μN) upon being pulled away from the surface than those having only a perpendicular preload (0.6 ± 0.7 μN)" [8]. This helps explain why geckos have more "grip" when their velocity increases, as shown in Figure 3. While walking, the gecko relies only on the contact angle to provide the parallel pulling force, so it is not very strong. As the gecko builds its speed, it gains momentum in the horizontal direction it is traveling, which provides a greater parallel force than walking. When the gecko prepares to remove its foot from a surface, it curls its toes upward by contracting the actins in its foot [8]. This creates an angle greater than 30° which renders the Van Der Waals interactions negligible and, thus, the attractive force also goes to zero [8]. In this way, geckos can remove their feet from a surface, one row of setae at a time, simply by changing the contact angle. This is advantageous to the gecko since it does not have to exert a large amount of energy to produce an equally large force to rip its foot away.

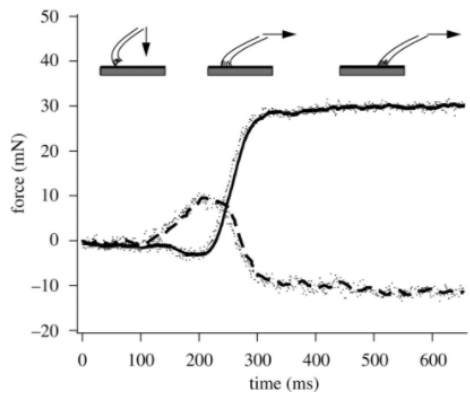

FIGURE 3 [5]
Graph of Adhesion Forces as Speed Increases Versus Time

ARTIFICIAL SETAE AND SPATULAE REPLICATION

While the recent innovations in nanoimagery have enabled scientists to understand the science of gecko adhesion, it is the innovations in microfabrication which have enabled them to synthetically recreate the conditions of gecko adhesion. Through both research of the mechanics of gecko adhesion, as well as experimental results regarding synthetic gecko tape, scientists have created a PSA able to support a magnitude of force exceeding that supported by natural gecko adhesion [1]. The first challenge scientists faced in their attempts of replicating setal hairs was determining the ideal setal material. This material needed to be able to be synthetically fabricated, while still maintaining, if not exceeding, the natural strength and durability of beta-keratin on a nanometer scale. The two primary microfabricated materials which emerged in this research are silicone elastomers and carbon nanotubes [1,9].

Initially, the solution of fabricating the setal hairs with silicone elastomers was supported by the ideas of contact mechanics. Since contact mechanics are "controlled by a balance between (surface-dependent) adhesive energy and (volume-dependent) elastic energy," increasing the surface area of the system requires a decrease in the elastic energy to maintain contact geometry similar to that of a natural gecko [1]. Essentially, in order to be able to have a tape with a surface area greater than that of a gecko's foot (~100 mm^2), the synthetic setal material must be more flexible [2]. The silicon elastomer, polydimethylsiloxane, has a low elastic modulus of 1.75 MPa, which is 8.6×10^{11} times smaller than that of the setal beta-keratin [1]. This makes it flexible enough to deform upon sliding. This flexibility upon sliding increases the contact between the setal hairs and spatulas with a surface and, consequently, increases the number of molecular attractions and adhesive forces between the setae and the surface.

The Use of Carbon Nanotubes as Synthetic Setae

Despite the successful trials and reasoning of using polydimethylsiloxane, experimental results reveal a different material capable of producing a force which exceeds not only that of polydimethylsiloxane, but also natural gecko adhesive forces. Carbon nanotubes have been proven to be an ideal material due to their excellent mechanical properties and their strength of adhesion to silicon substrate [9]. They are among earth's strongest structural materials, with their strength compensating for their relatively high elastic modulus [10]. Additionally, they are made through the process of microfabrication, which enables scientists to control their microscopic dimensions.

In addition to determining the best artificial setal material, scientists also tackled the question of how to arrange these setae. They experimented with two different arrangements - unpatterned and patterned - and collected substantial evidence supporting the latter. A patterned arrangement involves varying the length and width of the individual seta in the setae cluster; while an unpatterned arrangement uses uniform setae height, width, and placement on the substrate [9]. A patterned carbon nanotube gecko-like synthetic adhesive (GSA) has been demonstrated to support a force four times greater than that supported by gecko adhesion, four times greater than that supported by an unpatterned carbon nanotube GSA, and ten times greater than that supported by unpatterned silicone elastomers [9].

