

Research Article

Sliding across veins becomes slipperier: Counterintuitive directional friction on nepenthes inner walls

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Abstract

Directional friction on soft interfaces combining wetting heterogeneity with compliant contact remains unclear under ultralow normal loads, where lubrication and contact geometry may interact strongly. We probed the inner wall of *Nepenthes* pitchers, which is naturally divided into a hydrophobic waxy zone and a hydrophilic digestive zone, by sliding a compliant sphere parallel and perpendicular to the venation under dry contact, water lubrication, and oil lubrication. Both zones consistently exhibited a counterintuitive frictional anisotropy, with higher average friction during venation-parallel sliding than during venation-perpendicular sliding. The waxy and digestive zones encoded this anisotropy primarily through directional roughness and wettability, respectively, supporting a groove–wetting–hydrodynamic framework for direction-dependent liquid-film load sharing and interfacial shear.

Keywords : Nepenthes, texture–wettability coupling, direction-selective friction, counterintuitive friction anisotropy, ultralow-load tribology

1 Introduction

Directional transport and directional friction on biological interfaces often arise from a tight coupling among anisotropic texture, heterogeneous surface chemistry, and the resulting wetting state of interfacial liquids. [7, 27, 33] In such systems, orientation biases not only contact mechanics and shear pathways, but also liquid retention, drainage, and meniscus-mediated forces that collectively set frictional response. [5, 11, 42] These ideas have been widely leveraged in bioinspired surface science, where anisotropic or hybrid-wettability textures enable directional spreading, transport, and motion control [8, 16, 17, 21, 25, 39].

Nepenthes pitcher plants are an emblematic example: the peristome becomes extremely slippery when wet and can induce insect “aquaplaning”, enabling prey capture. [2, 3, 26] Later work demonstrated that the peristome supports continuous, directional water transport governed by multiscale ridges and capillarity, inspiring broad interest in Nepenthes-derived surface design and peristome-mimetic unidirectional liquid manipulation. [6, 7, 23, 28, 41, 42] Beyond geometry, the trap can integrate fluidic effects—such as lubrication-stabilized low-adhesion states and, in some species, viscoelastic pitcher fluids—that resonate with modern slippery-surface concepts and their broad technological translations (anti-fouling, anti-thrombosis, drag reduction, and robust omniphobicity) [9, 18, 19, 22, 24, 35, 38].

In contrast, the inner pitcher wall—the interface insects actually contact after entering the trap—remains comparatively underexplored in tribological terms, despite being strongly wetting-heterogeneous and typically consisting of a hydrophobic waxy zone and a hydrophilic digestive zone. [4, 13] The waxy zone is known to reduce insect attachment via epicuticular wax microstructures, and detachment/transfer of wax crystals can contaminate contact interfaces. [20, 31, 36, 37] This naturally connects to the third-body framework in tribology, where debris, transfer layers, and dynamically evolving interfacial “third bodies” mediate load sharing, shear localization, and dissipation beyond

ideal two-body contact. [14] In biological contacts, such third bodies may coexist with interfacial liquids and compliant deformation, leading to coupled solid–solid, solid–liquid, and debris-mediated interactions rather than a single idealized contact mode. Complementary studies have also quantified how inner-wall microstructure and anisotropy shape attachment and locomotion, suggesting that a friction-mechanics perspective is essential for completing the mechanistic picture[1, 40].

These biological observations can be conceptually connected to engineered contacts, in which friction anisotropy is routinely programmed by oriented grooves and surface texturing to tune lubricant entrainment, pressure build-up, and wear; laser surface texturing provides a scalable route to encode such directional effects. [12, 15, 29] In conventional engineered contacts, these behaviors are commonly interpreted using lubrication-regime concepts, including Stribeck-type transitions and Hersey-type scaling, which describe how viscosity, speed, and load alter the balance between direct contact and liquid-film support. [30, 34] In the present biological system, these concepts are invoked only as qualitative references for possible shifts among direct solid contact, liquid-film support, and third-body-mediated interactions, rather than as a direct regime-map classification. Recent work has further sharpened this perspective by explicitly relating lubricated friction to Hersey number in well-defined contacts. [10] Canonical wedge-bearing analyses—from wedge-shaped journal bearings to multiscale wedge-platform thrust bearing models—provide a useful analogy for how a converging liquid gap can generate load support and alter shear response; wedge-driven similarity scaling in confined-flow problems further underscores the general role of gap geometry in pressure–flow organization. [32] In the present study, however, this analogy is used only as a qualitative framework for possible liquid-film load support, rather than as a direct quantitative application of classical rigid-bearing theory, because the contact involves ultralow normal loads and compliant surfaces. Meanwhile, roughness-controlled wetting (Wenzel and Cassie-type states), metastability, and pinning determine whether liquids drain, remain trapped, or form composite contacts; wettability boundaries can even stabilize liquid configurations under perturbation.

Here we investigate directional friction on the natural wetting-heterogeneous inner wall of *Nepenthes* under ultralow loads, sliding parallel vs perpendicular to venation under dry contact, water lubrication, and oil lubrication. Building on repeated measurements rather than deterministic single-trace claims, we report a population-level trend: in both waxy and digestive zones, friction is higher parallel to venation than perpendicular on average, pointing to zone-specific structure–wetting–lubrication coupling mechanisms involving drainage, retention, third-body mediation, and lubrication-modified real contact.

