"Drop-printing" enables stress-free conformal wrapping of bioelectronic interfaces

Jieke Jiang[1,*] and Claas Willem Visser[1,*]

[1]Fluid Mechanics for Functional Materials group, Department of Thermal and Fluid Engineering, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

*Correspondence: j.jiang-1@utwente.nl (J.J.); c.visser@utwente.nl (C.V.)

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Conformally wrapping thin-film bioelectronic interfaces over soft, 3-dimensional (3D) biological surfaces remains a significant challenge due to the fundamental conflict between the need for non-stretchable, high-performance materials (such as crystalline silicon and metal) and the complex, curved geometries of soft biological tissues (such as nerves and brain surface). Although there are many advanced technologies that enable the fabrication of bioelectronics onto thin films, so far, the predominant method for transferring these films is still largely limited to mechanically pressing them onto the target surface.[1] In conventional pressing-based methods, a force generated by a stamp is applied to the thin film to secure contact between the bioelectronics and the cells on the tissue surface. However, this pressing inevitably stretches the film, leading to accumulated stress that easily exceeds the fracture strain of the material and thereby damages the integrated bioelectronics (Figure 1A). Therefore, damage-free wrapping of fragile and non-stretchable films onto 3D (soft) objects of arbitrary shapes remains a bottleneck that impedes the broader application of next-genera-