Forces Contributing to Adhesive Strength of PSA

In order to explain the significance of experimental findings regarding the adhesive strength, it is important to understand the primary forces which contribute to it: shear force and peeling force [9]. Shear force is the force which acts parallel to a plane [1]. To visualize this in terms of GSAs, it would be the primary force acting upon the artificial setae when trying to drag a stuck piece of gecko tape across a table. If the tape could only sustain a low shear force, it would easily become unstuck. The peeling force, on the other hand, is the force required to part two bonded materials [1]. In the case of GSAs, this force varies depending upon the angle at which the adhesive is being pulled from the surface. Figure 4 provides a visual of how these forces are tested. The desired values of the maximum forces which a GSA can sustain varies based upon the intended purpose of the adhesive. In nearly all cases, it is desirable for the adhesive to endure a high shear force [1]. This will prevent the tape from falling and enable more weight to be supported by the tape. Regarding peeling force, low peeling force is desired for applications in which the GSA will be repeatedly attaching and detaching, such as with wall-climbing robots. This would ensure that a minimum amount of energy is required for attachment and detachment [9].

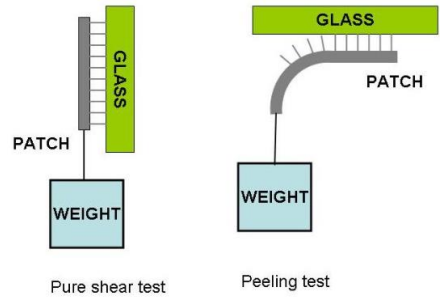

FIGURE 4 [11]
Diagram of Testing Shear Force Versus Peeling Force

Scientists initially conducted their experiments with unpatterned carbon nanotube gecko tape. With this tape, the force supported decreased upon increasing the surface area [9]. This would make it incapable of supporting a large amount of weight, regardless of the amount of tape used. In order to support larger shear forces, scientists discovered that a combination of micrometer-size setae, in addition to nanometer-sized setae, was necessary [9]. Upon including a range of 50-500 µm sized setal carbon nanotubes, the shear force supported increased by factors ranging from four to seven [9]. The shear force supported by a 100-500 µm patch of this tape was 3.7 N, or two to three times higher than that of a gecko [9]. Additionally, the shear force supported depends on the ratio of patch size to setal height; if the setae are too tall relative to the width of the patch, the shear force will decrease. Reducing the width-to-height ratio makes setae mechanically weak [9]. For example, when that same 100-500 µm patch of tape mentioned above was tested with a width of 50 µm, the shear force decreased [9]. However, upon adjusting the height of the setae from 300 µm to 200 µm, the 50 µm wide patch supported a shear force of 5.8 N, a factor four times higher than the natural gecko [9]. These results can be seen in Figure 5.

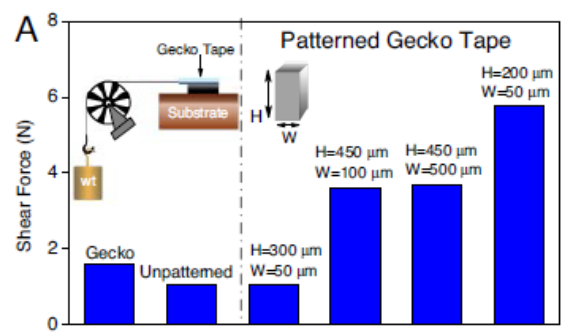

FIGURE 5 [9]
Data Results of Shear Force Sustained by Varying Width-to-Height Ratio

STRENGTH OF ADHESION

When testing the strength of adhesion, a shear force was

applied until a catastrophic rupture initiated. The amount of force necessary to reach this point is called the 'critical load' [9]. The type of rupture in patterned carbon nanotube GSA was different than that of unpatterned. There are two main types of adhesive failure: cohesive and interfacial [12]. Cohesive failure "is a failure in the bulk layer of the adhesive," this means that the adhesive detaches from the substrate rather than the surface to which it is adhered [12]. Cohesive failure is the desired mode of failure as it indicates a strong adhesive-to-surface bond [12]. The second mode of failure, interfacial, occurs when the bonds between an adhesive and the surface adhered to break [12]. This form of adhesive failure can be demonstrated by peeling a sticky note off a surface. It is not desired for GSAs, though, as it indicates a weak adhesion strength.