2 Experimental

2.1 Materials

To ensure comparable sample freshness and hydration state across tests, fresh segments from the corresponding waxy or digestive zone of the inner wall of *Nepenthes* pitchers were excised for each experiment (10 mm × 5 mm). All samples were obtained from the same commercially available *Nepenthes* variety but from multiple individual plants and pitchers, with each plant typically providing only approximately three usable pitchers; because the plant–pitcher identity of each specimen was not systematically recorded, the $n=10$ values represent test-level replicates rather than independent plant-level biological replicates. Each segment was used for a single tribological test only. A commercially purchased solid silicone rubber (SR) ball with a diameter of 10 mm (Hanshuo, China) was used as the counterface. Before each test, the SR ball was cleaned with alcohol and deionized water, allowed to dry completely, and then mounted in the holder. Ultrapure water and a commercially available low-erucic-acid pure rapeseed oil (New Shine Oil and Grain, Chengdu, China), labeled as Grade II according to GB/T 1536, were used as lubricants. The rapeseed oil was stored in a sealed amber glass bottle in the laboratory before use.

2.2 Materials characterization

Surface morphology of the hydrophilic and hydrophobic zones was characterized by field-emission scanning electron microscopy (FESEM, Sigma 500). Surface chemical composition and bonding states were analyzed by X-ray photoelectron spectroscopy (XPS, Thermo Scientific ESCALAB 250Xi). A high-speed camera (Phantom VEO 610L, Phantom High Speed) was used to image the post-test surface appearance and to record the dynamic interfacial processes during frictional sliding. Three-dimensional surface topography of both zones was measured using a digital microscope (VHX-6000, Keyence, Japan). Static water contact angles of the waxy and digestive zones were measured using a contact-angle goniometer (Powereach, China).

2.3 Tribology experiments

Reciprocating sliding tests were performed using a UMT TriboLab tribometer (Bruker). Samples were mounted on a rigid substrate using an ultrathin double-sided tape (3M). The normal load was set to 1 N, with a stroke length of 5 mm and a reciprocating frequency of 4 Hz. Prior to testing, pitcher inner surfaces were rinsed with ultrapure water to remove surface contaminants. Samples were then cut along the boundary between the hydrophilic and hydrophobic zones, and residual surface water was gently removed using absorbent paper.

Test durations were determined based on preliminary trials. For the hydrophobic zone, dry sliding was conducted for 900 s; water-lubricated tests were performed by dispensing 5 μ L of ultrapure water onto the contact region for 3600 s; oil-lubricated tests were performed by dispensing 5 μ L of edible oil for 1800 s. For the hydrophilic zone, dry sliding was conducted for 1800 s; water-lubricated tests were performed with 5 μ L of ultrapure water for 5000 s; oil-lubricated tests were performed with 5 μ L of edible oil for 3600 s. For all water-lubricated tests, the 5 μ L water droplet was introduced only once immediately before sliding and was not replenished during the test. Under oil lubrication, prolonged testing reduced the adhesion of the mounting tape and could cause sample displacement and test failure; moreover, the friction traces under oil lubrication were smooth and

remained in a steady regime from the beginning of the test. Therefore, the duration of the oil-lubricated tests was not further extended.

All experiments were carried out at 20 °C and 30% relative humidity. For each condition, at least 10 independent repeats were performed for each sliding direction (parallel and perpendicular to venation).

2.4 Data analysis

All results are reported as mean $\pm$ s.d. For tribology, the coefficient of friction (COF) from each run was summarized by the mean value over the entire sliding trace, from the onset to the end of the test, yielding one independent value per run ($n = 10$ per direction for each lubrication condition).

Directional anisotropy was quantified using a normalized index $A = \frac{2(\mu_{\parallel} - \mu_{\perp})}{\mu_{\parallel} + \mu_{\perp}}$, where μ_p and μ_v

denote the group means measured parallel ($\parallel$) and perpendicular ($\perp$) to venation, respectively. For each zone (waxy and digestive), COF data (wherein, COF denotes the coefficient of friction) were analyzed using two-way ANOVA with factors “lubrication condition” (dry, hydration-film, oil) and “direction” ($\parallel$, $\perp$), followed by Tukey’s post hoc multiple-comparisons test. In addition, planned pairwise comparisons between directions within each condition were evaluated using two-sided Welch’s t-test, with Benjamini–Hochberg false discovery rate correction across the six directional comparisons; all remained significant ($p = 4.1 \times 10^{-4} - 2.62 \times 10^{-2}$; $A = 0.093 - 0.318$).

Contact-angle measurements ($n = 50$ per direction) and line roughness metrics (Ra and Rz; $n = 31-39$ per direction after excluding missing entries) were compared using two-sided Welch’s t-test, and the Mann–Whitney U test was used as a nonparametric sensitivity check when Shapiro–Wilk tests indicated deviation from normality. This analysis revealed significant contact-angle anisotropy in the digestive zone ($p = 6.1 \times 10^{-5}$; $A \approx 0.062$) but not in the waxy zone ($p = 0.959$), and significant roughness anisotropy in the waxy zone (Ra: $p = 0.00426$, $A \approx -0.227$; Rz: $p = 0.00180$, $A \approx -0.211$) but not in the digestive zone ($p \geq 0.235$). Statistical analyses were performed in Python 3.11.2 using SciPy 1.14.1 and statsmodels 0.14.3. Statistical significance was set at $p < 0.05$.

