Integrative and Comparative Biology

Integrative and Comparative Biology, volume 59, number 1, pp. 214–226
doi:10.1093/icb/icz008

Society for Integrative and Comparative Biology

SYMPOSIUM

Stick or Slip: Adhesive Performance of Geckos and Gecko-Inspired Synthetics in Wet Environments

Alyssa Y. Stark[1] and Christopher T. Mitchell

Department of Biology, Villanova University, 800 East Lancaster Avenue, Villanova, PA 19085, USA

From the symposium “The path less traveled: Reciprocal illumination of gecko adhesion by unifying material science, biomechanics, ecology, and evolution” presented at the annual meeting of the Society of Integrative and Comparative Biology, January 3–7, 2019 at Tampa, Florida.

[1] E-mail: alyssa.stark@villanova.edu

Synopsis The gecko adhesive system has inspired hundreds of synthetic mimics principally focused on replicating the strong, reversible, and versatile properties of the natural system. For geckos native to the tropics, versatility includes the need to remain attached to substrates that become wet from high humidity and frequent rain. Paradoxically, van der Waals forces, the principal mechanism responsible for gecko adhesion, reduce to zero when two contacting surfaces separate even slightly by entrapped water layers. A series of laboratory studies show that instead of slipping, geckos maintain and even improve their adhesive performance in many wet conditions (i.e., on wet hydrophobic substrates, on humid substrates held at low temperatures). The mechanism for this is not fully clarified, and likely ranges in scale from the chemical and material properties of the gecko's contact structures called setae (e.g., setae soften and change surface confirmation when exposed to water), to their locomotor biomechanics and decision-making behavior when encountering water on a substrate in their natural environment (e.g., some geckos tend to run faster and stop more frequently on misted substrates than dry). Current work has also focused on applying results from the natural system to gecko-inspired synthetic adhesives, improving their performance in wet conditions. Gecko-inspired synthetic adhesives have also provided a unique opportunity to test hypotheses about the natural system in semi-natural conditions replicated in the laboratory. Despite many detailed studies focused on the role of water and humidity on gecko and gecko-inspired synthetic adhesion, there remains several outstanding questions: (1) what, if any, role does capillary or capillary-like adhesion play on overall adhesive performance of geckos and gecko-inspired synthetics, (2) how do chemical and material changes at the surface and in the bulk of gecko setae and synthetic fibrils change when exposed to water, and what does this mean for adhesive performance, and (3) how much water do geckos encounter in their native environment, and what is their corresponding behavioral response? This review will detail what we know about gecko adhesion in wet environments, and outline the necessary next steps in biological and synthetic system investigations.

Introduction

Observation of geckos' remarkable adhesive performance has driven intense scrutiny of the natural system, and focused efforts on the design of synthetic gecko-inspired adhesives for nearly 20 years (Autumn et al. 2014; Niewiarowski et al. 2017). While this work builds on centuries of interest in geckos, there are still large gaps in our understanding of how geckos stick in complex environments (Niewiarowski et al. 2016). This lack of understanding underpins our inability to fully replicate the adhesive performance of the natural system in synthetic designs. Specifically, synthetic mimics fail in conditions that are less than ideal, yet relevant for live geckos, such as rough substrates, surfaces that are moist, and those that are dirty (although see Campolo et al. 2003; Sitti and Fearing 2003b; Aksak et al. 2008; Lee and Fearing 2008; Sethi et al. 2008; Soltannia and Sameoto 2014). Looking to the natural system will allow us to improve or redesign synthetic mimics, however, we must first understand how the natural system behaves in non-pristine conditions (Niewiarowski et al. 2016). This review will focus on the effect of one

Advance Access publication April 27, 2019

environmental variable, water, in the form of relative humidity (RH) and surface water, on gecko and gecko-inspired synthetic adhesion. We focus on this variable because many species of gecko are native to the tropics, where rain and high humidity wet surfaces geckos cling to and move across. Improving our understanding of how geckos adhere in wet conditions will allow us to make synthetics capable of maintaining adhesion in the presence of water (e.g., RH, underwater, moist skin or tissue), and drive predictions about how, where, and when geckos use their adhesive systems in their local environment.

Geckos use small, hair-like structures (setae) on epidermal folds located on the bottom of flattened toe pads to adhere to substrates (Russell 1975; Autumn et al. 2000). In many species, the setae branch and flatten into ca. 200 nm wide tips (spatula; Maderson 1964; Ruibal and Ernst 1965; Williams and Peterson 1982; Rizzo et al. 2006). These tips make close contact with the surface a gecko attaches to, allowing geckos to take advantage of weak intermolecular van der Waals forces (Autumn et al. 2002). van der Waals forces are ineffective when the two attaching surfaces are separated by ca. 20 nm (Israelachvili and Tabor 1972). This small separation distance allows geckos to peel their toe from the surface and detach with ease, however, for those living in the tropics, regular surface wetting by rain and humidity can supply thick enough water layers to disrupt van der Waals forces and cause geckos to detach unintentionally. Although there are no accounts of geckos falling from trees when it rains, herpetologists have long used directed water streams to detach geckos in the field, and even gecko hobbyists observe geckos sliding from wet terrarium walls (Fig. 1). These observations contradict our prediction that geckos native to the tropics can adhere in the wet conditions common to their local habitat. Furthermore, material and structural properties of the adhesive toe pad, such as their "anti-wetting" behavior (i.e., superhydrophobicity; Autumn and Hansen 2006; Liu et al. 2012), suggests that geckos should be able to adhere to wet substrates (Stark et al. 2016b).

A strong, reversible adhesive that can adhere in wet environments has clear application potential. However, the way water interacts at multiple scales in both the natural and the synthetic systems is still unclear. For instance, hydration from high RH can impact setal materials, causing swelling, softening, and surface chemistry changes (Pesika et al. 2009; Puthoff et al. 2010, 2013; Prowse et al. 2011; Hsu et al. 2012). Thin water layers from high humidity, mist, or fog, also interact with the setae and spatulae structurally, potentially providing a water bridge that enhances adhesion (i.e., capillary adhesion; Huber et al. 2005; Sun et al. 2005; Kim and Bhushan 2008; Pesika et al. 2009). Thick water layers interact with the setal mat, toe pad, and whole animal, often making substrates slippery and difficult to adhere to when applying natural and repeated loads while clinging, walking, or running (Stark et al. 2012, 2013, 2015b; Garner et al. 2017). Current gecko-inspired synthetics are relatively limited in wet environments, although many are trying to reconcile this (Lee et al. 2007; Glass et al. 2009; Izadi et al. 2012; Kizilkan et al. 2013; Drotlef et al. 2014; Soltannia and Sameoto 2014; Grewal et al. 2016; Cadirov et al. 2017; Ko et al. 2017; Zhao et al. 2017; Ma et al. 2018). Recently, gecko-inspired synthetics have also been used as models to answer difficult questions about the natural system (Gravish et al. 2010; Puthoff et al. 2013; Stark et al. 2016a). Specifically, the controlled design parameters of gecko-inspired synthetics allow for independent manipulation of material, structure,

Fig. 1 Gecko (*Phelsuma dubia*) slipping on a glass substrate misted with water droplets simulating rain. Adapted from Stark et al. (2012).

surface chemistry, and loading that cannot be manipulated independently in the natural system.

In an effort to understand how environmental water affects geckos in their native habitat, and how synthetics can be improved or used as testable models to understand gecko adhesion in wet conditions, we will focus our review on the smallest component of the system, the setae, and scale up to the whole animal and synthetic design. At each level we will review what we have learned about how environmental water impacts gecko and gecko-inspired synthetic adhesive performance using many years of focused research, where we are currently focused or stalled, and what we as a field need to do to move forward.