Understanding these modes of adhesive failure further prove the strength and significance of patterned carbon nanotube GSAs. For the unpatterned carbon nanotube arrangement, the adhesive failure at critical load was interfacial, leaving no carbon nanotube residue behind [9]. For a patterned carbon nanotube structure, failure of adhesion was cohesive [9]. "The aligned and broken strands of the carbon nanotube bundles" indicated that there was large energy dissipation in the cohesive failure [9].

PEELING FORCE AND GEOMETRY

An increase in shear force supported also causes an increase in the peeling force. The peeling force factor of a patterned carbon nanotube GSA was ten times that of a uniform carbon nanotube GSA [9]. However, unlike a decrease in shear force, this increase in peeling force is not detrimental to the functioning of GSAs. This merely means that the GSA has a greater amount of energy of detachment. This energy of detachment can be determined by dividing the peeling force by the width of tape (N/m) [9]. The energy of detachment was tested at three different peeling angles. As the angle increased, the peeling force decreased, but the carbon nanotube breakage increased. At a 45° angle the energy of detachment was 16 N/m; at 30°, 20 N/m; and at 10°, 96 N/m [9]. While an angle of 10° had the highest energy of detachment, it involved no carbon nanotube breakage or transfer, meaning its number of repeated uses is theoretically limitless [9]. Though it is more difficult to peel a strong GSA at a small angle, it is necessary to maintain its reusability.

MICROFABRICATING CARBON NANOTUBES

The general process of fabricating carbon nanotubes varies depending on the purpose and experiment, but for the sake of GSAs, a specific three-step 'growing' process was used [6]. The first step, photolithography, utilized ultraviolet light to imprint the pattern of the carbon nanotube growth on the silicone substrate [6]. The silicone substrate is considered the 'backing' for the GSA. The second step, catalyst deposition, involved the deposition of iron (Fe) and aluminum (Al) onto substrate patches [6]. Using an electron beam, a 10 nm thick buffer layer of Al was deposited on the substrate. This buffer layer ensures that the 1.5 nm thick layer of catalyst, Fe, does not negatively interact with the silicone substrate [10]. The last step, chemical vapor deposition, utilizes the decomposition of hydrogen and ethylene gas as feedstock for the carbon nanotube growth [6,10]. This reaction was time controlled, with a range of 10-30 minutes, to control the dimensions of the nanotubes [6].

THE FINAL PRODUCT AND FEATURES

In summary, scientists were able to create a gecko-like synthetic adhesive so that 1 cm^2 of this tape can support 4 kg of weight, or 36N [9]. A single piece of this tape has an array of the previously mentioned micrometer sized patches of carbon nanotubes. Additionally, tests of its time dependence showed that, unlike viscoelastic PSAs, this tape did not wear out when supporting weight in a time test [9].

Self-Cleaning Properties of Gecko-Like Adhesives

Another interesting property, in addition to the GSA's time independence, is its self-cleaning ability. When considering traditional PSAs, it is difficult to believe that a gecko is able to maintain its adhesive abilities despite climbing in non-ideal, contaminated environments. A gecko can recover 50% of the force from clean feet after walking in a dirty environment after just eight steps [9]. Similar self-cleaning properties have been observed with gecko-tape made with carbon nanotubes. A group of researchers studied this by soiling samples of carbon nanotube based tape with silica particles ranging from 1 to 100 μm to simulate dust and dirt [6]. Then, they cleaned one group of samples with water and the other by applying it to a glass substrate a couple of times. In both cases, most of the silica particles were washed away and the carbon nanotubes remained relatively undamaged [6]. Only some of the nanotubes in the water-washed group experienced minimal damage, but this was due to the drying of the water after they were cleaned. Although most of the silica particles were cleaned off, researchers were still interested in whether the samples retained their adhesive abilities. They found that the water-washed samples retained 60-90% of their original strength [6]. They inferred that the decrease in adhesion was due to the slight damage to the nanotubes. In the samples cleaned by application to a substrate, they found that the tape retained 90% of its original strength [6]. Since no pillars were damaged in these samples, they attributed the small loss of adhesion to the smaller silica particles potentially trapped in between the pillars, unable to easily be cleaned. However, they concluded that both of these flaws (cracking due to drying and pillar distance) could be fixed by optimizing the adhesion between the carbon nanotubes and the polymer substrate, and by reducing the spacing in between tubes.