3 Results and discussion

3.1 Experimental design and control framework

Fig. 1 summarizes the experimental setup, the heterogeneous inner-wall microstructures, and the physical picture underlying directional friction. Fig. 1a illustrates the ultralow-load sliding configuration; normal and tangential signals were recorded by the built-in force sensors to quantify friction coefficients and their temporal evolution. More details about experiment methods can be found in Supporting Information-1. Fig. 1b shows an optical image of a *Nepenthes* pitcher and SEM characterizations of the hydrophobic waxy zone (HB) and the hydrophilic digestive zone (HL) on the inner wall. The HB region is covered by relatively uniform waxy microstructures, whereas the HL region exhibits pronounced vein-aligned microgrooves (Fig. S1), highlighting strong structural heterogeneity and directionality.

To rationalize the directional effect, Fig. 1c schematically compares sliding of a compliant silicone rubber sphere parallel versus perpendicular to venation. Perpendicular sliding more readily may facilitate lateral exudation and accumulation of cellular water into surface grooves, potentially producing a locally wet shear state with thin-liquid participation in the contact. In contrast, parallel sliding tends to drive exuded liquid toward the ends of the wear track. These possible differences in liquid redistribution are consistent with the statistically lower friction observed during venation-perpendicular sliding, but were not directly quantified in the present experiments. Video S1 in the ESM provides qualitative slow-motion visualization of the initial sliding process and the movement of interfacial liquid near the silicone rubber ball. However, discrete liquid droplets being expelled from the tissue were not directly resolved. The proposed release and redistribution of tissue water is therefore regarded as a qualitative interpretation, also supported indirectly by the compressed tissue observed in the post-test optical images.

Fig. 1d depicts the distinct wetting states of the two zones: the HB region can be approximated as a Cassie–Baxter-like composite wetting state, where the nano waxy layer and capillarity hinder full impregnation and maintain an air cushion, resulting in a large apparent contact angle θ_{CB} . The HL region is closer to a Wenzel-like state, where liquid imbibes into grooves and microstructures, enhancing liquid retention under the action of surface tension γ_{LV} . Fig. 1e further illustrates that, when a thin liquid layer is present during perpendicular sliding, shear-driven flow of a viscous liquid (viscosity η) through a position-dependent film thickness $h(x)$ may generate a Reynolds-type local pressure contribution $p(x)$, providing partial local load support and reducing friction. This hydrodynamic contribution is presented as a physically consistent framework, with its magnitude governed by film thickness, texture geometry, sliding speed, and liquid viscosity.