Effect of water on gecko setae

Gecko setae are composed of β-keratin, several small proteins (now jointly termed corneous beta proteins), and lipids, which include phospholipids and non-polar lipids (Rizzo et al. 2006; Toni et al. 2007; Alibardi 2009, 2012, 2013a,b; Alibardi et al. 2011; Hsu et al. 2012). Fibrils, likely made primarily of protein, span the length of the setae and are ca. 100 nm wide (Rizzo et al. 2006; Huber et al. 2008; Jain et al. 2015). Fibrils are encased in matrix material which is hypothesized to consist of covalently and non-covalently bonded lipids, along with proteins (Fig. 2; Jain et al. 2015). Non-covalently bonded lipids dominate the surface, contributing to the lipid footprints geckos leave behind (Hsu et al. 2012; Jain et al. 2015). Fibrils make up ca. 69% of the setal structure, and matrix composes ca. 31% (Huber et al. 2008). When exposed to water, both the material properties and the surface chemistry of the setae can change (Pesika et al. 2009; Puthoff et al. 2010; Hsu et al. 2012). The effect of these changes on adhesive performance is discussed in the following sections.

Material properties

Early studies of gecko setae show that the transverse modulus measured in 3-point bending tests is independent of RH ranging from 2% to 60% (Huber et al. 2008), and elastic modulus using a resonance technique also does not change in variable humidity (i.e., 16–64% RH; Peattie et al. 2007). This is in contrast to β-keratin-based bird feathers and claws that become softer, less strong, and more extensible when hydrated (Bonser and Farrent 2001; Bonser 2002; Taylor et al. 2004). Both studies that investigated gecko setae note potential confounding factors in sample preparation (i.e., high vacuum and drying; Huber et al. 2008) and data acquisition (uneven distribution of humidity tested; Peattie et al. 2007), and neither include RH set points common to tropical habitats where many geckos are native (i.e., >ca. 60% RH).

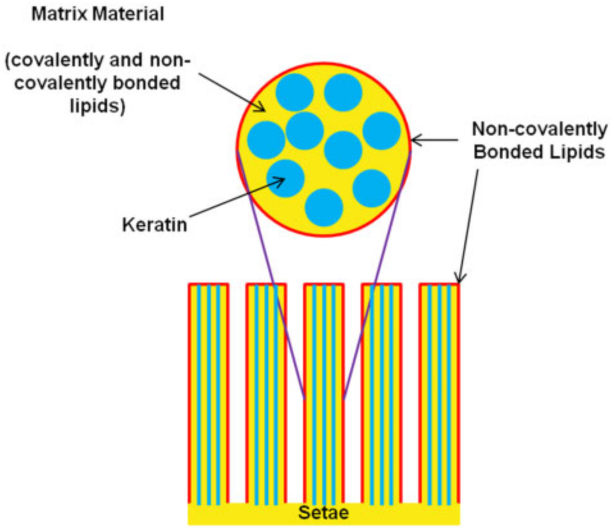

Fig. 2 Hypothesized setal structure (simplified) and composition (side and cross sectional view). Keratin fibrils are represented as blue, matrix material is yellow, and non-covalently bonded lipids are colored red. Simplified and adapted from Jain et al. (2015).

More recent work has shown that gecko setae and lamellar epidermis become less stiff, more extensible, and more viscous-like at 80% RH when compared to dry (Prowse et al. 2011). Estimations of the effective elastic modulus (E_{eff}) of multiple setae in an array show that at 30% RH, E_{eff} is near 100 kPa, the upper limit of the Dahlquist criterion for tacky, whereas at 80% RH E_{eff} is much lower, making the array more sticky (Prowse et al. 2011). Direct measurements of the adhesive performance of hydrated setal arrays showed that adhesion increased as humidity increased, regardless of substrate type (hydrophobic or hydrophilic) or shear rate (Puthoff et al. 2010). Likewise, simulation and models of spatular adhesion show that softer structures increase pull-off force (Chen and Gao 2010; Puthoff et al. 2010). Increased adhesion of setal arrays, spatula, and models due to humidity is likely a result of setal swelling and subsequent changes in the contact geometry, softening of the setae (i.e., reduced elastic modulus), and increased energy dissipation, all of which can contribute to higher adhesive performance (Puthoff et al. 2010). Interestingly, the effect of RH on friction force of setal arrays is limited to low velocities (Puthoff et al. 2013), and adhesion and friction increases become saturated when RH >40% at low preloads and low sliding velocity (Tao et al. 2015).

Surface chemistry

Chemical groups at the surface of the setae make direct adhesive contact, yet surface chemistry has only recently been investigated (Hsu et al. 2012; Badge et al. 2014; Jain et al. 2015; Stark et al. 2016b). Work of adhesion models used to predict gecko adhesion in wet environments assume the setae are oil-like, because they leave behind lipid footprints (Hsu et al. 2012; Stark et al. 2013). Models closely approximate live animal adhesion in several contexts, supporting this assumption (Stark et al. 2013, 2014a,b, 2015a,c, 2016b). It is surprising that simplified models of adhesion in air and water predict live animal adhesion, particularly considering that setal surface groups at the adhesive interface change orientation when exposed to water (increasing surface energy from hydrophobic methyl to methylene-dominated surface groups; Pesika et al. 2009; Hsu et al. 2012), and the protein constituent of setae that interacts with water is either positively or neutrally charged (Alibardi 2018), neither of which is taken into account by current models.

To experimentally investigate the role of setal surface chemistry on adhesion in dry and wet conditions, surface chemistry was altered, by either stripping setae of the lipid layer, or by artificially changing the setal surface chemistry (i.e., depositing a thin layer of a hydrophobic or a hydrophilic polymer). Alteration of surface chemistry changed the wettability of gecko toe pad skin sheds (naturally molted skin that still retains adhesive properties), where hydrophilic coated setae and stripped setae wet immediately upon contact with water or in high RH (Badge et al. 2014). All toe pad shed samples adhered equally well in air and water when tested on a hydrophobic substrate, and all samples adhered poorly in water when tested on a hydrophilic substrate (Badge et al. 2014). This is contrary to the predictions of thermodynamic work of adhesion models used in live animal experiments. Instead, models predicted that stripped and hydrophilic sheds should have much weaker adhesion in water than air (Badge et al. 2014). The discrepancy between the performance of model and modified toe pad shed adhesion in air and water is unclear. In a second study, where only unbound surface lipids were chemically removed (rather than stripping the setae or artificially coating setae), adhesion on a hydrophobic substrate did not differ among treatments in air and in water (i.e., treated samples adhere the same as untreated in air and in water; Stark et al. 2016b), supporting the conclusion that substrate wettability is more important than setal surface chemistry when separated setae adhere in wet environments.

Wetting properties of the gecko toe pad

Gecko skin is water repellant (Hiller 2009; Watson et al. 2015a,b), and early measurements of the wettability of the smooth side of naturally shed gecko skin and eye scales revealed that the water contact angle (the angle a drop of water makes on the surface of a material) is ca. 70° and ca. 90°, respectively (Autumn and Hansen 2006; Hiller 2009). This suggests that the surface of gecko setae are neither strongly hydrophobic nor hydrophilic (a hydrophobic material has a water contact angle of >90°). These values were later confirmed with models (i.e., water contact angle of the setal surface is most likely between 70° and 90°; Badge et al. 2014).

Unlike setae, gecko toe pads are superhydrophobic (water contact angle ca. 160°) and have very low contact angle hysteresis (i.e., the angle a surface is tilted to induce a water droplet to roll; Autumn and Hansen 2006; Liu et al. 2012). These two properties make it very hard to wet the gecko toe pad, as water is suspended above the setae (known as the Cassie–Baxter wetting state; Cassie and Baxter 1944; Fig. 3), and rolls off when the toe is tilted by only 2–3° in almost any orientation (Autumn and Hansen 2006; Liu et al. 2012). When pressed into water, an air plastron forms around the superhydrophobic gecko toe pad and hydrophobic skin (Stark et al. 2013; Fig. 3). When removed from water, the toe and skin are dry, and only if the air plastron is broken does the pad and skin become wet (Badge et al. 2014; Stark et al. 2014a).

