

Wetting of the adhesive fluid controls underwater adhesion in insects: Supplementary material

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S.1 Simulation method: Single capillary bridge

Capillary force due to a single adhesive fluid or bubble meniscus (termed “capillary bridge”) is calculated by performing simulations in Surface Evolver¹, similar to the method described by De Souza et al.². A simple cubic geometry, mimicking the capillary bridge, of constant volume, V , is defined as the initial condition with an interfacial tension, γ , with the surrounding medium. Interfacial tension of the capillary bridge with the substrate is given by $\gamma \cos \theta$, where θ is the corresponding contact angle inside the bridge. For the case of a bubble meniscus, θ is defined w.r.t. the surrounding water, since θ can also directly characterise the substrate wettability. The capillary bridge spans a gap distance d between the top face and the substrate. The boundary conditions are set corresponding to a pinned contact line of diameter D on the top face and constant interfacial tension with the substrate on the bottom. All lengths are normalised relative to length $s = (3V/4\pi)^{1/3}$. An appropriate geometry refinement routine is chosen to evolve the capillary bridge shape to its minimum energy

state. The normalised total capillary force, $\hat{f} = f/\gamma s$, is the sum of the Laplace pressure and surface tension contributions, where:

$$f = f_{laplace} + f_{surface\ tension} = \Delta P_{laplace} A_{bottom} + 2\pi R_{bottom} \gamma \sin \theta \quad (S.1)$$

Here, $\Delta P_{laplace}$ is the Laplace pressure of the equilibrium capillary bridge, A_{bottom} is the contact area of the capillary bridge with the substrate at bottom and R_{bottom} is the corresponding radius of contact, all obtained from the simulation output for the equilibrium surface.

The gap distance d is varied stepwise and the capillary force is calculated each time to obtain force-distance curves for a particular choice of D and θ .

S.2 Single capillary bridge: Effect of volume

Surface Evolver simulation results showing the effect of volume on the maximum capillary force of a single fluid bridge. Since the fluid is pinned at the top to the same diameter, D , a smaller volume would result in high interfacial curvatures, which increases the capillary force due to the negative Laplace pressure. In this case, small contact angles lead to a greater increase in adhesion.