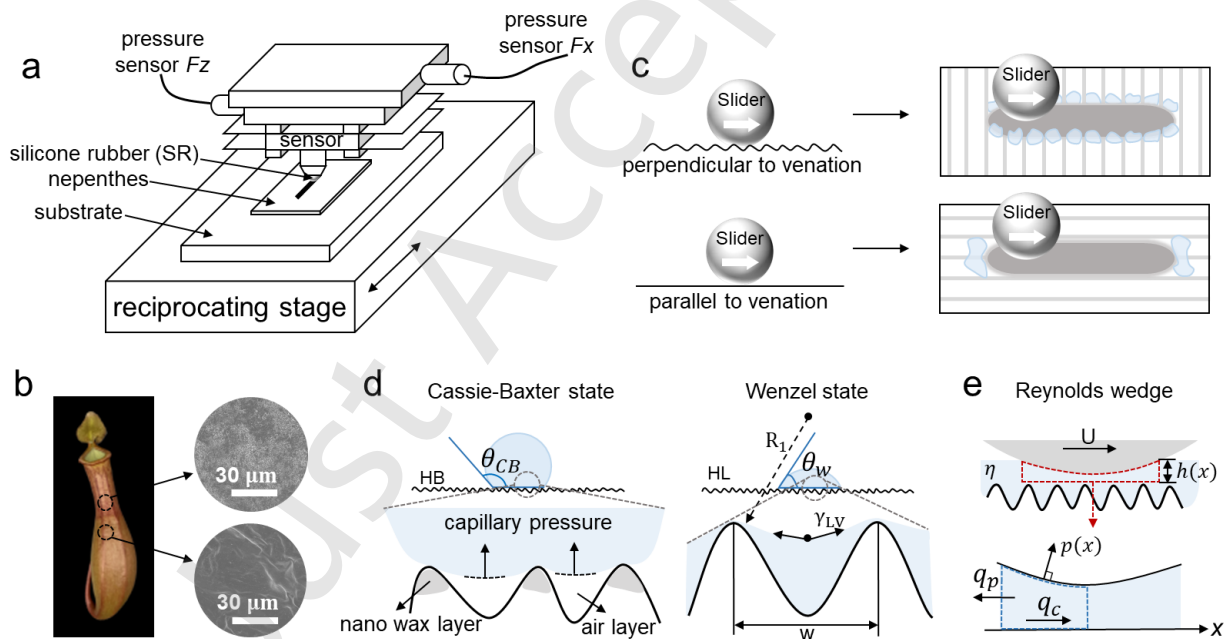


Fig. 1 (a) Schematic illustration of the experimental setup. (b) SEM images of hydrophilic and hydrophobic regions on the inner wall of a nepenthes pitcher. (c) Schematic of sliding directions relative to venation: perpendicular and parallel. (d) Schematic of static water wettability mechanisms: the Cassie–Baxter state on the hydrophobic zone and the Wenzel state on the hydrophilic zone. (e) Mechanistic schematic of Reynolds wedge–induced hydrodynamic pressure arising from relative sliding within a converging fluid film on the inner wall surface of a Nepenthes pitcher.

3.2 Post-wear morphological features and counterintuitive friction anisotropy

To investigate the anisotropic friction phenomenon at ultra-low loads on the inner walls of *Nepenthes* pitcher surfaces, this study conducted 10 friction experiments under different orientations and operating conditions, recording the data. Analysis of this phenomenon begins with surface topography. Fig. 2a presents representative high-resolution optical micrographs of the waxy and digestive zones after friction tests under dry contact, water lubrication, and oil lubrication in the venation-parallel and venation-perpendicular directions. These images visualize the friction tracks, localized surface damage, and the evolution of the contact regions.

Fig. 2b shows the three-dimensional profiles of the surface-dried, unfractionized fresh inner wall hydrophobic and hydrophilic zones. The hydrophobic zone exhibits a flatter overall surface, while the hydrophilic zone features prominent glandular protrusions and microstructural undulations. Consistent with the high-resolution optical micrograph in Fig. S2: the hydrophobic zone shows almost no glands or distinct protrusions, whereas the hydrophilic zone displays densely packed glandular elevations. This structural disparity inherently differentiates the two zones in terms of actual contact area, micro-scale liquid storage capacity, and interfacial shear mechanisms, providing a “structural foundation” for subsequent operational differences. Figures 2c–e and 2f–h show the COF–time curves for the hydrophobic and hydrophilic regions, respectively, under dry sliding, pure-water lubrication, and oil lubrication. Overall, consistent directional trends emerge regardless of region type or lubrication state—whether dry contact, hydrated film lubrication, or oil lubrication: throughout most friction duration, the coefficient of friction tends to be higher in the direction parallel to the grain orientation than in the direction perpendicular to it. This result constitutes the core “counterintuitive” phenomenon of the study. Under the common intuition of groove/texture lubrication, sliding along the texture direction is often considered more conducive to forming a continuous liquid film and reducing friction. However, the statistical trend here indicates that the

direction perpendicular to the texture is more likely to reduce friction. The pronounced COF fluctuations under dry sliding in Figs. 2c and 2f suggest continuous evolution of the compliant contact rather than a single steady friction state. Although intermittent interfacial pinning and release may contribute, the irregular traces alone are insufficient to confirm classical stick–slip behavior. In the waxy zone, detachment and redistribution of epicuticular wax may generate transient third bodies that alter the real contact area and interfacial shear resistance. In the digestive zone, where a comparable wax layer is absent, the fluctuations are more likely associated with local deformation of the glandular topography and changes in the real contact area. The post-test morphologies in Figs. S4 and S5 provide further context for the COF evolution. Under dry and pure-water conditions, the flattened venation traces indicate progressive compression of the plant tissue, which may alter the real contact area and promote local water release or redistribution during sliding. Such interfacial evolution is consistent with the fluctuations and abrupt decreases observed in several COF curves in Figs. 2c, 2d, 2f, and 2g, reflecting a possible transition from the initial running-in state to a relatively moist, lower-shear contact. In contrast, the oil-lubricated surfaces show much less pronounced friction tracks, consistent with the low and comparatively stable COF values in Figs. 2e and 2h and suggesting that the oil film reduced direct contact and local tissue deformation. To validate the authenticity of this directional discrepancy and elucidate its origin, we further investigated the interplay between wettability anisotropy and topographical roughness anisotropy. This approach, combined with XPS chemical evidence, established a comprehensive explanatory framework (Fig. 3).