Superhydrophobicity is a product of surface chemistry and surface roughness. When coated with a hydrophobic polymer or chemically treated to remove the surface layer of unbound lipids, structurally rough gecko toe pad sheds did not wet with water droplets (Badge et al. 2014; Stark et al. 2016b). Moreover, sheds treated with a hydrophobic polymer did not wet in high RH (100% for 3–4 days) or when submerged (7–8 h at 11.95 kPa pressure). Instead, live gecko toes, untreated separated setal mats, and toe pad skin sheds wet when agitated in a wet environment for extended periods of time (Pesika et al. 2009; Stark et al. 2012, 2014b), when exposed to 100% RH for 3–4 days (Badge et al. 2014), when the surface tension of water is reduced (Stark et al. 2014a), or when setal surface chemistry is manipulated (Badge et al. 2014; Stark et al. 2016b).

Transition from dry toe pads (Cassie–Baxter wetting state) to wet toe pads (Wenzel wetting state;

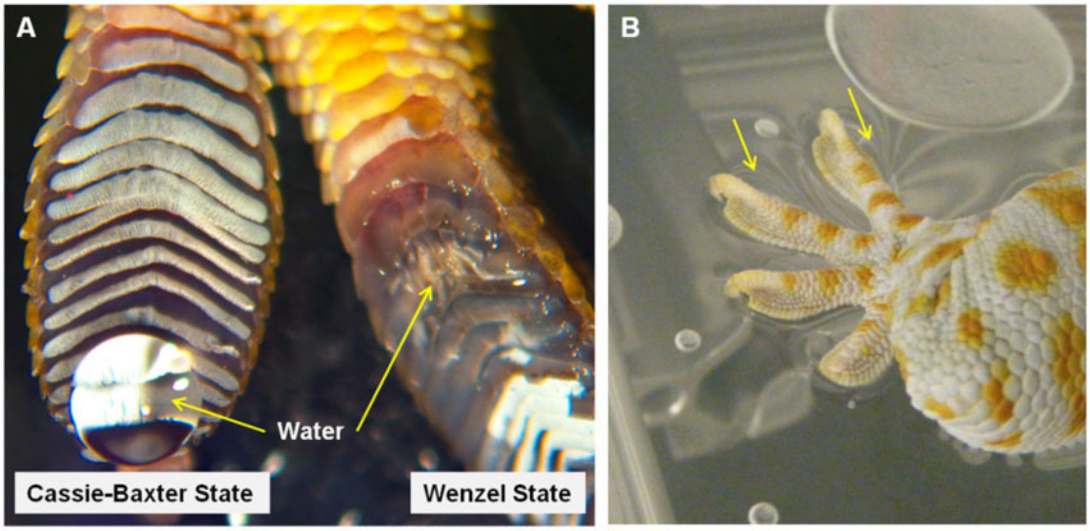

Fig. 3 Two different gecko toes, on the same gecko (*Gekko gecko*), one in the Cassie–Baxter wetting state (i.e., water drop is suspended above the toe pad) and one in the Wenzel wetting state (i.e., water has infiltrated the toe pad; **A**). Undisturbed gecko toes maintain an air plastron when submerged in water (arrows highlight where water dimples and bends around the toes; **B**).

Wenzel 1936; Fig. 3) is not favorable for gecko adhesion, where geckos with wet toe pads slip and fall from substrates (Stark et al. 2012, 2014a,b). Wetting of manipulated toe pad sheds (polymer coated, plasma stripped), however, does not result in a loss of adhesive performance (Badge et al. 2014). The reason for this discrepancy is unclear. Unexpectedly, the Wenzel wetting regime is the thermodynamically stable wetting state of gecko toe pads (Badge et al. 2014), suggesting that either gecko toe pads are unable to retain a stable Cassie–Baxter state, there is no functional need to maintain this extreme anti-wetting state, or there is a biological tradeoff that limits the stability of gecko toe pad superhydrophobicity.

Gecko–substrate adhesive interface and capillary adhesion

Gecko spatulae make direct adhesive contact with the substrate a gecko clings to. However, thin water layers from atmospheric humidity are always present on surfaces (Huber et al. 2005), and these water layers may disrupt or enhance adhesion between gecko setae and a substrate. Enhancement stems from capillary adhesion, which is not only dependent on ambient humidity, but also dependent on wettability of the contacting substrates (i.e., hydrophilic substrates promote capillary adhesion) and time (high shear or pull-off rates limit the number of capillary bridges that have time to form). The role of capillary adhesion, if any, on gecko adhesion has been debated for years (Hiller 1968; Autumn et al. 2002; Huber et al. 2005; Sun et al. 2005; Kim and Bhushan 2008; Niewiarowski et al. 2008; Pesika et al. 2009; Prowse et al. 2011; Puthoff et al. 2010, 2013; Tao et al. 2015).

Direct probing of the adhesive interface between a gecko toe and a sapphire substrate shows no trace of water, even after depositing a thin film of water on the substrate (Hsu et al. 2012). This suggests that the gecko plastron expels even monolayers of water at the adhesive interface, and that capillary adhesion is not possible. Experimental investigation supports this result, as adhesion of setal mats increases as shear rate increases, and adhesion is substrate insensitive (i.e., capillary adhesion should be negligible at high shear rates and on hydrophobic substrates; Puthoff et al. 2010). However, several experimental and theoretical studies find that gecko adhesion is enhanced in high humidity, a result typically characteristic of capillary adhesion (Huber et al. 2005; Sun et al. 2005; Kim and Bhushan 2008; Niewiarowski et al. 2008; Pesika et al. 2009). Although reduction in setal modulus at high humidity may drive this result, a gecko-inspired synthetic model, where pillar stiffness was fixed (Stark et al. 2016a), and a theoretical model where stiffness was not altered (Kim and Bhushan 2008), report increased adhesion as humidity increases. Taken together, it appears neither capillary adhesion nor material changes of the setae fully explain the adhesive performance of geckos in humid conditions.

Whole animal adhesive performance in wet and humid conditions

Geckos apply a normal and shear load to engage and align their adhesive setae (Autumn et al. 2000, 2006).

Consequently, geckos who have naturally placed all four of their feet adhere better than those who were not allowed to naturally position their feet (Stark et al. 2012). However, when a substrate is wet with water, natural loading does not improve adhesion. Specifically, geckos tested on a glass substrate wetted either with water droplets (simulating rain) or a thick water layer (ca. 0.5 cm), did not adhere better after natural alignment, and overall, shear adhesion on wet glass (misted or submerged) was significantly lower than on dry glass (Stark et al. 2012). Single spatula pull-off force was also lower on a wet hydrophilic substrate (Huber et al. 2005), as was normal adhesive force of setal arrays tested underwater (Pesika et al. 2009). When a live gecko's toes are wet (i.e., Wenzel wetting state), adhesion remains low regardless of natural positioning or substrate wetting condition (dry, misted, submerged; Stark et al. 2012), unlike toe pad skin sheds where wetting state (Cassie–Baxter or Wenzel) did not have a significant effect on adhesion (Badge et al. 2014).

