Reduction of Water Surface Tension Significantly Impacts Gecko Adhesion Underwater

Alyssa Y. Stark,1,* Brandon McClung,* Peter H. Niewiarowski* and Ali Dhinojwala†

*Integrated Bioscience Program, The University of Akron, Akron, OH 44325, USA; †Department of Polymer Science, The University of Akron, Akron, OH 44325, USA

From the symposium “Shaking, Dripping, and Drinking: Surface Tension Phenomena in Organismal Biology” presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2014 at Austin, Texas.

1E-mail: ays3@zips.uakron.edu

Synopsis  The gecko adhesive system is dependent on weak van der Waals interactions that are multiplied across thousands of fine hair-like structures (setae) on geckos’ toe pads. Due to the requirements of van der Waals forces, we expect that any interruption between the setae and substrate, such as a water layer, will compromise adhesion. Our recent results suggest, however, that the air layer (plastron) surrounding the superhydrophobic toe pads aid in expelling water at the contact interface and create strong shear adhesion in water when in contact with hydrophobic surfaces. To test the function of the air plastron, we reduced the surface tension of water using two surfactants, a charged anionic surfactant and a neutral nonionic surfactant. We tested geckos on three substrates: hydrophilic glass and two hydrophobic surfaces, glass with a octadecyl trichlorosilane self-assembled monolayer (OTS-SAM) and polytetrafluoroethylene (PTFE). We found that the anionic surfactant inhibited the formation of the air plastron layer and significantly reduced shear adhesion to all three substrates. Interestingly, the air plastron was more stable in the nonionic surfactant treatments than the anionic surfactant treatments and we found that geckos adhered better in the nonionic surfactant than in the anionic surfactant on OTS-SAM and PTFE but not on glass. Our results have implications for the evolution of a superhydrophobic toe pad and highlight some of the challenges faced in designing synthetic adhesives that mimic geckos’ toes.

Introduction  Recently, we discovered that geckos are able to adhere to wet substrates that have an intermediate or hydrophobic water contact angle ($\theta_w$) (Stark et al. 2013). This result was somewhat surprising given that the gecko adhesive system is van der Waals-based (Autumn et al. 2002), and even thin layers of water should disrupt the weak intermolecular forces between the setae (hair-like adhesive structures) and substrate (Hosoda and Gorb 2012; Lee et al. 2007), causing geckos to fall from wet surfaces. Interestingly, this behavior has been observed on substrates with low water contact angles, such as glass. When directly tested on submerged glass ($\theta_w = 50 \pm 1.4^\circ$), geckos cannot reliably support their body weight (Stark et al. 2012, 2013). On the contrary, when making contact to more hydrophobic substrates such as polymethylmethacrylate (PMMA; $\theta_w = 85 \pm 0.5^\circ$) and an octadecyltrichlorosilane self-assembled monolayer formed on the surface of glass (OTS-SAM; $\theta_w = 94 \pm 0.5^\circ$), geckos adhered equally well when submerged in water as when in air (Stark et al. 2013). Finally, when tested on polytetrafluoroethylene (PTFE; $\theta_w = 97 \pm 0.3^\circ$), a substrate to which geckos cannot adhere in air, we found that shear adhesion was significantly better in water than in air (Stark et al. 2013). Taken together, these results suggest that substrates with higher contact angles are better for wet shear adhesion than are substrates with lower water contact angles. While it is unlikely that a gecko will encounter a completely submerged surface in their natural habitat, nor is it likely they will regularly move across glass or Teflon surfaces, it is entirely reasonable to expect natural substrates to be periodically wet from rainfall and humidity, especially in the tropics where many species of gecko are native. Furthermore, substrate wettability can vary significantly in natural
surfaces, e.g., wax on leaf cuticles, dirt and water deposits, making our findings relevant for understanding how geckos utilize their adhesive under free-ranging conditions.