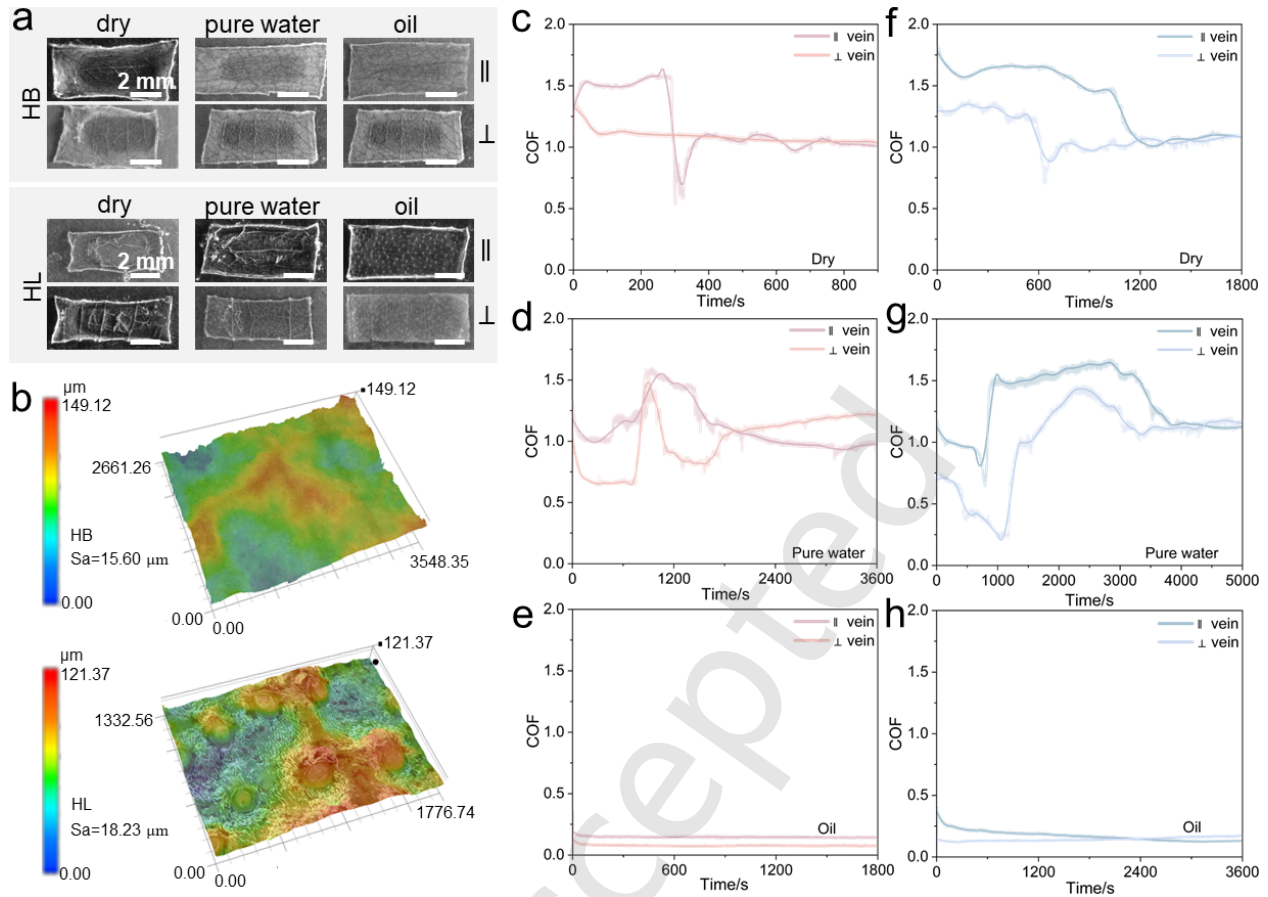


Fig. 2. (a) Optical images of the wear tracks on the hydrophobic (HB) and hydrophilic (HL) regions after sliding parallel and perpendicular to the venation under dry, pure-water-lubricated, and oil-lubricated conditions. (b) Three-dimensional surface topographies of representative wear tracks on the HB and HL regions. (c–e) COF curves of the HB region under (c) dry sliding, (d) pure-water lubrication, and (e) oil lubrication. (f–h) COF curves of the HL region under (f) dry sliding, (g) pure-water lubrication, and (h) oil lubrication, comparing sliding parallel and perpendicular to the venation.

3.3 Quantification and statistical validation of friction anisotropy

Figure 3a schematically illustrates static water contact-angle measurements on the hydrophilic zone when the droplet is viewed along a line of sight parallel or perpendicular to the venation. Extensive measurements and statistical analysis show that the apparent contact angle observed from the parallel viewing direction is typically larger than that observed from the perpendicular direction. The normal-distribution plots in Fig. 3d further confirm that, in the hydrophilic zone, the mean contact angle in

the parallel direction is markedly higher than that in the perpendicular direction, indicating pronounced wettability anisotropy. In contrast, the hydrophobic zone exhibits a much weaker dependence of contact angle on viewing direction, approaching an overall direction-insensitive distribution. Statistical analysis confirmed a significant directional difference in the digestive zone, whereas no significant contact-angle anisotropy was detected in the waxy zone ($p=0.959$). More details about contact angle data can be found in Supporting Information-Table S3.

This phenomenon points to direction-dependent contact line pinning and microscale liquid transport behavior on the hydrophilic region surface: oriented microstructures and chemical inhomogeneities may result in differing energy barriers and pinning strengths for the three-phase line in different directions, causing the apparent contact angle to vary with the observation direction. Wetting anisotropy provides crucial clues for friction anisotropy, as the wetting state may provide a directional wetting bias that influences whether the interface is more likely to form a continuous film or maintain solid-liquid composite contact during shear.

In the Wenzel state (Fig. 1d), the roughness factor r amplifies the substrate's intrinsic wettability, allowing liquids to more readily infiltrate and spread within the microstructures, thereby promoting the formation of a continuous thin liquid/hydration film. In contrast, in the Cassie–Baxter state, the liquid is supported by asperity tops with trapped air beneath, reducing the effective solid–liquid contact area fraction (f_s) and promoting intermittent contact during sliding; this alters lubricant supply and load-bearing pathways and may contribute to friction anisotropy. More details about the principles of the Wenzel and Cassie–Baxter wetting models can be found in Section 2 of the Supporting Information. The detailed contact angle data are provided in Table S3 of the Supporting Information.