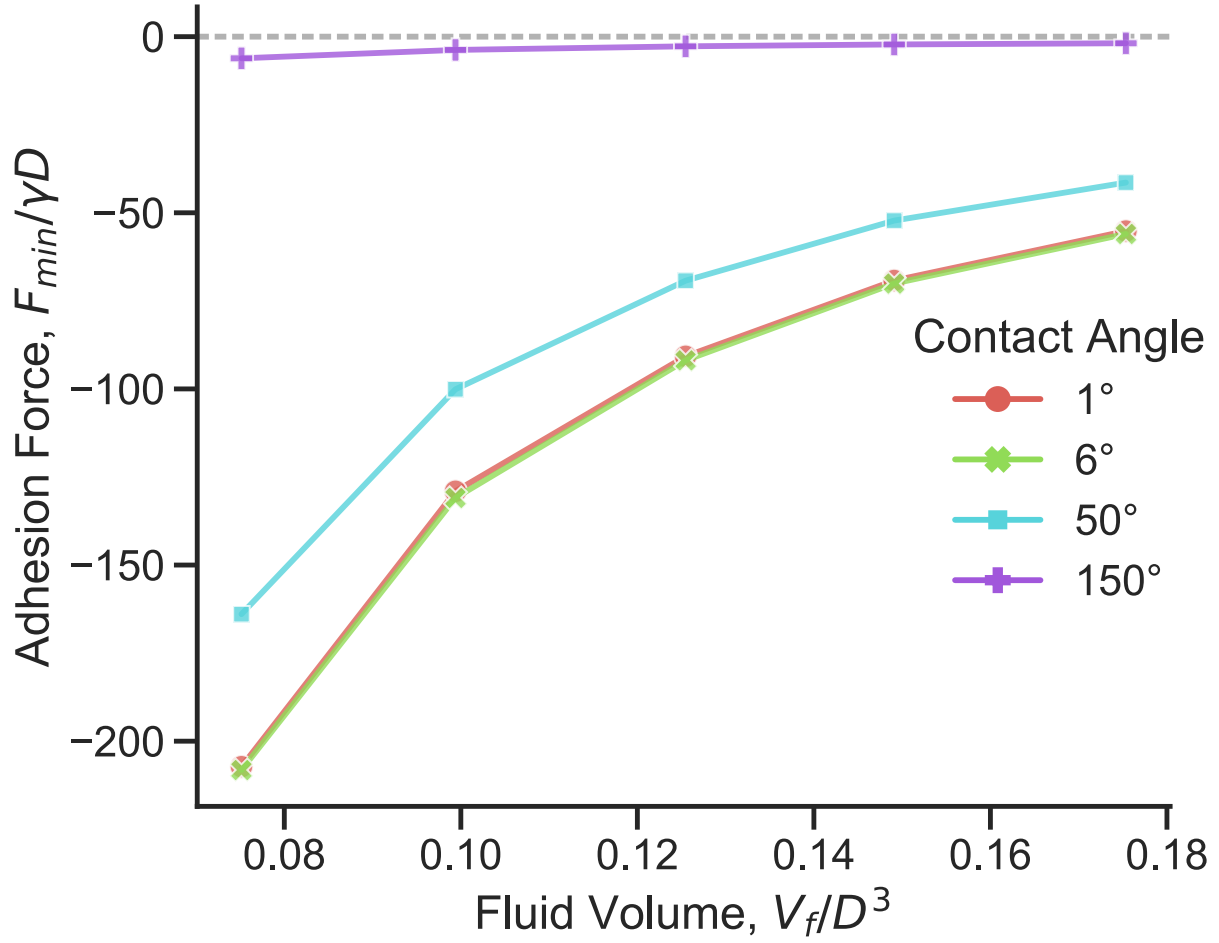


Figure S.1: Normalised maximum capillary force for a single bridge as a function of fluid volume

bsectionCapillary Bridge Model: Effect of hair diameter at constant fluid volume

Here, instead of scaling the fluid volume relative to the hair diameter, we now assume a fixed total fluid volume distributed equally among the N hairs. Total fluid volume, $V_{total} = NV_f = 2000$. Hair diameter is varied while keeping the total hair contact area constant. Length is in arbitrary units. Forces increase at a much smaller rate on decreasing diameter when compared to the case with self-similar scaling of fluid volume (Figure 8 in main text).