We hypothesized that the key to adhesion underwater is the gecko’s ability to remove water from the contact interface (Stark et al. 2013). One way geckos’ toe pads may achieve dry contact with the substrate is by utilizing its innate superhydrophobicity ($\theta_w = \sim 150^\circ$) and very low contact angle hysteresis, which causes water to roll off the toe pad at very small tilt angles (only 2–3°) (Autumn and Hansen 2006; Liu et al. 2012). Despite the superhydrophobicity of geckos’ toe pads, they can be wetted, a phenomenon known as a Cassie–Baxter to Wenzel transition, after repeated or prolonged exposure to water (Pesika et al. 2009; Stark et al. 2012). In the Cassie–Baxter wetting state, the water droplet is held above the setal mat (Fig. 1a), resulting in a liquid–air–solid interface (Cassie and Baxter 1944). In the Wenzel state, the water droplet penetrates into the setal mats and the toe wets, resulting in a liquid–solid interface without air pockets (Fig. 1b) (Wenzel 1936). When the wetting transition occurs, whole-animal shear adhesion is significantly decreased in air and in water (Stark et al. 2012). Thus, it is clear that the maintenance of dry toe pads is also a key to shear adhesion in any condition (air or water). Although it has never been directly tested, we believe that geckos are able to keep their toe pads dry by forming an air plastron (Poetes et al. 2010), or bubble, around their toes, as shown schematically in Fig. 2a. In addition, it is also likely that this plastron works in tandem with hydrophobic substrates to push water out of the adhesive interface (Hosoda and Gorb 2012; Stark et al. 2013). This behavior is shown schematically in Fig. 2b. The formation of the air plastron is related to the high surface tension of water (72 mN/m) and also the superhydrophobicity of the toe. Therefore, similar to a study with aquatic beetles walking on submerged substrates (Hosoda and Gorb 2012), we hypothesize that when geckos are forced to adhere in a liquid with surface tension lower than pure water, shear adhesion will be significantly reduced due to the loss of the air plastron and the resulting difficulty of squeezing water out of the contact interface.

A relatively easy way to decrease the surface tension of water is to introduce a surfactant that adsorbs at the air–water surface. In the geckos’ adhesive system, we expect the surfactant to affect shear adhesion in two ways. First, the decrease in surface tension should cause the air plastron to be unstable or fail to form, which would cause the superhydrophobic toe pads (Cassie–Baxter state) to wet (Wenzel state) (Chang et al. 2007; Ferrari et al. 2006; Mohammadi et al. 2004) and likely be nonadhesive and unable to aid the expulsion of water from the interface. Second, surfactant can also alter the surface properties of both the substrate and the gecko’s surface (setae). We expect surfactants to adsorb on the setae and the substrate according to their chemistry (Briscoe et al. 2006; Chang et al. 2007; Ferrari et al. 2006; Haidara et al. 1995; Mohammadi et al. 2004). For some substrates this is relatively straightforward to predict, such as substrates like OTS-SAM formed on glass. On this substrate, polymer tail groups point away from the glass surface and we would expect the surfactant to align itself so that the head groups face outward (Fig. 3), thus reducing the interfacial tension. On other substrates, such as glass or PTFE, the ordering, if any, is more difficult to predict. Likewise, the alignment of surfactant on geckos’ setae that have become wet is also hard to predict, due to our limited knowledge of the surface chemistry of the setae. Specifically, there is increasing support that the surface material of the setae actually changes upon contact with water, causing the surface to be either Cassie–Baxter state) to wet (Wenzel state) (Chang et al. 2007; Ferrari et al. 2006; Mohammadi et al. 2004) and likely be nonadhesive and unable to aid the expulsion of water from the interface. Second, surfactant can also alter the surface properties of both the substrate and the gecko’s surface (setae). We expect surfactants to adsorb on the setae and the substrate according to their chemistry (Briscoe et al. 2006; Chang et al. 2007; Ferrari et al. 2006; Haidara et al. 1995; Mohammadi et al. 2004). For some substrates this is relatively straightforward to predict, such as substrates like OTS-SAM formed on glass. On this substrate, polymer tail groups point away from the glass surface and we would expect the surfactant to align itself so that the head groups face outward (Fig. 3), thus reducing the interfacial tension. On other substrates, such as glass or PTFE, the ordering, if any, is more difficult to predict. Likewise, the alignment of surfactant on geckos’ setae that have become wet is also hard to predict, due to our limited knowledge of the surface chemistry of the setae. Specifically, there is increasing support that the surface material of the setae actually changes upon contact with water, causing the surface to be either
negatively charged (SDS) or neutral (POE) (Fig. 3). If the plastron is unstable or fails to form and the setae become wet, surfactant can also align on the setae themselves in relation to the unknown and likely dynamic chemical groups at the surface of the gecko’s setae. By testing each of these treatment pairs, we hope to shed light on what occurs at the adhesive interface when a gecko’s toe contacts a substrate in water. Specifically, our results will help to inform the setal–substrate interaction and the importance of the air plastron in keeping the toe pads dry and able to expel water from the contact interface.