Figures 3b–c show the normal-distribution plots of line roughness for the hydrophobic and hydrophilic zones measured along directions parallel and perpendicular to the venation. The hydrophobic zone exhibits a clear roughness anisotropy, with the perpendicular direction typically

showing higher line roughness than the parallel direction, whereas the hydrophilic zone shows no significant directional difference. These results suggest that the directionality in the hydrophobic zone arises from surface geometric textures that modulate the real contact area and micro-asperity interlocking, while the hydrophilic zone—despite weak roughness anisotropy—displays pronounced wettability anisotropy, implying that its directional effects are more closely related to liquid transport and contact-line pinning induced by oriented microstructures. The directional roughness data are provided in Tables S4 and S5 in the ESM. In the waxy zone, both R_a and R_z showed significant directional differences ($p=0.00426$ and $p=0.00180$, respectively), whereas no significant directional difference was detected in the digestive zone.

The XPS survey spectra in Fig. 3g show a higher O atomic fraction in the hydrophilic zone than in the hydrophobic zone, while the hydrophobic zone exhibits a higher C fraction than the hydrophilic zone, indicating higher surface polarity and stronger hydration capability in the hydrophilic region. Consistently, the high-resolution N 1s spectra in Fig. S3 show a markedly stronger N 1s signal in the hydrophilic zone than in the hydrophobic zone, further confirming the difference in surface chemical composition between the two regions. The high-resolution O 1s spectrum in Fig. 3h and C 1s spectrum in Fig. 3i further reveal differences in functional-group composition: the hydrophilic zone displays stronger signals from oxygen-containing moieties associated with hydrogen-bond networks and hydration layers, whereas the hydrophobic zone is enriched in wax-like carbon frameworks and other low-polarity components. These chemical differences not only affect the static contact angle but also directly govern, under shear, the formation of boundary adsorption layers and hydration films as well as the interfacial adhesive shear strength, thereby acting together with wetting state and microstructure to control the frictional response.

Figs. 3e–f summarize the COF results for the waxy and digestive zones during venation-parallel and venation-perpendicular sliding under the three test conditions. Each point represents the mean COF obtained from one complete friction test, as calculated by the UMT software, with 10 test-level mean

values shown for each sliding direction. The statistics agree with the trends of the COF–time curves in Fig. 2, indicating that the directional differences are reproducible rather than incidental fluctuations. Overall, the observed directional friction can be viewed as a coupled outcome of wetting state, surface geometry, and chemical composition. For each lubrication condition, 10 independent COF values were obtained for each sliding direction. The individual values are provided in Tables S1 and S2 in the ESM for the waxy and digestive zones, respectively, and all six zone–lubrication combinations exhibited a higher mean COF during venation-parallel sliding.