Failure of the live animal adhesive system in wet conditions is surprising given that many species of gecko are native to the tropics. Furthermore, the extreme hydrophobicity of the gecko toe pad suggests that water should be easily shed from the adhesive toes. By remodeling the experimental conditions above to mimic wet vegetation natural to a gecko's environment (i.e., wet hydrophobic substrates), the substantial reduction of adhesive performance live geckos experience when tested on wet hydrophilic glass disappears. Geckos naturally positioning their feet on a wet hydrophobic substrate (octadecyltrichlorosilane self-assembled monolayer [OTS-SAM] formed on the surface of glass) and commercially available acrylic, which is intermediately wetting, suffer no loss in adhesive performance compared to adhesion on these substrates when dry (Stark et al. 2013). This suggests geckos can cling well to most wet vegetation in their environment. Although capillary bridging via nano-bubbles has been proposed as a mechanism to explain underwater adhesion in geckos (Peng et al. 2014), relatively simple thermodynamic models of the work of adhesion between experimental substrates and a gecko-like substrate are sufficient to support whole animal adhesion results (Stark et al. 2013). Thus, while nano-bubbles cannot be ruled out, it appears contact between the experimental substrates and gecko setae are a function of basic thermodynamic principles.

When geckos are tested on polytetrafluoroethylene (PTFE; commercially known as Teflon$^{\text{TM}}$) geckos adhere better than expected on wet PTFE than dry. Thermodynamic models of the work of adhesion do not accurately predict the magnitude of this effect, though they do predict the behavior (i.e., higher adhesion in water than air). Further investigation of this phenomena suggests that the inherent surface roughness associated with PTFE is not the primary cause of improved adhesive performance in water, nor is the level of surface fluorination (although this does influence whole animal adhesive performance on fluorinated substrates in air; Stark et al. 2015a). Collectively, this suggests that the lower than expected adhesion values of live geckos in air on fluorinated substrates is more surprising than their adhesive performance on wet fluorinated substrates (Stark et al. 2015a). Similar results were reported when testing adhesion of a PTFE gecko-inspired synthetic underwater (Izadi et al. 2012). In addition to fluorinated substrates, live geckos also adhere better to submerged polydimethylsiloxane (PDMS) than dry PDMS (Stark et al. 2015c). The mechanism for this remains unclear, but is supported by thermodynamic adhesion models and experimental results of a simplified system (i.e., PDMS–PDMS contact in air and water; Defante et al. 2015; Stark et al. 2015c).

Although substrate wettability clearly influences the ability of live geckos to adhere to wet substrates in pristine laboratory conditions, several other environmental factors may also influence gecko adhesion on wet substrates, particularly in their natural environment. For instance, large-scale roughness, like that at the scale of wet leaves and bark (modeled with PDMS), reduces whole animal adhesive performance of geckos when these substrates are wetted, although, interestingly, shear adhesion is dependent on the orientation of roughness patterns (Stark et al. 2015c). Furthermore, as shown in experimental trials with live animals and thermodynamic models of the work of adhesion, the adhesive toe pads must remain dry to take advantage of the interaction between the superhydrophobic toe pad and the hydrophobic substrate (i.e., retain the air plastron; Stark et al. 2012, 2013). If this property is disrupted by wetting the toes (i.e., transition from Cassie–Baxter to Wenzel wetting regime), altering the surface of the setae (e.g., adsorption of anionic surfactant), or changing the surface tension of water via a surfactant, geckos cannot generate enough shear adhesive force to support their body weight (Stark et al. 2014a). In the instance that gecko toe pads become wetted naturally, geckos can self-dry their toes by taking steps on dry substrates in ca. 15 min (acrylic or glass; Stark et al. 2014b).

While much work on whole animal adhesive performance has focused on geckos in wet conditions (misted and flooded substrates), whole animal adhesion of geckos in humid environments has also been studied. In response to two contradicting studies (Losos 1990; Bergmann and Irschick 2005), Niewiarowski et al. (2008) measured adhesive performance of geckos in a range of humidity and temperature set points. The results of this study show that gecko adhesion increases as RH increases, but only at low temperature (12°C). At 32°C there was no difference in adhesive performance at the extreme humidity set points (30% and 80% RH; Niewiarowski et al. 2008). This result is partially supported by the results of a gecko-inspired synthetic tested in the same conditions (Stark et al. 2016a).

Gecko locomotor performance and behavior in a wet environment

Most geckos are sit-and-wait predators (Vitt 1983; Persaud et al. 2003, although see Henle 1990; Gil et al. 1994; Werner et al. 2004, 2011; Aowphol et al. 2006; Hódar et al. 2006 for examples of broad foraging strategies), thus they need to cling well to substrates while waiting for prey, but they also need to sprint quickly to catch prey, and run away from predators or conspecifics (Short and Petren 2008). To investigate how geckos adhere while moving in wet and humid environments, temporary adhesion (Gorb 2008) was estimated by measuring maximum sprint speed. Previous work shows that adhesive performance while clinging reduced with every step a gecko took on glass misted with water, to the point where a gecko should not be able to support its body weight after four steps (Stark et al. 2012). In contrast, when induced to run along horizontal and vertical tracks misted with water, maximum sprint speed did not differ on wet and dry substrates (glass and acrylic) in five species of gecko after taking more than two full strides (Stark et al. 2015b). In fact, in some cases speed appeared to increase on wet substrates when compared with dry (Stark et al. 2015b). The same results were repeated when the distance a gecko ran increased from 1 to 2 m (Garner et al. 2017).

The reason for the discrepancy between clinging, walking, and running is unclear, but may be related to rate-dependent adhesion and/or gecko behavior. First, gecko setae show rate-dependence, where friction and adhesion increase as sliding velocity increases (Gravish et al. 2010; Puthoff et al. 2010, 2013). This increase in adhesion may help geckos gain traction and speed in challenging conditions like misted substrates. Second, behavior and perhaps ecology may play an important role in running speed on wet substrates. For instance, frequency of stopping during a 1 m run differed across species, where those who ran fast on wet substrates (i.e., *Phelsuma dubia* and *Gekko gecko*, both native to the tropics) tended to stop more than those that did not (Stark et al. 2015b). Only one species from an arid habitat (*Chondrodactylus bibronii*) slipped on 1 and 2 m long misted running tracks (Stark et al. 2015b; Garner et al. 2017). During runs, toe pads of all five gecko species did become wet, however there was no significant effect of running orientation or substrate type on propensity to wet. Instead, toe pad wetting appeared to occur randomly, though more frequently in one low-climbing temperate species (*Rhacodactylus auriculatus*; Stark et al. 2015b).

The discrepancy between clinging, walking, and running is further compounded by the fact that we have very little knowledge of how geckos behave and interact with their environment. Some antidotal reports and observations suggest that geckos hide or reduce activity in the rain, however others report that geckos remain active on wet vegetation in the rain (Marcellini 1971; Werner 1990). These results may be further confounded when considering additional environmental factors like temperature, wind, and even predators (Marcellini 1971; Lopez-Darias et al. 2012).

Gecko-inspired synthetic adhesives

For nearly 20 years, engineers and material scientists have fabricated gecko-inspired synthetic adhesives that range from polymer micropillars and nanopillars, carbon nanotubes, polymer sheets, and hydrogels, to the more complex electrically and magnetically actuated pillar systems (Sitti and Fearing 2003a; Yurdumakan et al. 2005; Gorb et al. 2007; Kim and Sitti 2006; Aksak et al. 2007; Del Campo et al. 2007; Ge et al. 2007; Greiner et al. 2007; Northen et al. 2008; Lee et al. 2009; Murphy et al. 2009a,b; Boesel et al. 2010; Bartlett et al. 2012; Chen et al. 2012; Izadi et al. 2012; Jin et al. 2012; Drotlef et al. 2014; Heepe et al. 2014; King et al. 2014; Guo et al. 2015; Li et al. 2018; Yi et al. 2018). Although many synthetics can resist incredible shear and adhesive forces in pristine laboratory conditions, performance of these adhesives in real-world scenarios, such as in wet or moist conditions, is relatively limited. Considering the number of robotic, biomedical, commercial, and industrial applications for these synthetics, there has been an increasing demand for gecko-inspired synthetics that can retain adhesion in wet environments.

