

Supplementary materials

February 2, 2026

S1 Pipette's tip area measurement

In patch-clamp-based measurements, the electrical resistance of the micropipette (R_p) provides a practical estimate of the tip surface area (A_{tip}). Since the resistance is inversely related to the cross-sectional area at the tip [1–3], this relationship can be exploited for calibration.

To determine A_{tip} in each experiment, we measured R_p using a pair of electrodes—one inside the pipette and one in the bath—connected to a patch-clamp amplifier (RK300, Bio-Logic Company, Grenoble, France). An empirical calibration was established by imaging pipette tips of known resistance using a scanning electron microscope (ZEISS Ultra55). A least-squares regression on the log-transformed data yielded:

$$\ln A_{\text{tip}} = -1.3 \ln R_p + 2.1 \quad \Rightarrow \quad A_{\text{tip}} = \frac{8.16}{R_p^{1.3}}$$

where A_{tip} is in μm^2 and R_p in $\text{M}\Omega$. This relation was used to estimate tip areas throughout the study.

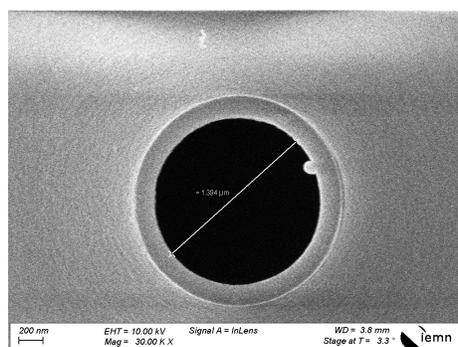


Figure S1-1. Example SEM image of a micropipette tip used in the resistance-based calibration.

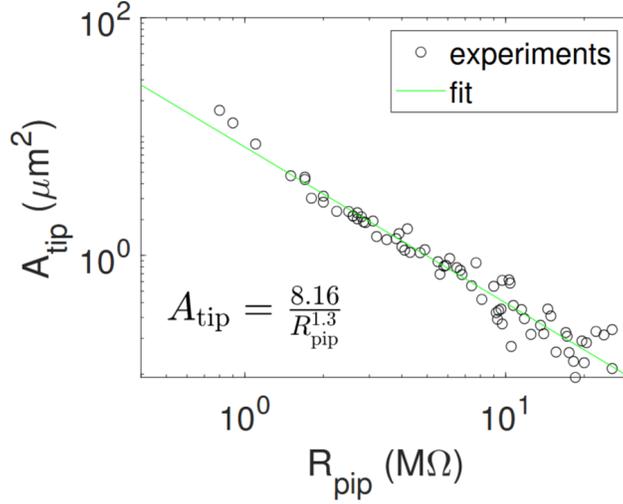


Figure S1-2. Calibration curve relating pipette resistance R_p and tip surface area A_{tip} (adapted from [4]).

S2 Detachment force calculation from depression

The calculation of the detachment force is based on the principle that force equals pressure multiplied by the surface area over which it acts. In our setup, the applied suction through the micro-pipette generates a force vector aligned with the pipette's axis as it moves *away from the particle* at an angle of 45° relative to the substrate.

Since we are interested in the force component *perpendicular to the substrate*—which is responsible for lifting and detaching the particle—we compute only the *vertical component* of the applied suction force.

The detachment force is therefore calculated using the formula:

$$F_d = 10^{-1} \cdot \Delta p \cdot A_{\text{tip}} \cdot \sin(\alpha)$$

where:

- Δp is the applied pressure difference (in millibar),
- A_{tip} is the cross-sectional area of the pipette tip (in μm^2),
- $\alpha = 45^\circ$ is the angle between the pipette axis and the substrate,
- 10^{-1} is a unit conversion factor to express the result in nanonewtons (nN).

Using $\sin(45^\circ) = \frac{\sqrt{2}}{2} \approx 0.707$, the formula simplifies to:

$$F_d = 0.071 \cdot \Delta p \cdot A_{\text{tip}}$$

This expression provides the effective vertical force responsible for particle detachment, taking into account the geometry of the pipette’s movement during aspiration.