Materials and methods

Animals

Seven adult tokay geckos (Gekko gecko) were used in experimental trials. Geckos were weighed at the completion of each experimental trial and this weight is reported as an average weight over the duration of the experiments. Outside of experimental trials, animals were housed individually and given cockroaches three times a week. Glass terraria were misted twice a day with water. Geckos were acclimated to the experimental conditions for half an hour prior to testing. Ambient temperature, water temperature, and humidity were maintained at 24.4 ± 0.1°C, 23.7 ± 0.3°C, and 32.6 ± 0.33%, respectively, over the acclimation period and during experimental trials. All procedures using live animals were approved by the University of Akron IACUC protocol 07-4G and are consistent with the guidelines published by the Society for the Study of Amphibians and Reptiles (SSAR 2004).

Experimental treatments

Two surfactants were used in experimental trials: negatively charged anionic sodium dodecyl sulfate...
Surface tension impacts gecko adhesion

Substrates and gecko feet were washed thoroughly and immediately with water at the completion of each set of trials. Geckos were never tested more than once a day and all geckos were given at least one day between trials. Substrates were washed with alcohol and water prior to experimental trials.

Statistical analysis

The effect of substrate type (glass, OTS-SAM-coated glass, or PTFE) and surfactant treatment (anionic or nonionic) on shear adhesion was tested using a repeated-measures MANOVA. Each gecko was tested in all combinations of treatments, which effectively removed the need to account for individual differences in substrates or surfactants. A matched-pairs analysis was used to compare specific treatments of interest, such as the comparison between the two surfactant types on each of the three substrates. Means are reported as mean ± 1 standard error of mean.

Results

The average weight of the seven Tokay geckos (G. gecko) used during experimental trials was 93.7 ± 2.3 g. When testing the effect of substrate type (glass, OTS-SAM-coated glass, or PTFE) and surfactant treatment (anionic or nonionic) on shear adhesion, we found that shear adhesion was significantly affected by substrate, treatment, and the interaction of substrate and treatment (P = 0.0271; Table 1). Specifically, we found that there was no significant difference in shear adhesion between the two surfactant types when tested on glass (0.32 ± 0.02 N anionic, 0.35 ± 0.03 N nonionic; t = −1.00, df = 6, P = 0.3547), but there was a significant difference in shear adhesion when tested on the OTS-SAM substrate (0.32 ± 0.05 N anionic, 0.51 ± 0.06 N nonionic; t = 4.87, df = 6, P = 0.0028) and the PTFE substrate (0.27 ± 0.02 N anionic, 1.20 ± 0.27 N nonionic; t = −3.50, df = 6, P = 0.0129). On both of the latter substrates (OTS-SAM and PTFE), the nonionic surfactant allowed for significantly higher shear adhesion than did the anionic surfactant. Values of shear adhesion from animals tested when each of the three substrates was fully submerged in water or was tested in air were adapted from Stark et al. (2013) and are included in Figure 4 for reference, but were not quantitatively compared due to differences in experimental subjects.

We inferred whether an air plastron formed or not by noting the presence or absence of dry setae at the completion of each test. When geckos were tested in

Experimental procedure

A force-sensing apparatus, similar to the one used by Niewiarowski et al. (2008), was used to measure frictional or shear adhesive force of geckos positioned horizontally in the surfactant bath. Geckos were chosen at random, as were the treatment conditions (substrate and surfactant). Prior to experimentation, two small harnesses were secured around the gecko’s pelvis and attached to a force sensor. Geckos were then placed onto the substrate and allowed to naturally position themselves on the substrate by taking at least four steps, one step per foot. After taking all four steps, geckos were pulled backwards along the substrate by a custom-designed force apparatus positioned on a motorized track. The two pelvic harnesses attached to the moving force apparatus allowed us to measure the force geckos produce while clinging to a substrate. Maximum shear adhesion was defined as the force reading at the point all four of the gecko’s feet began to slip along the substrate. Test substrates were attached to the force apparatus as described by Stark et al. (2012, 2013), in which a large Rubbermaid container held the surfactant solution and allowed the gecko’s feet to be completely submerged (~1 cm in height). During the course of the experiment, the presence or absence of dry patches on the adhesive toe pads after the completion of each trial was noted as a way to measure the maintenance of an air plastron. Dry patches appear white and are dry to the touch, whereas wet toe pads become grey (see Fig. 2 in Stark et al. 2012). This was logged in a sub-set of trials and thus percentages of wet or dry toe pads are calculated based on this sub-set of trials rather than on the entire set of experimental trials.