Effect of RH on synthetic adhesive performance

Like live geckos and their adhesive elements (setae, spatulae), the amount of atmospheric water in the air can have direct consequences for the adhesive performance of gecko-inspired synthetics. However, unlike the gecko, most synthetics do not undergo changes in surface chemistry, material stiffness, or swelling in humid environments, and rather are impacted directly by interfacial interactions between the gecko-inspired synthetic, water layers, and substrate. In support of the role water layers play on gecko-inspired synthetics adhering in variable RH, several studies have shown humidity-dependent adhesive performance. For instance, a PDMS gecko-inspired synthetic comprised of angled micropillars showed a peak in frictional forces when tested in intermediately humid environments, followed by a sharp drop as RH approached 80% (Cadirov et al. 2017). Polymethylmethacrylate and PTFE gecko-inspired synthetics also exhibited frictional force plateaus around 60–80% RH (Grewal et al. 2016).

Few studies test adhesion at levels >80% RH, where thicker water layers adsorbed on substrate surfaces may disrupt the van der Waals-based adhesive system. This is supported by a theoretical model that shows a distinct drop in adhesion force after 80% RH when adhesion takes place on a hydrophilic substrate, but not a hydrophobic substrate (Kim and Bhushan 2008). Interestingly, a polyurethane (PU) mushroom-tipped synthetic showed an increase in shear adhesion as RH increased from 30% to 70%, and then sharply dropped at 80% RH. However, this relationship is temperature dependent, where adhesion only increases with humidity at low temperatures (12°C). At high temperature (32°C), humidity had no effect on adhesion (Stark et al. 2016a). Temperature has a direct effect on humidity (Peng et al. 2017), and the influence this coupled effect has on gecko and gecko-inspired synthetic performance remains unclear.

Synthetic adhesive performance underwater

The presence of a thick interfacial water layer generally reduces both normal and shear adhesion of micropillared and nanopillared synthetics tested underwater due to van der Waals interference and lubrication effects (Izadi et al. 2012; Kizilkan et al. 2013; Drotlef et al. 2014; Heepe and Gorb 2014; Soltannia and Sameoto 2014; Ko et al. 2017). However, attempts to optimize underwater adhesion have led to the exploration of several new design parameters. For example, hydrophobic gecko-inspired synthetics adhere more strongly underwater than hydrophilic synthetic adhesives (Soltannia and Sameoto 2014). This is hypothesized to be the result of trapped air bubbles that introduce dry contact between the synthetic and substrate, capillary adhesion effects, and potential suction effects (Hosoda and Gorb 2012; Kizilkan et al. 2013; Heepe and Gorb 2014; Soltannia and Sameoto 2014). Hydrophobic gecko-inspired synthetics provide a potentially fruitful direction for reversible underwater adhesive design, however, in some hydrophobic materials (i.e., PDMS) surface molecule rearrangement can lead to locally trapped water molecules that interfere with dry adhesion (Defante et al. 2015). Material-specific factors such as surface energy have also been proposed to explain irregularities in adhesive performance among certain hydrophobic synthetics tested underwater (De Souza et al. 2008; Izadi et al. 2012). Furthermore, like the gecko, gecko-inspired synthetics can also be substrate dependent (i.e., perform best underwater on intermediately wetting and hydrophobic substrates; Estrada A and Lin 2017), which can limit application potential.

Attempts to uniformly increase adhesion in completely wetted and submerged environments have led to designs that combine gecko-inspired dry adhesives and chemically-based wet adhesives. Coating the pillars of gecko-inspired synthetics with a mussel-inspired chemical adhesive has repeatedly shown to increase underwater adhesion by introducing a chemical medium that expels water molecules to form bonds to multiple types of surfaces (Lee et al. 2007; Glass et al. 2009; Zhao et al. 2017). However, the introduction of a chemical adhesive mechanism has diminished the repeatability (attachment and subsequent detachment) quality of traditional gecko-inspired synthetics. Recently, efforts to correct this have led to UV-sensitive adhesives that chemically detach under the presence of UV light (Ma et al. 2018). However, complexity brings with it inherent scalability concerns that are common with bio-inspired technology (Liu et al. 2017).

Synthetics as a model to understand the natural adhesive system

Although derived from the study of the natural system, gecko-inspired synthetics can illuminate details about the mechanisms of the biological system by creating a bidirectional pathway of knowledge. For example, a polymer bead model suggests that slight differences in gecko setal stalk material properties aid adhesion at high humidity (Endoh et al. 2018). Similarly, synthetic nanofilms were used as a gecko spatula mimic to understand water molecule mechanics and surface chemistry at the nanoscale (Peng and Chen 2011). Through direct comparative experimental methods, gecko-inspired synthetics have shown performance similarities to the natural system in environments of varying humidity and temperature (i.e., adhesion increases as humidity increases, but only at low temperature; Stark et al. 2016a). Interestingly, deviation between the natural and the synthetic systems (i.e., at low temperature and high humidity geckos outperform the gecko-inspired synthetic) has proven fruitful for the generation of new research questions focused on uncovering the fundamental mechanism responsible for these differences.

Outstanding questions

Investigation of the role water plays on gecko adhesive performance has primarily focused on mechanistic explanations for adhesion in wet and humid environments at the level of setal mats and live animals. In synthetic analogs, focus has been driven by the desire to create a strong, reversible underwater adhesive. While these studies have formed an important foundation of information to build upon, there are still several outstanding questions related to both the natural and the synthetic systems. First, there remains several discrepancies related to the adhesive elements of the natural system, where setal mats, sheds, and spatulae do not predict whole animal adhesive performance. Furthermore, whole animal clinging performance does not predict locomotor performance or behavior while running. These results call into question how environmental water interacts with each element in the natural system, which has significant implications for the ecology and evolution of geckos and their adhesive toe pads, as well as for improved synthetic design. Future work should address how experimental methods differed in previous work, such as preloads and rate of testing, to clarify if these differences are real or an artifact of several different testing methodologies. Either answer would be interesting, as differences at each level of adhesion could lead to new design principles and evolutionary and ecological hypotheses, and variation in load and rate control leads to hypotheses about how geckos may control their own preload and rate of adhesive application, perhaps modifying either of these depending on local conditions. Second, despite hundreds of synthetic mimics made of carefully selected material, we know surprisingly little about the material and structure of gecko setae, particularly in relation to how water interacts with the setal material and surface chemistry. Deeper exploration into the setal material composition and organization will provide new design parameters for gecko-inspired synthetics. We believe that techniques such as Nuclear Magnetic Resonance spectroscopy and Atomic Force Microscopy paired with Confocal Laser Scanning Microscopy will be particularly helpful in achieving this goal. Third, the role water plays at the adhesive interface is unclear, in both systems, where capillary or capillary-like adhesion, bubbles, and dry contact all have been used to describe adhesive performance in wet and humid conditions, yet none can seem to fully describe all experimental results to-date. Careful studies investigating the contact interface between geckos and gecko-inspired synthetics are necessary [e.g., using techniques like Sum Frequency Generation (SFG) spectroscopy], and modified, controlled synthetic adhesives may be particularly useful for sequentially testing hypotheses about the adhesive contact interface in wet conditions. Finally, despite the gecko's immense popularity, we know almost nothing about how geckos interact with water in their natural environment, if geckos native to habitats with contrasting levels of RH and environmental water differ at any level, nor how water interacts with other common environmental parameters (e.g., temperature, surface roughness). Broad, multi-species characterization, experimentation, and field-based observations are necessary to clarify these large-scale questions about geckos. Most of these next steps will require interdisciplinary teams that take a broad approach to examine how geckos adhere in complex and dynamic environments. We believe that the current state of the field, both in terms of the technology and the expertise available, are primed to answer these unresolved and important questions.