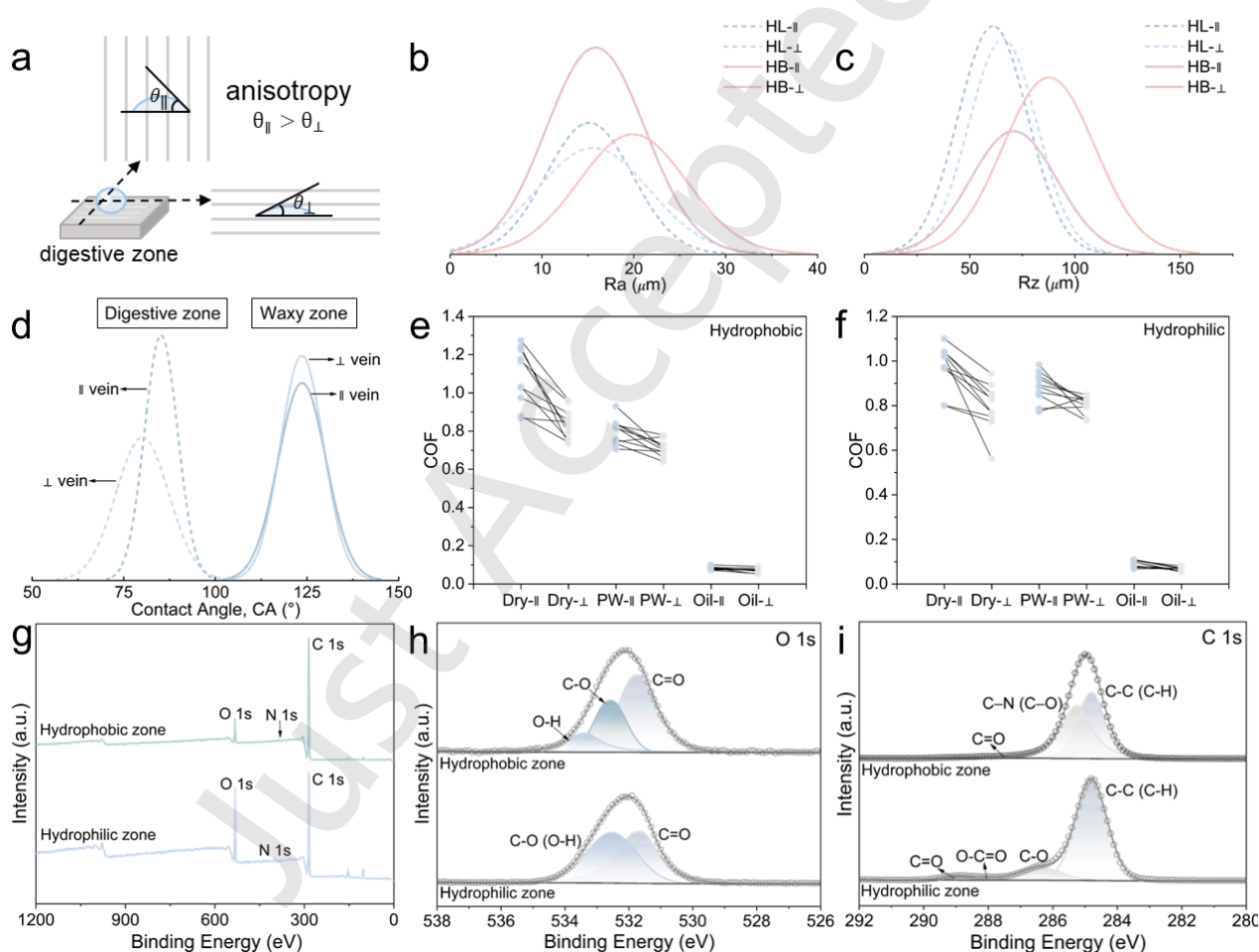


Fig. 3 (a) Schematic of static water contact-angle measurements viewed perpendicular and parallel to venation in the hydrophilic region. (b-c) Quantitative comparisons of surface roughness for the hydrophilic and hydrophobic regions measured along the directions parallel and perpendicular to venation, highlighting the roughness anisotropy of the two surfaces. (d) Mapping of venation-guided wettability anisotropy highlights the contrasting wetting behaviors of the digestive and waxy zones. (e-f) Direction-dependent COF on the hydrophilic and hydrophobic

regions under dry sliding, hydration-layer lubrication, and oil lubrication. (g) XPS full spectrum. (h) High-resolution O 1s XPS spectra. (i) High-resolution C 1s XPS spectra.

3.4 Directional lubrication mechanisms interpreted via Reynolds-type hydrodynamic effects

Fig. 4 illustrates the friction mechanisms under three lubrication conditions, with the sliding direction defined as the positive x-axis. The normal load is denoted as W , and the tangential friction force as F_t . Here, F_t represents the total tangential force measured by the force sensor. Under lubricated conditions, it may include contributions from both viscous shear and asperity contact, which were not quantitatively separated in the present study. The fundamental differences among the three conditions lie in whether a load-bearing thin fluid film can form at the interface, and whether the film thickness $h(x)$ exhibits a gradient in the sliding direction, thereby inducing dynamic pressure $p(x)$.

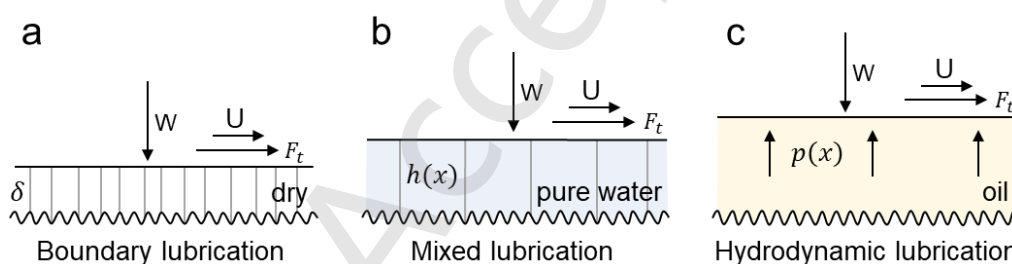


Fig. 4 (a) Schematic of the boundary-lubrication regime under dry friction. (b) Schematic of the mixed-lubrication regime under water lubrication. (c) Schematic of the hydrodynamic-lubrication regime under oil lubrication.

As shown in Fig. 4a, under dry conditions, the load is primarily borne by the actual solid contact points, with friction originating from adhesive shear, microscopic plowing, and potential material transfer. The directional variation can be explained by the combined effects of two factors: First, the anisotropic roughness of the hydrophobic region alters the actual contact area and the engagement pattern with micro-asperities, leading to directional variations in shear resistance. Second, glands and microstructures in hydrophilic regions may induce differences in the exudation, retention, and drainage pathways of cellular fluid moisture. This alters the probability of interfacial adhesion strength and quasi-boundary layer formation in different directions, thereby influencing the COF.

Under hydrated film conditions (Fig. 4b), a water film of thickness $h(x)$ exists at the interface. In this scenario, friction arises from both fluid shear and localized solid contact shear. The wetting state becomes the decisive boundary condition: Hydrophilic regions, supported by oxygen-containing groups and hydration, more readily form stable hydration layers/thin water films, tending toward Wenzel wetting or strong hydration states. Hydrophobic regions, conversely, are more likely to exhibit solid–liquid composite contact or discontinuous films. Concurrently, the orientation of microstructures alters water film replenishment and drainage behavior, causing the spatial distribution of $h(x)$ to vary directionally. This manifests macroscopically as directional dependence of the COF.