(1029)
the anionic surfactant all toes wetted immediately and the plastron failed to form (except for one instance on glass). When tested in the nonionic surfactant, geckos tested on glass and OTS-SAM-coated glass finished the shear adhesion tests with partially dry toes about 60% of the time (60% for glass; 58.8% for OTS-SAM). Conversely, when tested in the nonionic surfactant on PTFE, we observed full or partially dry toes in all of the trials measured (100%).

Discussion

Compared to studies in laboratory environments, published observations of geckos in their natural environment are rare. Even fewer reports document how geckos and other pad-bearing lizards behave under wet conditions, such as rain, high humidity, or fog (Lopez-Darias et al. 2012; Marcelli 1971; Werner 1990), conditions that should be challenging for adhesive pad-bearing species that rely on a van der Waals-based adhesive system (Autumn et al. 2002). We hypothesized that the dry contact necessary for shear adhesion in water is facilitated by an air plastron that keeps the toes dry by expelling water from the shear adhesive interface (Fig. 2). Because a surfactant lowers the surface tension of water, we predicted that the plastron would fail to form and shear adhesion would be significantly impaired. We also hypothesized that variation in the amount of surfactant absorbed on the gecko’s toe and the wettability of different substrates would have a significant effect on shear adhesion. To investigate these hypotheses, we tested geckos on three substrates with different \( \theta_p \) in two different surfactants (anionic and nonionic). We found that shear adhesion in surfactant solutions is significantly lower than in water on all substrates (Fig. 4). This was especially true for the anionic surfactant, for which the air plastron failed to form in virtually all trials. Conversely, when testing shear adhesion in the nonionic surfactant, geckos generated significantly higher shear adhesion on the OTS-SAM and PTFE substrates than when tested in the anionic surfactant, and in most cases the plastron was sustained in the nonionic treatment.

When observing the toe pads after experimental trials in the anionic surfactant, we found that the toes were immediately and completely wetted (Wenzel wetting state; Fig. 1b). Because the plastron did not form, it is likely that water was not excluded from the adhesive interface (Fig. 2b); however, it is possible that water could be expelled on a microscopic scale during shear-sliding along the substrate, resulting in direct contact between the setae and substrate. To investigate the interaction of the two surfaces in the surfactant solution when water is completely expelled at the interface, we used a generalized work of adhesion model that can predict the relative work of adhesion in a surfactant–water solution \( (W_{wet}) \) when two surfaces are separated in the direction normal to each other. Model calculations were made in the normal geometry, rather than shear, due to the lack of a clear approach to modeling shear adhesion. There is a correlation between normal and shear adhesion however (Israelachvili et al. 1994), and thus our model allows us to predict adhesion in the shear direction. In calculating normal adhesion we neglected the effect of capillary forces because we expect capillary forces to be negligible in shear. We consider one surface to be a gecko’s hair-like surface \( (h') \), which can either be coated with surfactant or not, and the other surface to be one of the three substrates used in

### Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Wilks’ lambda</th>
<th>Exact F</th>
<th>Numerator df</th>
<th>Denominator df</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>1.040</td>
<td>12.474</td>
<td>1</td>
<td>12</td>
<td>0.0041*</td>
</tr>
<tr>
<td>Substrate</td>
<td>0.735</td>
<td>4.042</td>
<td>2</td>
<td>11</td>
<td>0.0483*</td>
</tr>
<tr>
<td>Substrate*</td>
<td>0.927</td>
<td>5.098</td>
<td>2</td>
<td>11</td>
<td>0.0271*</td>
</tr>
</tbody>
</table>

The \( F \)-statistic is from the Wilks’ lambda test. Asterisks denote statistically significant values (\( P < 0.05 \)).