Acknowledgments

We thank Peter H. Niewiarowski, Ali Dhinojwala, and their laboratory groups for years of valuable insight and collaboration studying gecko and gecko-inspired synthetic adhesion in wet and humid environments. We also thank the speakers and attendees of the associated symposium for their enthusiastic comments and questions.

Funding

This manuscript was supported by The Company of Biologists [EA1696], the National Science Foundation [1832815], and the Society for Integrative and

Comparative Biology by generous contribution to the associated symposium.

References

Aksak B, Murphy MP, Sitti M. 2007. Adhesion of biologically inspired vertical and angled polymer microfiber arrays. Langmuir 23:3322–32.

Aksak B, Murphy MP, Sitti M. 2008. Gecko inspired microfibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces. Proceedings of the IEEE International Conference on Robotics and Automation. Curran Associates, Inc., Red Hook, NY USA. p. 3058–63.

Alibardi L. 2009. Cell biology of adhesive setae in gecko lizards. Zoology 112:403–24.

Alibardi L. 2012. Immunolocalization of keratin-associated beta-proteins (beta-keratins) in the regenerating lizard epidermis indicates a new process for the differentiation of the epidermis in lepidosaurians. J Morphol 273:1272–9.

Alibardi L. 2013a. Immunolocalization of keratin-associated beta-proteins (beta-keratins) in pad lamellae of geckos suggest that glycine–cysteine-rich proteins contribute to their flexibility and adhesiveness. J Exp Zool A Ecol Genet Physiol 319:166–78.

Alibardi L. 2013b. Immunolocalization of specific keratin associated beta-proteins (beta-keratins) in the adhesive setae of *Gekko gecko*. Tissue Cell 45:231–40.

Alibardi L. 2018. Mapping proteins localized in adhesive setae of the tokay gecko and their possible influence on the mechanism of adhesion. Protoplasma 55:1785–97.

Alibardi L, Edward DP, Patil L, Bouhenni R, Dhinojwala A, Niewiarowski PH. 2011. Histochemical and ultrastructural analyses of adhesive setae of lizards indicate that they contain lipids in addition to keratins. J Morphol 272:758–68.

Aowphol A, Thirakhupt K, Nabhitabhata J, Voris HK. 2006. Foraging ecology of the tokay gecko, *Gekko gecko* in a residential area in Thailand. Amphibia-Reptilia 27:491–503.

Autumn K, Dittmore A, Santos D, Spenko M, Cutkosky M. 2006. Frictional adhesion: a new angle on gecko attachment. J Exp Biol 209:3569–79.

Autumn K, Hansen W. 2006. Ultrahydrophobicity indicates a non-adhesive default state in gecko setae. J Comp Physiol A Neuroethol Sens Neural Behav Physiol 192:1205–12.

Autumn K, Liang YA, Hsieh ST, Zesch W, Chan WP, Kenny TW, Fearing R, Full RJ. 2000. Adhesive force of a single gecko foot-hair. Nature 405:681–5.

Autumn K, Niewiarowski PH, Puthoff JB. 2014. Gecko adhesion as a model system for integrative biology, interdisciplinary science, and bioinspired engineering. Annu Rev Ecol Evol Syst 45:445–70.

Autumn K, Sitti M, Liang YCA, Peattie AM, Hansen WR, Sponberg S, Kenny TW, Fearing R, Israelachvili JN, Full RJ. 2002. Evidence for van der Waals adhesion in gecko setae. Proc Natl Acad Sci U S A 99:12252–6.

Badge I, Stark AY, Paoloni EL, Niewiarowski PH, Dhinojwala A. 2014. The role of surface chemistry in adhesion and wetting of gecko toe pads. Sci Rep 4:6643.

Bartlett MD, Croll AB, King DR, Paret BM, Irschick DJ, Crosby AJ. 2012. Looking beyond fibrillar features to scale gecko-like adhesion. Adv Mater 24:1078–83.

Bergmann PJ, Irschick DJ. 2005. Effects of temperature on maximum clinging ability in a diurnal gecko: evidence for a passive clinging mechanism? J Exp Zool A Comp Exp Biol 303A:785–91.

Boesel LF, Greiner C, Arzt E, Del Campo A. 2010. Gecko-inspired surfaces: a path to strong and reversible dry adhesives. Adv Mater 22:2125–37.

Bonser R. 2002. Hydration sensitivity of ostrich claw keratin. J Mater Sci Lett 21:1563–4.

Bonser R, Farrent J. 2001. Influence of hydration on the mechanical performance of duck down feathers. Br Poult Sci 42:271–3.

Cadirov N, Booth JA, Turner KL, Israelachvili JN. 2017. Influence of humidity on grip and release adhesion mechanisms for gecko-inspired microfibrillar surfaces. ACS Appl Mater Interfaces 9:14497–505.

Campolo D, Jones S, Fearing RS. 2003. Fabrication of gecko foot–hair like nano structures and adhesion to random rough surfaces. 2003 Third IEEE Conference on Nanotechnology, IEEE. p. 856–9.

Cassie ABD, Baxter S. 1944. Wettability of porous surfaces. Trans Faraday Soc 40:546–51.

Chen B, Gao H. 2010. An alternative explanation of the effect of humidity in gecko adhesion: stiffness reduction enhances adhesion on a rough surface. Int J Appl Mech 02:1–9.

Chen B, Goldberg Oppenheimer P, Shean TA, Wirth CT, Hofmann S, Robertson J. 2012. Adhesive properties of gecko-inspired mimetic via micropatterned carbon nanotube forests. J Phys Chem C 116:20047–53.

De Souza E, Brinkmann M, Mohrdieck C, Crosby A, Arzt E. 2008. Capillary forces between chemically different substrates. Langmuir 24:10161–8.

Defante AP, Burai TN, Becker ML, Dhinojwala A. 2015. Consequences of water between two hydrophobic surfaces on adhesion and wetting. Langmuir 31:2398–406.

Del Campo A, Greiner C, Arzt E. 2007. Contact shape controls adhesion of bioinspired fibrillar surfaces. Langmuir 23:10235–43.

Drotlef DM, Blümler P, del Campo A. 2014. Magnetically actuated patterns for bioinspired reversible adhesion (dry and wet). Adv Mater 26:775–9.

Endoh KS, Kawakatsu T, Müller-Plathe F. 2018. Coarse-grained molecular simulation model for gecko feet keratin. J Phys Chem B 122:2203–12.

Estrada ASA, Lin HR. 2017. Fabrication of biomimetic gecko toe pads and their characterization. Polym Eng Sci 57:283–90.

Garner AM, Stark AY, Thomas SA, Niewiarowski PH. 2017. Geckos go the distance: water's effect on the speed of adhesive locomotion in geckos. J Herpetol 51:240–4.

Ge L, Sethi S, Ci L, Ajayan PM, Dhinojwala A. 2007. Carbon nanotube-based synthetic gecko tapes. Proc Natl Acad Sci U S A 104:10792–5.

Gil M, Guerrero F, Perez-Mellado V. 1994. Seasonal variation in diet composition and prey selection in the Mediterranean gecko *Tarentola mauritanica*. Isr J Zool 40:61–74.

Glass P, Chung H, Washburn NR, Sitti M. 2009. Enhanced reversible adhesion of dopamine methacrylamide-coated elastomer microfibrillar structures under wet conditions. Langmuir 25:6607–12.

Gorb S, Varenberg M, Peressadko A, Tuma J. 2007. Biomimetic mushroom-shaped fibrillar adhesive microstructure. J R Soc Interface 4:271–5.

Gorb SN. 2008. Biological attachment devices: exploring nature's diversity for biomimetics. Phil Trans R Soc A Math Phys Eng Sci 366:1557–74.

Gravish N, Wilkinson M, Sponberg S, Parness A, Esparza N, Soto D, Yamaguchi T, Broide M, Cutkosky M, Creton C, et al. 2010. Rate-dependent frictional adhesion in natural and synthetic gecko setae. J R Soc Interface 7:259–69.