MEDICAL APPLICATIONS

In the arsenal of today's medical technologies, doctors lack a biodegradable adhesive that is flexible and able to move with the body, while staying firmly attached to internal tissue, that doesn't involve strong chemical adhesives. If such a technology was developed and perfected, it could potentially replace sutures and staples as a means of sealing wounds, all the while delivering drugs to accelerate healing. Current research efforts have been aimed at the challenges of making the tape biodegradable and at finding the optimal nanostructure for adhesion to tissue. Previous efforts by P. Messersmith's research group showed that a gecko-adhesive that works while wet with reversible, noncovalent bonding is possible [13]. These findings indicate a complete success for the future of medical gecko-inspired adhesive bandages. However, applications in the body require strong irreversible bonds to tissue, as to ensure that they remain applied when neighboring tissue moves [13]. Thus, researchers must take advantage of the setae's nanostructure while finding a way to make the bonds irreversible.

To test the effect of using fibrillar adhesives versus traditional flat-surface adhesives, poly(glycerol sebacate acrylate) (PGSA), a tough biodegradable elastomer, was nanopatterned to mimic gecko setae using techniques of photolithography and reactive ion etching [13]. The PGSA was patterned with only a single layer of nanopillars, differing from gecko feet which contain a hierarchy of nanostructures from the larger setae to their substructures, spatulas [13]. Pillar tip diameters were varied between 100 nm and 1 μm, and pillar heights varied between 0.8 and 3 μm in different samples to study their relative impacts on stickiness [13]. In order to simulate real human tissue, porcine intestinal tissue was used as the organic substrate in vitro [13]. Once the PGSA and the organic substrate were married, shear or sliding forces were applied to simulate natural movement. Across the board, nanopatterned PGSA samples had about twice the adhesive strength of the flat unpatterned polymer [13]. The treatment that created the nanopattern clearly had a positive effect on adhesion strength, making researchers question how much more they could optimize adhesion by changing the pillar geometry.

Ideal Pillar Geometry for Use in Tissue

With the task of finding the best pillar geometry in mind, researchers varied the tip diameter, base diameter, pitch, and height of the pillars [13]. What they found is that a decrease in the ratio of tip diameter to pitch leads to a decrease in adhesion strength [13]. They also found that increasing the ratio of tip diameter to base diameter decreased adhesion [13]. A sharper loss of adhesion was noted when both of these ratios increased together [13]. With these factors in mind, researchers observed that structure 9 in Figure 4 produced the strongest adhesion, and therefore would be the structure that they continued testing. Notably, this involves a counterintuitive finding: the pattern with the lowest density of pillars produced the largest enhancement [13]. This is specific to the substrate being used: tissue. Since tissue is easily deformed, lower pillar density allows tissue to deform into the nanostructures.

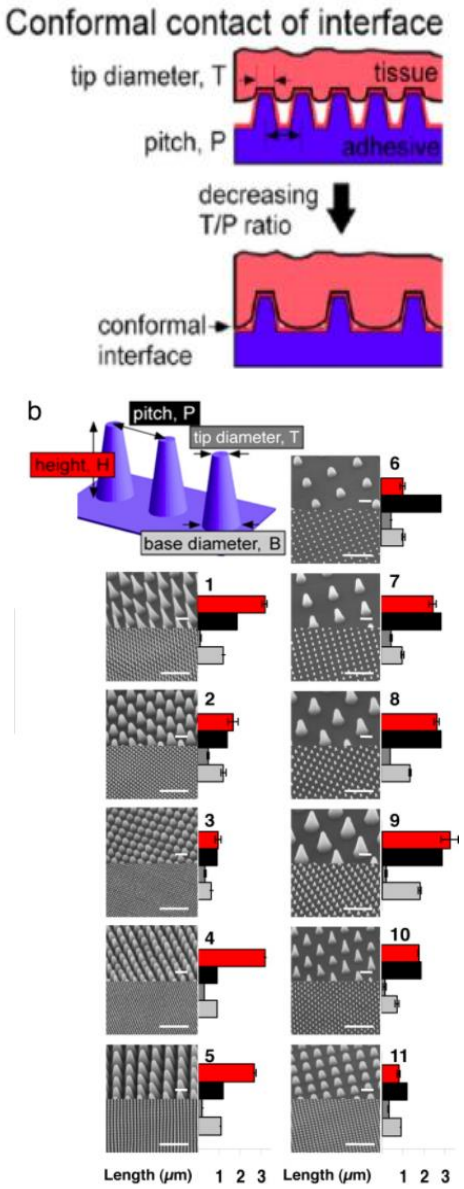

FIGURE 6 [13]
Pillar Structure Patterns for the Use of GSAs in Tissue

After researchers found the best nanostructure by varying pillar dimensions, they became interested in making the adhesive durable and functional in "underwater" or wet conditions inside the body. Previous studies, involving bonding animal tissue and hydrogel materials, gave researchers insight into a possible coating. They coated the PGSA nanotips with a thin layer of oxidized dextran with