Under oil-lubricated conditions (Fig. 4c), a continuous or partially continuous oil layer may reduce direct solid contact. If a converging film geometry develops, Reynolds-type hydrodynamic pressure may contribute to load support. Under idealized one-dimensional, steady-state, incompressible, and isoviscous conditions, this possible relationship can be described qualitatively by the Reynolds equation. The Reynolds equation can be written as:

$$\frac{d}{dx} \left(\frac{h^3}{\eta} \frac{dp}{dx} \right) = 6U \frac{dh}{dx}$$

Where η is the dynamic viscosity of the lubricant, U is the relative sliding velocity, $h(x)$ is the film thickness, and $p(x)$ is the dynamic pressure. The batch-specific oil viscosity and the validity of the isoviscous assumption were not experimentally determined; therefore, no quantitative calculation of film thickness or hydrodynamic pressure was performed.

To emphasize the physical significance of pressure flow and drag flow, the volumetric flow rate per unit width can be decomposed as:

$$q = q_p + q_c = -\frac{h^3}{12\eta} \frac{dp}{dx} + \frac{Uh}{2}$$

Where $q_p = -\frac{h^3}{12\eta} \frac{dp}{dx}$ denotes pressure gradient-driven Poiseuille flow (q_p , Fig. 1e), and represents drag flow generated by surface motion (Couette flow, q_c , Fig. 1e). Within this qualitative framework,

the film thickness and its gradient may influence pressure generation, lubricant flow, and the fraction of direct solid contact. Direction-dependent surface structures and wetting conditions may affect lubricant retention, drainage, and replenishment, thereby contributing to the observed COF differences. However, these interfacial quantities were not directly measured in the present study.

The higher surface polarity and oxygen-containing groups in hydrophilic regions enhance hydration and wetting (Fig. 3g–i), facilitating the formation of continuous water films and stable boundary adsorption layers. Hydrophobic regions exhibit composite contact and discontinuous films, showing strong sensitivity to film stability and contact-line pinning. The wetting state therefore serves as the initial condition for film formation and rupture under varying operating conditions.

Although the hydrophilic region exhibits minimal variation in line-roughness orientation, glandular protrusions and oriented microstructures introduce direction-dependent liquid retention/supply and contact-line pinning. In contrast, the anisotropic line roughness of the hydrophobic region directly alters the real contact geometry and promotes local film rupture. This directionality therefore translates into directional film parameters, specifically the directional dependence of $h(x)$ and its gradient.

In mixed and hydrodynamic lubrication, film thickness and its gradient determine the pressure distribution and flow allocation (i.e., Poiseuille flow and Couette flow), thereby controlling the fraction of direct solid contact and the pathways of interfacial shear dissipation. Consequently, friction reduction depends on whether the contact zone continuously replenishes and maintains film thickness. Perpendicular orientation enables cross-grain replenishment, suppresses local cavitation, and sustains stable film load-bearing; accordingly, an overall trend emerges in which the perpendicular orientation yields lower friction.

4 Conclusion

In this work, we show that the *Nepenthes* pitcher inner wall is not simply a juxtaposition of hydrophilic and hydrophobic materials, but a directional, liquid-rich interface in which orientation

modulates fluid management and frictional response. Across multiple specimens and repeated trials, we observe a robust and counterintuitive anisotropy under ultralow normal loads: venation-parallel sliding yields higher friction on average than venation-perpendicular sliding under dry contact, water lubrication, and oil lubrication. These results suggest that direction may contribute contact-line pinning and wetting state, thereby reshaping the lubricant film thickness and its gradient, which in turn may influence hydrodynamic pressure generation and load sharing through a coupled groove-wetting-Reynolds mechanism. Importantly, the two zones encode directionality through distinct cues—roughness anisotropy in the waxy zone and contact-angle anisotropy in the digestive zone—yet converge to the same frictional outcome, highlighting how topography and surface energy can be co-optimized to regulate liquid replenishment, film stability, and shear-dissipation pathways on a compliant substrate.

This coupled design principle could be exploited to create directionally lubricated soft surfaces by co-optimizing groove orientation, wettability, and compliance. Potential opportunities include flow-guiding and antifouling coatings in confined liquid handling, surfaces that stabilize or redistribute thin water films for moisture management and directional transport, and controllable-friction skins for soft gripping in wet environments. At the same time, the present study primarily addresses physical coupling between structure, wetting, and film formation. Chemical contributions, including tribochemical reactions, interfacial chemistry evolution, and possible reaction-layer formation under repeated sliding, are not systematically resolved here and may further modulate shear strength. Future work combining time-resolved surface analysis with controlled lubricant chemistry will be valuable for further quantifying the interplay between interfacial chemistry and directional lubrication.

Credit author statement

On behalf of all authors, I certified that this paper consists of original, unpublished work which is not under consideration for publication elsewhere, in whole or in part.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Electronic Supplementary Material

Supplementary material containing additional surface characterization, statistical results, and representative high-speed recordings of the directional sliding processes (Video S1) is available in the online version of this article.

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