Greiner C, del Campo A, Arzt E. 2007. Adhesion of bioinspired micropatterned surfaces: effects of pillar radius, aspect ratio, and preload. Langmuir 23:3495–502.

Grewal H, Piao S, Cho I-J, Jhang K-Y, Yoon E-S. 2016. Nanotribological and wetting performance of hierarchical patterns. Soft Matter 12:859–66.

Guo D-J, Liu R, Cheng Y, Zhang H, Zhou L-M, Fang S-M, Elliott WH, Tan W. 2015. Reverse adhesion of a gecko-inspired synthetic adhesive switched by an ion-exchange polymer–metal composite actuator. ACS Appl Mater Interfaces 7:5480–7.

Heepe L, Carbone G, Pierro E, Kovalev AE, Gorb SN. 2014. Adhesion tilt-tolerance in bio-inspired mushroom-shaped adhesive microstructure. Appl Phys Lett 104:011906.

Heepe L, Gorb SN. 2014. Biologically inspired mushroom-shaped adhesive microstructures. Annu Rev Mater Res 44:173–203.

Henle K. 1990. Population ecology and life history of three terrestrial geckos in arid Australia. Copeia 1990:759–81.

Hiller U. 1968. Untersuchungen zum feinbau und zur funktion der haftborsten von reptilien. Zoomorphology 62:307–62.

Hiller UN. 2009. Water repellence in gecko skin: how do geckos keep clean?. In: Gorb S. editor. Functional surfaces in biology. Little structures with big effects vol 1. Dordrecht: Springer. pp. 47–53.

Hódar J, Pleguezuelos J, Villafranca C, Fernández-Cardenete J. 2006. Foraging mode of the Moorish gecko *Tarentola mauritanica* in an arid environment: inferences from abiotic setting, prey availability and dietary composition. J Arid Environ 65:83–93.

Hosoda N, Gorb SN. 2012. Underwater locomotion in a terrestrial beetle: combination of surface de-wetting and capillary forces. Proc R Soc Lond B Biol Sci 279:4236–42.

Hsu PY, Ge LH, Li XP, Stark AY, Wesdemiotis C, Niewiarowski PH, Dhinojwala A. 2012. Direct evidence of phospholipids in gecko footprints and spatula–substrate contact interface detected using surface-sensitive spectroscopy. J R Soc Interface 9:657–64.

Huber G, Mantz H, Spolenak R, Mecke K, Jacobs K, Gorb SN, Arzt E. 2005. Evidence for capillarity contributions to gecko adhesion from single spatula nanomechanical measurements. Proc Natl Acad Sci 102:16293–6.

Huber G, Orso S, Spolenak R, Wegst UGK, Enders S, Gorb SN, Arzt E. 2008. Mechanical properties of a single gecko seta. Int J Mater Res 99:1113–8.

Israelachvili JN, Tabor D. 1972. The measurement of van der Waals dispersion forces in the range 1.5 to 130 nm. Proc R Soc Lond A 331:19–38.

Izadi H, Zhao B, Han Y, McManus N, Penlidis A. 2012. Teflon hierarchical nanopillars with dry and wet adhesive properties. J Polym Sci B Polym Phys 50:846–51.

Jain D, Stark AY, Niewiarowski PH, Miyoshi T, Dhinojwala A. 2015. NMR spectroscopy reveals the presence and association of lipids and keratin in adhesive gecko setae. Sci Rep 5:9594.

Jin K, Tian Y, Erickson JS, Puthoff J, Autumn K, Pesika NS. 2012. Design and fabrication of gecko-inspired adhesives. Langmuir 28:5737–42.

Kim S, Sitti M. 2006. Biologically inspired polymer microfibers with spatulate tips as repeatable fibrillar adhesives. Appl Phys Lett 89:261911.

Kim TW, Bhushan B. 2008. The adhesion model considering capillarity for gecko attachment system. J R Soc Interface 5:319–27.

King DR, Bartlett MD, Gilman CA, Irschick DJ, Crosby AJ. 2014. Creating gecko-like adhesives for "real world" surfaces. Adv Mater 26:4345–51.

Kizilkan E, Heepe L, Gorb S. 2013. Underwater adhesion of mushroom-shaped adhesive microstructure: an air-entrapment effect. Cambridge (UK): The Royal Society of Chemistry.

Ko H, Seong M, Jeong H. 2017. A micropatterned elastomeric surface with enhanced frictional properties under wet conditions and its application. Soft Matter 13:8419–25.

Lee H, Lee BP, Messersmith PB. 2007. A reversible wet/dry adhesive inspired by mussels and geckos. Nature 448:338.

Lee J, Bush B, Maboudian R, Fearing RS. 2009. Gecko-inspired combined lamellar and nanofibrillar array for adhesion on nonplanar surface. Langmuir 25:12449–53.

Lee J, Fearing RS. 2008. Contact self-cleaning of synthetic gecko adhesive from polymer microfibers. Langmuir 24:10587–91.

Li X, Peng Z, Yang Y, Chen S. 2018. Tunable adhesion of a bio-inspired micropillar arrayed surface actuated by a magnetic field. J Appl Mech 86:011007.

Liu KS, Du JX, Wu JT, Jiang L. 2012. Superhydrophobic gecko feet with high adhesive forces towards water and their bio-inspired materials. Nanoscale 4:768–72.

Liu Z, Meyers MA, Zhang Z, Ritchie RO. 2017. Functional gradients and heterogeneities in biological materials: design principles, functions, and bioinspired applications. Prog Mater Sci 88:467–98.

Lopez-Darias M, Schoener TW, Spiller DA, Losos JB. 2012. Predators determine how weather affects the spatial niche of lizard prey: exploring niche dynamics at a fine scale. Ecology 93:2512–8.

Losos J. 1990. Thermal sensitivity of sprinting and clinging performance in the tokay gecko (*Gekko gecko*). Asiat Herpetol Res 3:54–9.

Ma Y, Ma S, Wu Y, Pei X, Gorb SN, Wang Z, Liu W, Zhou F. 2018. Remote control over underwater dynamic attachment/detachment and locomotion. Adv Mater 30:1801595.

Maderson P. 1964. Keratinized epidermal derivatives as an aid to climbing in gekkonid lizards. Nature 203:780–1.

Marcellini DL. 1971. Activity patterns of the gecko *Hemidactylus frenatus*. Copeia 1971:631–5.

Murphy MP, Aksak B, Sitti M. 2009. Gecko-inspired directional and controllable adhesion. Small 5:170–5.

Murphy MP, Kim S, Sitti M. 2009b. Enhanced adhesion by gecko-inspired hierarchical fibrillar adhesives. ACS Appl Mater Interfaces 1:849–55.

Niewiarowski PH, Lopez S, Ge L, Hagan E, Dhinojwala A. 2008. Sticky gecko feet: the role of temperature and humidity. PLoS ONE 3:e2192.

Niewiarowski PH, Stark AY, Dhinojwala A. 2016. Sticking to the story: outstanding challenges in gecko-inspired adhesives. J Exp Biol 219:912–9.

Niewiarowski PH, Stark AY, Dhinojwala A. 2017. A Bibliometric Analysis of Gecko Adhesion: A View of Its Origins and Current Directions. In: Heepe L, Xue L, Gorb S, editors. Bio-inspired Structured Adhesives. Biologically-Inspired Systems, vol 9. Cham: Springer.

Northen MT, Greiner C, Arzt E, Turner KL. 2008. A gecko-inspired reversible adhesive. Adv Mater 20:3905–9.

Peattie AM, Majidi C, Corder A, Full RJ. 2007. Ancestrally high elastic modulus of gecko setal beta-keratin. J R Soc Interface 4:1071–6.