![Fig. 4](https://example.com/image.png)

Fig. 4 Bars represent maximum shear adhesion when tested in an anionic surfactant (black bars) and a nonionic surfactant (gray bars) on three substrates (glass, OTS-SAM-coated glass, and PTFE). Points represent maximum values of shear adhesion from a previous study in which geckos were tested in air (black) and in water (white) on each of the three substrates; values for air and water are adapted from Stark et al. (2013). Error bars are mean ± 1 standard error of mean.
experimental trials (s), which may also have a surfactant coating. We can then estimate the \( W_{\text{wet}} \) using the following equation (Equation 1), where \( A_s \) is the contact area, \( \gamma_{s-w} \) is the interfacial energy of the substrate and the surfactant–water solution, \( \gamma_{h-s} \) is the interfacial energy of the gecko’s hair-like surface and the surfactant–water solution, and \( \gamma_{s-h} \) is the interfacial energy of the substrate and the gecko’s hair-like surface. This equation assumes that the surfaces in contact are dry and when separated, the surfaces are in contact with the surfactant–water solution.

\[
W_{\text{wet}} = A_s (\gamma_{s-w} + \gamma_{h-s} - \gamma_{s-h})
\]  

(1)

Considering the OTS-SAM substrate first, we know that \( \gamma_{s-w} \) will be lower than pure water because the anionic surfactant adsorbs with the charged head groups facing the surfactant–water solution (Fig. 3), causing the surface to become negatively charged and lowering the interfacial energy. Because the plastron failed to form it is also likely that the surfactant molecules have adsorbed with the hydrophobic tail facing the surface of the gecko’s toe (Hsu et al. 2012), leading to wetting of the toe pads. Thus, \( \gamma_{h-s} \) should also decrease when compared to that of the gecko’s surface in contact with pure water. Finally, we expect that the paired negative charges on the toe and the substrate will cause electrostatic repulsion and thus increase the interfacial energy (\( \gamma_{s-h} \)). Incidentally, these negatively charged surfaces can also cause water to become trapped (Hsu and Dhinojwala 2012), which would further reduce adhesion. As a result of all these effects, we predict that the value of \( W_{\text{wet}} \) is lower on OTS-SAM in anionic surfactant solution than the work of adhesion in water alone (\( W_{\text{wet}} \)). This matches our results (Fig. 4).

A similar argument can be used to predict the trend of \( W_{\text{wet}} \) for the glass and PTFE substrates, in which the \( \gamma_{h-s} \) term is consistently lower in the anionic surfactant solution than when tested in pure water due to surfactant adsorption on the toe. On the glass and PTFE substrates it is possible that the surfactant does not adsorb on the surface; however, again, the overall net \( W_{\text{wet}} \) should still be lower in the anionic surfactant than in water, simply based on \( \gamma_{h-s} \) alone. On the PTFE substrate, the effect on \( \gamma_{s-h} \) is unclear as the interaction of the surfactant-covered toe and fluorinated groups at the surface of PTFE may cause \( \gamma_{s-h} \) to increase; however, this would still cause an overall net decrease of \( W_{\text{wet}} \).

In conclusion, we can expect that the gecko’s adhesion should be lower in the anionic surfactant solution than in water on all three substrates. This prediction is based on three possible scenarios: (1) the toes become wet and shear adhesion is reduced as it is in pure water (Stark et al. 2012), (2) the plastron is unstable and therefore cannot help to create a dry contact interface, and (3) if a dry contact interface does occur, \( W_{\text{wet}} \) should still be lower based on changes in interfacial energy due to the adsorption of surfactant molecules.

In contrast to the anionic solution, which was completely wetting, we found that in about 60–100% of the observed experimental trials, parts or all of the toe remained dry when tested in the nonionic surfactant. Interestingly, this only resulted in improved shear adhesion (when compared to the anionic treatment) on the OTS-SAM and PTFE substrates. Using Equation 1, we can make predictions about the work of adhesion in the nonionic surfactant solution, assuming that dry contact occurs. Unlike the anionic surfactant, the plastron is maintained in 60–100% of the nonionic surfactant treatments; thus, the nonionic surfactants are not adsorbed, or are only partially adsorbed, on the toe pads. Furthermore, the nonionic surfactant is not charged. Taken together, we would expect \( \gamma_{h-s} \) to be lower for the nonionic surfactant treatment than for a pure water treatment, but not as low as \( \gamma_{h-s} \) for the charged and fully wetting anionic treatment. This should be relatively consistent across all three substrate treatments, given the percentage of dry toe pads observed.