S3 Supplementary Video — Microparticle Detachment Test

This video illustrates an experimental measurement of the detachment force for a microparticle. The particle was previously dried at a temperature of 80°C and a relative humidity of 80% for 24 hours.

An isolated microparticle is selected, and a micro-pipette is carefully positioned near its surface. The electrical resistance measured at the pipette tip is 17.9 MΩ, corresponding to a tip surface area of 0.19 μm².

In the first trial, a pressure drop of 34 mbar (corresponding to a detachment force of 0.46 nN) is applied, but the particle remains attached to the substrate when the pipette is withdrawn. In the second attempt, the applied pressure is increased to 42 mbar (0.57 nN), and the pipette is again brought into contact with the particle. This time, the particle detaches and adheres to the pipette tip, confirming successful detachment without being aspirated into the pipette.

It is worth noting that the approach of the micropipette tip often induces a slight vibration or tilting of the particle. This artifact, which is inherent to the technique and consistently present across all measurements, is assumed not to affect the comparative trends analyzed in this study, which focus on relative differences across drying conditions. While we cannot entirely exclude its impact on individual detachment events, we consider it negligible—especially in light of the absence of alternative methods to quantify detachment force at this scale.

S4 Logistic function variables

Throughout each experiment conducted under strictly controlled drying conditions, a total of 22 particles were systematically dislodged from the substrate. The force required to detach each particle was meticulously recorded and subsequently arranged in ascending order. Consequently, each particle’s detachment-achieved by applying its corresponding force value-represents a probabilistic occurrence within the overall detachment process.

This dataset is visually represented in Figures 4-7 of the study, where the results were fitted to a logistic regression model using the coefficient of determination (R^2) as the fitting criterion. The fitting procedure was executed via a custom-developed Python algorithm, with the constraint that the R^2 value must not fall below 0.95 to ensure a robust fit. Through this analysis, the key parameters of the logistic function-specifically, the coefficients b and c , were derived. The subsequent table summarize these parameters for each distinct drying condition:

Table S1. Logistic function variables for each experience mentioning the drying condition. The last column indicates the Figure number in which the mentioned drying condition is found.

T [°C]	H [%]	Δt [h]	b	c	Fig. No.
35	20	24	12.67	-9.59	4(a), 5(a), 6, 7
		48	16.28	-7.10	4(a), 5(a)
		72	19.27	-6.68	4(a), 5(a)
	40	24	14.09	-0.89	6
	60	24	33.11	-2.73	6
	80	24	1.79	-0.63	4(a), 5(b), 6
		48	31.27	-74.95	4(a), 5(b)
		72	18.57	-11.48	4(a), 5(b)
	50		24	5.52	-40.22
57.5	20	24	4.95	-22.75	7
65		24	3.87	-5.11	7
80	20	24	3.19	-110.1	4(b), 5(a), 7
		48	2.20	-8.02	4(b), 5(a)
		72	3.66	-145.6	4(b), 5(a)
	80	24	6.85	-192.7	4(b), 5(b)
		48	6.60	-7.97	4(b), 5(b)
		72	12.48	-7.59	4(b), 5(b)

References

- [1] Bert Sakmann. *Single-channel recording*. Springer Science & Business Media, 2013.
- [2] Peter H Barry and Joseph W Lynch. Liquid junction potentials and small cell effects in patch-clamp analysis. *The Journal of membrane biology*, 121(2):101–117, 1991.
- [3] Elisabetta Tognoni, Paolo Baschieri, Cesare Ascoli, Monica Pellegrini, and Mario Pellegrino. Characterization of tip size and geometry of the pipettes used in scanning ion conductance microscopy. *Micron*, 83:11–18, 2016.
- [4] Anna Ipatova. *Detachment of immersed microparticles and the collective dynamics of microspheres in evaporating droplets*. PhD thesis, Université de Lille, 2023.