Peng Z, Chen S. 2011. Effects of the relative humidity and water droplet on adhesion of a bio-inspired nano-film. Colloids Surf B Biointerfaces 88:717–21.

Peng Z, Wang C, Chen S. 2014. Effects of surface wettability on gecko adhesion underwater. Colloids Surf B Biointerfaces 122:662–8.

Peng Z, Yang Y, Chen S. 2017. Coupled effects of the temperature and the relative humidity on gecko adhesion. J Phys D Appl Phys 50:315402.

Persaud D, Werner N, Werner YL. 2003. Foraging behaviour of three sphaerodactylin geckos on Trinidad and Tobago (Sauria: Gekkonomorpha: Sphaerodactylini: Gonatodes). J Nat Hist 37:1765–77.

Pesika NS, Zeng HB, Kristiansen K, Zhao BX, Tian Y, Autumn K, Israelachvili J. 2009. Gecko adhesion pad: a smart surface? J Phys Condens Mat 21:464132.

Prowse MS, Wilkinson M, Puthoff JB, Mayer G, Autumn K. 2011. Effects of humidity on the mechanical properties of gecko setae. Acta Biomater 7:733–8.

Puthoff JB, Holbrook M, Wilkinson MJ, Jin K, Pesika NS, Autumn K. 2013. Dynamic friction in natural and synthetic gecko setal arrays. Soft Matter 9:4855–63.

Puthoff JB, Prowse MS, Wilkinson M, Autumn K. 2010. Changes in materials properties explain the effects of humidity on gecko adhesion. J Exp Biol 213:3699–704.

Rizzo NW, Gardner KH, Walls DJ, Keiper-Hrynko NM, Ganzke TS, Hallahan DL. 2006. Characterization of the structure and composition of gecko adhesive setae. J R Soc Interface 3:441–51.

Ruibal R, Ernst V. 1965. The structure of the digital setae of lizards. J Morphol 117:271–93.

Russell AP. 1975. A contribution to the functional analysis of the foot of the Tokay, *Gekko gecko* (Reptilia: Gekkonidae). J Zool 176:437–76.

Sethi S, Ge L, Ci L, Ajayan PM, Dhinojwala A. 2008. Gecko-inspired carbon nanotube-based self-cleaning adhesives. Nano Lett 8:822–5.

Short KH, Petren K. 2008. Boldness underlies foraging success of invasive *Lepidodactylus lugubris* geckos in the human landscape. Anim Behav 76:429–37.

Sitti M, Fearing RS. 2003a. Synthetic gecko foot–hair micro/nano-structures as dry adhesives. J Adhes Sci Technol 17:1055–73.

Sitti M, Fearing RS. 2003b. Synthetic gecko foot–hair micro/nano-structures for future wall-climbing robots. Proceedings of the IEEE International Conference on Robotics and Automation, ICRA'03, IEEE. p. 1164–70.

Soltannia B, Sameoto D. 2014. Strong, reversible underwater adhesion via gecko-inspired hydrophobic fibers. ACS Appl Mater Interfaces 6:21995–2003.

Stark AY, Badge I, Wucinich NA, Sullivan TW, Niewiarowski PH, Dhinojwala A. 2013. Surface wettability plays a significant role in gecko adhesion underwater. Proc Natl Acad Sci U S A 110:6340–5.

Stark AY, Dryden DM, Olderman J, Peterson KA, Niewiarowski PH, French RH, Dhinojwala A. 2015a. Adhesive interactions of geckos with wet and dry fluoropolymer substrates. J R Soc Interface 12:20150464.

Stark AY, Klittich MR, Sitti M, Niewiarowski PH, Dhinojwala A. 2016a. The effect of temperature and humidity on adhesion of a gecko-inspired adhesive: implications for the natural system. Sci Rep 6:30936.

Stark AY, McClung B, Niewiarowski PH, Dhinojwala A. 2014a. Reduction of water surface tension significantly impacts gecko adhesion underwater. Integr Comp Biol 54:1026–33.

Stark AY, Ohlemacher J, Knight A, Niewiarowski PH. 2015b. Run don't walk: locomotor performance of geckos on wet substrates. J Exp Biol 218:2435–41.

Stark AY, Palecek AM, Argenbright CW, Bernard C, Brennan AB, Niewiarowski PH, Dhinojwala A. 2015c. Gecko adhesion on wet and dry patterned substrates. PLoS ONE 10:e0145756.

Stark AY, Subarajan S, Jain D, Niewiarowski PH, Dhinojwala A. 2016b. Superhydrophobicity of the gecko toe pad: biological optimization versus laboratory maximization. Phil Trans R Soc A 374:20160184.

Stark AY, Sullivan TW, Niewiarowski PH. 2012. The effect of surface water and wetting on gecko adhesion. J Exp Biol 215:3080–6.

Stark AY, Wucinich NA, Paoloni EL, Niewiarowski PH, Dhinojwala A. 2014b. Self-drying: a gecko's innate ability to remove water from wet toe pads. PLoS ONE 9:e101885.

Sun W, Neuzil P, Kustandi TS, Oh S, Samper VD. 2005. The nature of the gecko lizard adhesive force. Biophys J 89:L14–7.

Tao D, Wan J, Pesika NS, Zeng H, Liu Z, Zhang X, Meng Y, Tian Y. 2015. Adhesion and friction of an isolated gecko setal array: the effects of substrates and relative humidity. Biosurf Biotribol 1:42–9.

Taylor A, Bonser R, Farrent J. 2004. The influence of hydration on the tensile and compressive properties of avian keratinous tissues. J Mater Sci 39:939–42.

Toni M, Dalla Valle L, Alibardi L. 2007. The epidermis of scales in gecko lizards contains multiple forms of beta-keratins including basic glycine–proline–serine-rich proteins. J Proteome Res 6:1792–805.

Vitt LJ. 1983. Tail loss in lizards: the significance of foraging and predator escape modes. Herpetologica 39:151–62.

Watson GS, Green DW, Schwarzkopf L, Li X, Cribb BW, Myhra S, Watson JA. 2015a. A gecko skin micro/nano structure—a low adhesion, superhydrophobic, anti-wetting, self-cleaning, biocompatible, antibacterial surface. Acta Biomater 21:109–22.

Watson GS, Schwarzkopf L, Cribb BW, Myhra S, Gellender M, Watson JA. 2015b. Removal mechanisms of dew via self-propulsion off the gecko skin. J R Soc Interface 12:20141396.

Wenzel RN. 1936. Resistance of solid surfaces to wetting by water. Ind Eng Chem 28:988–94.

Werner Y, Takahashi H, Yasukawa Y, Ota H. 2004. The varied foraging mode of the subtropical eublepharid gecko *Goniurosaurus kuroiwae* orientalis. J Nat Hist 38:119–34.

Werner YL. 1990. Habitat-dependent thermal regimes of two Hawaiian geckos (Reptilla: Gekkonidae). J Thermal Biol 15:281–90.

Werner YL, Bouskila A, Davies S, Werner N. 2011. Observations and comments on active foraging in geckos. Russ J Herpetol 4:34–9.

Williams E, Peterson J. 1982. Convergent and alternative designs in the digital adhesive pads of scincid lizards. Science 215:1509–11.

Yi H, Lee SH, Seong M, Kwak MK, Jeong HE. 2018. Bioinspired reversible hydrogel adhesives for wet and underwater surfaces. J Mater Chem B 6:8064–70.

Yurdumakan B, Raravikar NR, Ajayan PM, Dhinojwala A. 2005. Synthetic gecko foot–hairs from multiwalled carbon nanotubes. Chem Commun 14:3799–801.

Zhao Y, Wu Y, Wang L, Zhang M, Chen X, Liu M, Fan J, Liu J, Zhou F, Wang Z. 2017. Bio-inspired reversible underwater adhesive. Nat Commun 8:2218.