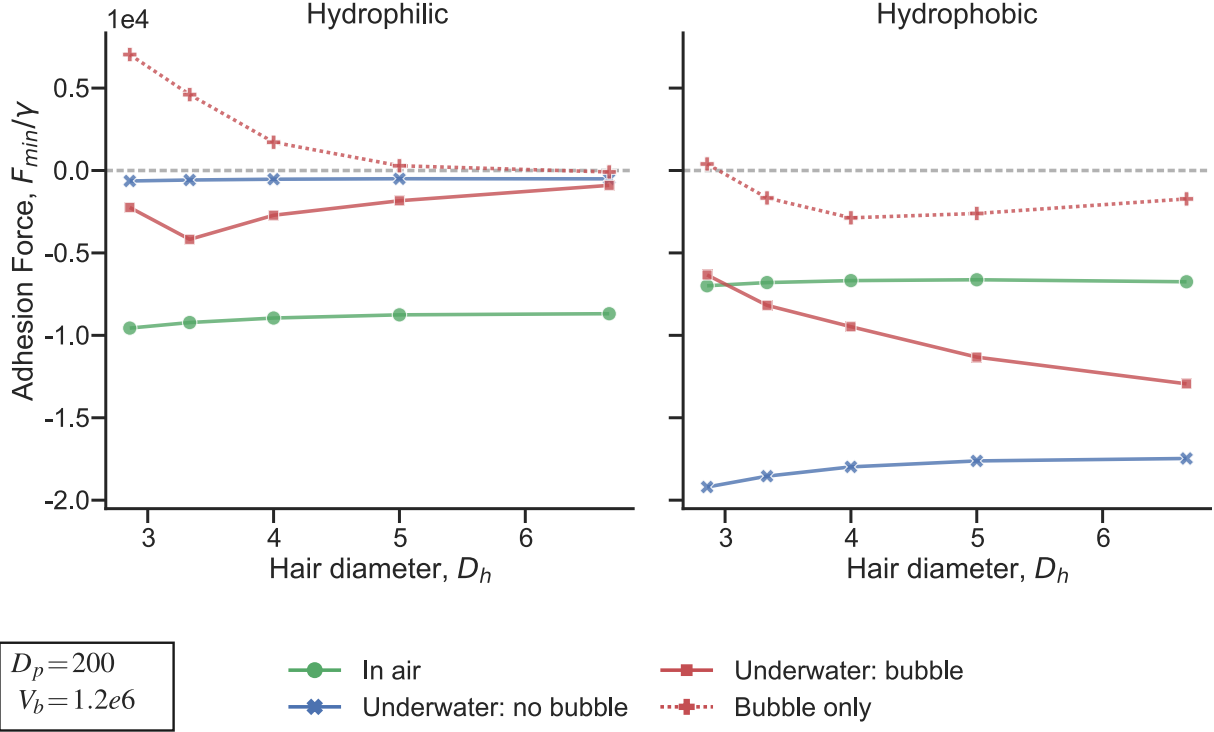


Figure S.2: Normalised adhesion force of hairy pad system on a hydrophilic and hydrophobic substrate as a function of hair diameter (D_h), calculated from the capillary bridge model. The total adhesive fluid volume is fixed to 2000. Adhesion forces are calculated from minima of the respective force-distance curves. Negative force value represents attraction. The bubble's contribution to the net force for an *underwater: bubble* contact is denoted by plus symbols. Bubble volume and pad diameter are kept fixed. All lengths are scaled relative to D_p .

S.3 Statistical comparison

Pairwise statistical comparison of single leg adhesion force measurements of the ladybug beetle (*Coccinella septempunctata*) for each contact type and substrate are shown (Table S.1). The uncorrected p-values and Common Language Effect Size (CLES) are obtained from post-hoc pair-wise Student t-test between A and B while keeping the third parameter fixed. p-values showing statistically significant difference between A and B are in boldface. The condition for statistical significance is based on the Bonferroni-corrected critical p-value of 0.008.

Table S.1

Fixed	A	B	p-value	CLES
In air	PFOTS	Glass	0.959	0.48
Underwater: bubble	PFOTS	Glass	0.011	0.96
Underwater: no bubble	PFOTS	Glass	< 0.001	1.0
PFOTS	In air	Underwater: bubble	0.897	0.48
PFOTS	In air	Underwater: no bubble	0.828	0.48
PFOTS	Underwater: bubble	Underwater: no bubble	0.721	0.44
Glass	In air	Underwater: bubble	0.002	1.0
Glass	In air	Underwater: no bubble	< 0.001	1.0
Glass	Underwater: bubble	Underwater: no bubble	0.07	0.84

S.4 Capillary force due to a bubble

Capillary force of a single bubble against a PFOTS surface are compared for two different volumes. The volumes correspond to the expected range in the case of the trapped bubble in a ladybug. Here, the bubble is pinned to a micropatterned PDMS substrate on the top. The maximum adhesion force of any of the bubble never exceeds 50 μN , significantly lower than the beetle’s underwater adhesion to the same substrate ($> 400 \mu\text{N}$). Thus, the bubble’s contribution to adhesion in the “*underwater: bubble*” contact of a ladybug’s pad should be negligible.