When investigating the surface term, \( \gamma_{s-w} \) in the nonionic surfactant treatment on OTS-SAM, we know that \( \gamma_{s-w} \) is reduced because the surfactant is expected to adsorb with the polar head group facing the surfactant–water solution (Fig. 3); however, we expect that \( \gamma_{s-w} \) for the nonionic surfactant is not as low as \( \gamma_{s-w} \) for the anionic surfactant. Thus, we would expect \( \gamma_{s-w} \) to be lower than for pure water but not as low as \( \gamma_{s-w} \) in presence of anionic surfactants. For both the glass and PTFE substrates, it is possible that \( \gamma_{s-w} \) does not differ from \( \gamma_{s-w} \) as surfactant may not be adsorbing on either of these substrates, similar to our predictions with the anionic surfactants. Therefore, the surface term (\( \gamma_{s-w} \)) suggests that glass and PTFE have higher predicted adhesion values than does OTS-SAM when making dry contact, which is not entirely the case here (Fig. 4).

Finally, due to plastron formation on the toes and the alignment of surfactant on the substrates, it is difficult to predict \( \gamma_{s-h} \) for the nonionic surfactant treatments. Overall, however, the partial reduction of \( \gamma_{h-s} \) should lower \( W_{\text{wet}} \) when compared to water but not be as low as \( W_{\text{wet}} \) for the anionic surfactant solution that completely wets and coats the toe pads. Again, this equation is assuming dry contact between
the two surfaces, which may also be more likely to occur in these treatments due to the maintenance of the plastron. Interestingly, however, the plastron does not always aid in making dry contact, as we found with geckos tested in water on hydrophilic glass (Stark et al. 2013). In this context, we found that the air plastron, in coordination with the hydrophilic glass substrate, caused a water layer to become trapped between the foot and the glass substrate, disallowing it from making adhesive contact. This behavior may be occurring here, causing our values of shear adhesion on glass to be lowered further.

Using our observations of the toe pads, our results on whole-animal shear adhesion, and our estimates from simplified models, we can begin to describe how surface tension and surface energy relates to wet adhesion in the gecko adhesive system. Our results are relevant for two reasons. First, although it is unlikely that a gecko would encounter fluids with low surface tension in their natural environment, our results with surfactant highlight the importance of the air plastron and its ability to keep the toes dry and help expel water at the contact interface. Interestingly, a plastron is required for wet shear adhesion (in water or surfactant); however, it does not guarantee adhesion, as pointed out in the case of hydrophilic substrates where water can become trapped. Second, the adsorption of anionic surfactant molecules, which was confirmed by the complete and immediate wetting of the toe pads, suggests that the toes themselves were hydrophobic prior to the adsorption of surfactant. Interestingly, the uncharged surfactant did not cause the toes to fully wet. This difference should not relate to the difference in surface tension of the surfactant solutions, which is similar (γ = 37 mN/m for SDS and γ = 39.4 mN/m for POE), but rather relates to the adsorption of the anionic surfactant molecules on hydrophobic toe pads. Our results show that the interaction of the superhydrophobic toe pad, the plastron it creates, the substrate it contacts, and the interfacial energies of each of the surfaces and interfaces are all essential for adhesion to occur on wet surfaces.

The retention of an air plastron is directly related to the superhydrophobicity of the geckos’ toe pad (Poetes et al. 2010). With the recent discovery of lipids on geckos’ setae (Alibardi et al. 2011; Hsu et al. 2012), we hypothesize that lipids aid in the formation of a superhydrophobic surface and the resulting air plastron. Cutaneous lipids in the reptilian epidermis are mainly associated with reducing water loss (Alibardi et al. 2011; Lillywhite 2006); however, we believe that the evolution of the lipid-keratin association in the setae may also help create this highly important property for wet adhesion. Our results provide a first step in exploring how setal surface chemistry and the charge on the substrate can affect adhesion underwater. Additionally, our results also have significant implications for the design of a synthetic adhesive that can be reused repeatedly in air and water (Kizilkan et al. 2013) and perhaps even in fluids with lower surface tensions, like blood (γ = 58 mN/m), for the potential development of a more versatile medical bandage.

**Acknowledgments**

The authors would like to give special thanks to Kyle Garra, Sophia Elliott, and Amanda Palecek for help with experimental trials.

**Funding**

This work was supported by The University of Akron (to P.H.N.) and the National Science Foundation (NSF-DMR-1105370 to A.D.).

**References**


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