aldehyde functionalities (DXTA) [13]. They selected this coating for its cross-linking capabilities which will help the nanostructures bond to the tissue [13]. In addition, the coating has been shown to produce minimal inflammation to tissue in the study mentioned previously. This is important because swelling is an indicator of poor biocompatibility. It is also significant because researchers want to be sure that the adhesive strength is due to the structure and the bonds formed by the coating, and not any temporary mechanical interlocking that may occur from tissue swelling around the nanotubes [13].

The Sustainable Impact of Medical Innovation

The societal aspect of sustainability applies to nearly all medical innovations and treatments. Medical innovations and treatments are almost always sustainable because they improve the quality of life of those who receive them. Traditional methods of closing wounds internally involves uncomfortable stitches and sutures which can also put the wound at risk for infection because of how the tissue around the wound is penetrated [13]. The nature of gecko tape means that it is a thin, flexible tape that can move easily with the body, making it more comfortable. Also this method does not require penetrating the skin while also providing a protective barrier above the skin.

ETHICS REGARDING THE USE OF GECKO-LIKE SYNTHETIC ADHESIVES

The ethics regarding GSAs relates to both the general ethical responsibilities in the field of engineering, and the risks which entail the research and release of a new medical device. According to the American Society of Mechanical Engineer's Code of Ethics, it is an engineer's ethical responsibility to use "their knowledge and skill for the enhancement of human welfare" [14]. In a general sense, the use of GSAs does just this. It has a wide array of potential applications, being able to improve the field in which it is used, whether it be robotics or medicine. Regarding medicine, it is paramount that this technology has been tested and perfected before being used in patients, as to not harm any recipients of this device. This includes researching both short-term and long-term effects of this device and its biocompatibility.

In terms of environmental ethics and responsibilities, GSAs are promising. In addition to the reusability and strength of GSAs explained above, biodegradable GSAs have been created. However, these specific qualities of GSAs are not sole reason they are environmentally conscious. The entire inspiration behind this invention, biomimicry, is a hallmark example of environmental sustainability.

The field of biomimicry advocates that we stop "seeing nature as a source of raw materials" and start seeing "nature as a source of ideas, as a mentor" [3]. Sustainability will be achieved in two aspects if engineers, as a community, adhere to the template of biomimetic design. Firstly, we will stop rapidly consuming the earth's nonrenewable resources; and secondly, by modeling and improving upon the example nature has presented us, the intelligence and efficiency of engineered designs will increase. These two effects work together: as these designs improve by modeling nature, they require less resources to build, function, and maintain. Biomimicry inherently incorporates sustainability because it takes after nature itself, the very force that renews itself continuously.

THE POTENTIAL AND FUTURE OF GECKO-LIKE SYNTHETIC ADHESIVES

Traditional viscoelastic adhesives are useful in a pinch for weak applications, however they have their drawbacks and limitations. Beyond the minor annoyances like sticky residue, viscoelastic tapes are functionally deficient in the mechanisms they use to stick to various surfaces. Generally, they wear out after just a single use, if not becoming completely useless by the second and third application. Gecko-inspired tape, that replicates nano-sized setae and spatulae, eliminates the limitations of repeated use by taking advantage of the physical phenomenon of Van der Waal's interactions. Additionally, researchers have replicated gecko setae by using microfabrication to grow carbon nanotubes. As this process becomes more streamlined and cost-effective, the popular use of GSAs is becoming a substantial possibility.

Other researchers are focusing on the potential medical applications for this technology in tissue and wound repair, both internally and externally. Both groups have optimized their technology by testing various nanostructure dimensions and properties. By utilizing the ideology of biomimicry, scientists have gleaned inspiration and information from gecko adhesion to create an unprecedented PSA. Due to its strong adhesive forces, time-independence, reusability, and versatility, this technology is superior to traditional PSAs and holds promise in a wide variety of future applications.

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ACKNOWLEGMENTS

We would like to thank our co-chair, Nick Malagari, and our chair, Dr. Irene Mena, for advising us and providing critical feedback. We would also like to thank our writing instructor, Julianne McAdoo.