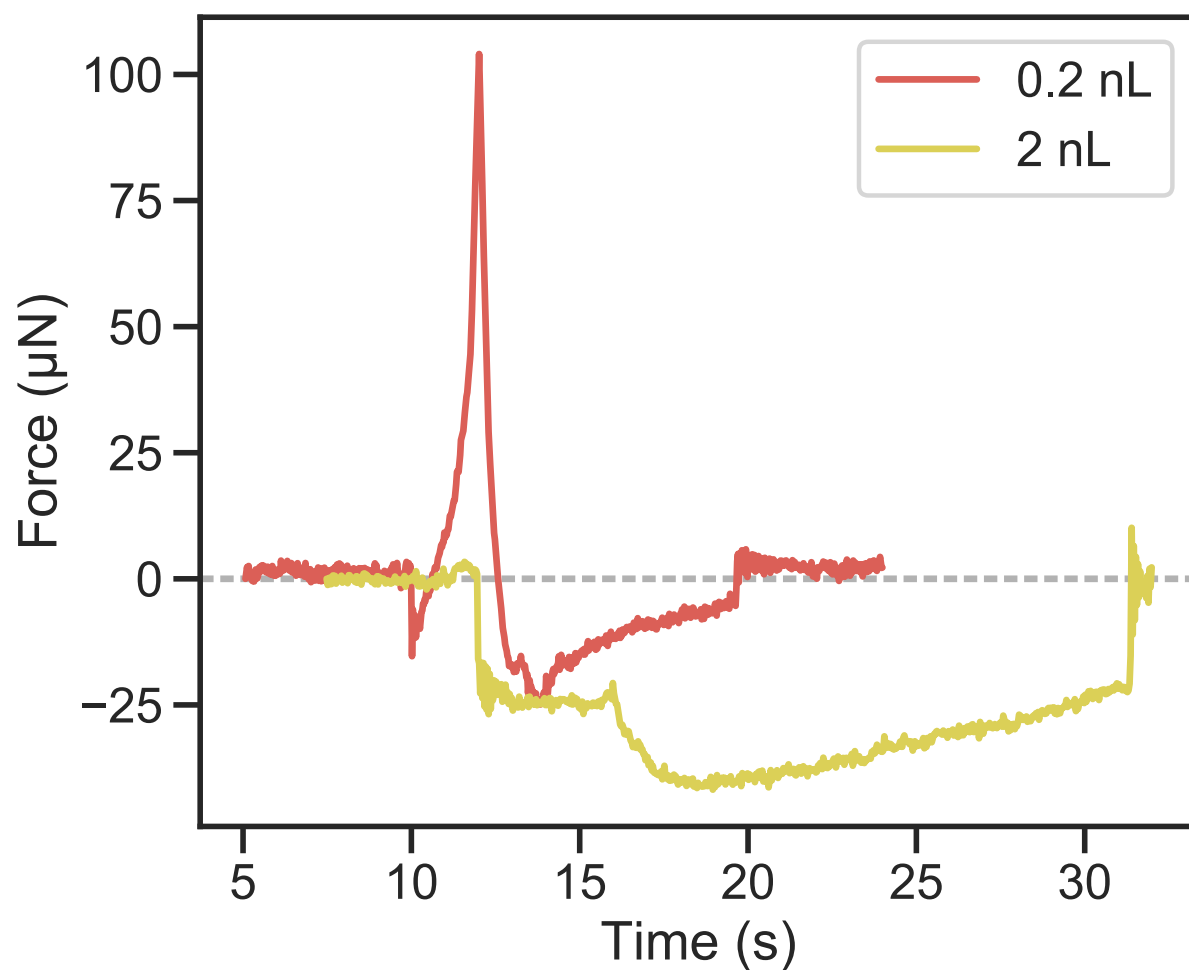


Figure S.3: Capillary force of the bubble

References

- (1) Brakke, K. A. The surface evolver. *Experiment. Math.* **1992**, *1*, 141–165.
- (2) De Souza, E. J.; Brinkmann, M.; Mohrdieck, C.; Arzt, E. Enhancement of Capillary Forces by Multiple Liquid Bridges. *Langmuir* **2008**, *24*, 8813–8820.