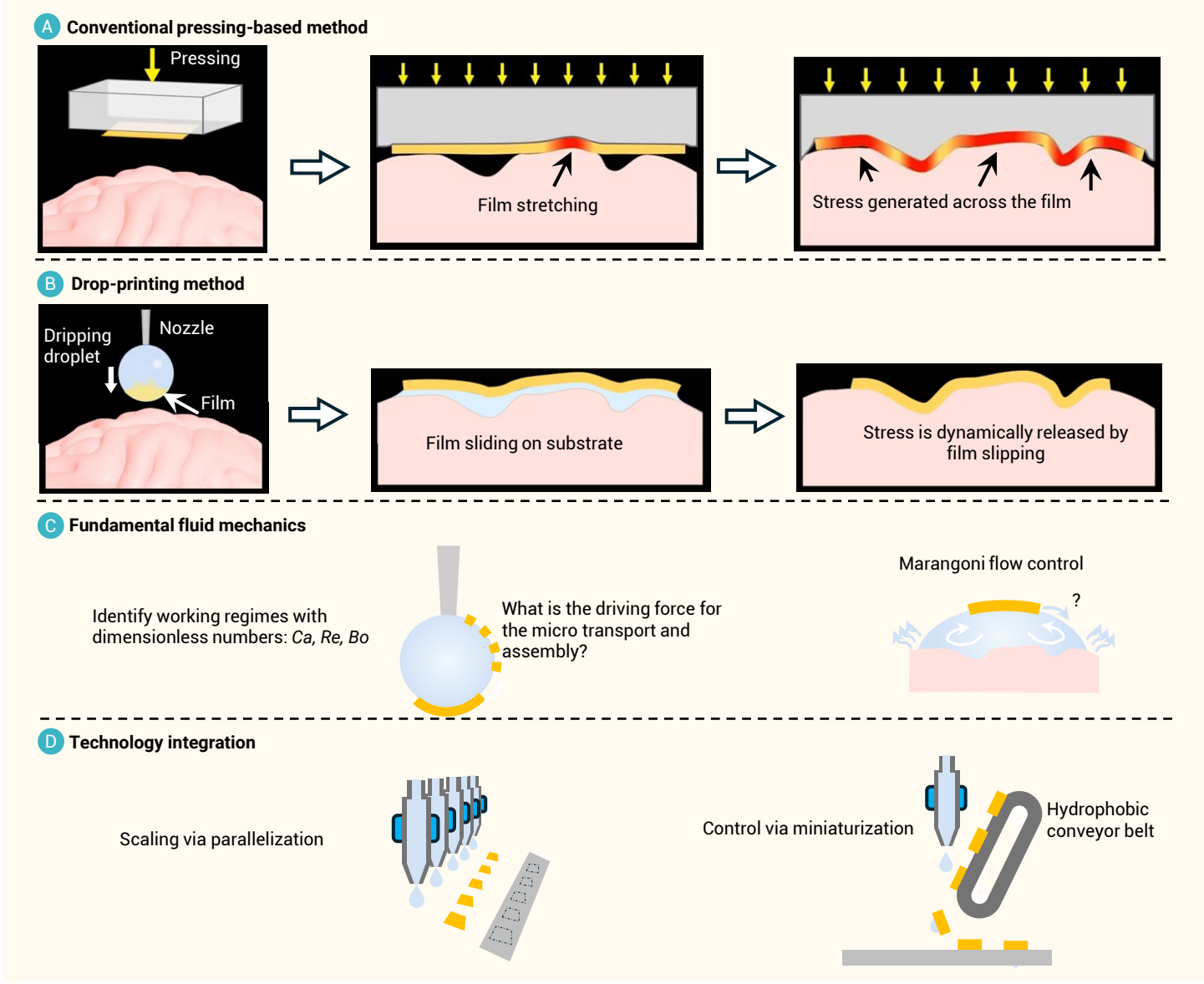

Figure 1. Drop-printing for stress-free wrapping of bioelectronic interfaces (A) In the conventional pressing-based method, a mechanical force is applied to the thin film, often resulting in uneven stress and potential damage to the delicate bioelectronic interface. (B) In contrast, the drop-printing approach enables stress-free wrapping of thin-film bioelectronics onto soft, complex surfaces through the controlled dewetting of a liquid droplet. (C) Research directions in fluid mechanics to uncover the driving force for the microscale transport phenomenon on the surface of droplet. (D) Technology integration of the drop printing method. Scaling up can be achieved by parallelization, while improved controllability by miniaturization. (A) and (B) are adopted from reference.[2]

tion, high-performance but brittle sensors and electronics.

Writing in Science, Li et al.[2] report a "drop-printing" strategy that enables transfer of bioelectronics without applying mechanical pressure. As shown in Figure 1B, a hanging droplet is used to pick up and transfer ultrathin films. The film moves to the top of the droplet, presumably driven by capillary forces. Therefore, when deposited onto a soft surface, the droplet serves as a temporary lubricating layer between the electronic film and the target surface, allowing the stress generated during film deformation to be dynamically released through localized sliding and thereby preventing rupture of the film. This mechanism is inspired by the stress-release process found in the skin's stratum corneum, which similarly dissipates stress through interlayer sliding. The resulting milli-Newton-scale forces applied to the substrate during transfer are three orders of magnitude smaller than for conventional methods. As a proof of concept, this gentle approach was demonstrated for extremely fragile films, such as millimeter-scale, 150-nm-thick gold patterns that were wrapped onto complex-shaped surfaces. "Drop-printing" also enables the conformal wrapping of non-stretchable thin electronic films onto optical fibers, planar surfaces, and even microorganisms or living tissues *in-vivo*. For example, the authors applied the method to create high-performance neural-electronic interfaces by wrapping fragile silicon heterojunction films onto the surfaces of a mouse sciatic nerve and a rat brain. Using these interfaces, infrared light was able to induce periodic limb movements in the animals, demonstrating high spatiotemporal resolution and sustained, repeatable neural activity. A related example highlights the potential for tissue engineering *via* transfer of cell-laden films onto tissues, where the interaction between the film and substrate can be tuned by adjusting the chemical composition of the droplet. In future studies, organ-on-chip technology could be considered as a screening method to reduce animal use, streamline ethical and practical aspects of the research, and expand application of artificial tissues towards new enabling solutions in health care.

Expanding the proposed drop-printing method towards even more precisely controlled deposition and scalable manufacture would go hand in hand with answering scientific questions that bridge fluid mechanics and the physics and chemistry of soft matter. For example, successful deposition requires that transporting the film over the surface of the (micro)droplet happens before the droplet reaches the substrate (Figure 1C). The driving mechanisms governing the transport of particles or films over asymmetric liquid surfaces have recently received ample attention, for example in research on the "Cheerios effect" (a capillary interaction in which particle-induced surface curvature leads to attractive forces and motion along the interface). In the present system, the driving force may be the asymmetry of the droplet that exerts an asymmetric line tension over the edge of the film, pulling the film towards the apex of the droplet. Gravity and viscosity are expected to resist this motion. Therefore, as a first step, the velocity of the moving film could be measured as a function of the Bond number (*Bo*, a dimensionless parameter describing the relative importance of gravitational forces over capillary forces) and the Ohnesorge number (*Oh*, comparing viscous forces to inertial and surface tension forces). One would expect "free" inertia-limited flow for $Bo \lesssim 1$ and $Oh \gtrsim 1$, which could be evaluated using basic high-speed imaging. Such basic quantification would already allow a practical method to control this crucial step of the system. However, we would like to stress that more subtle mechanisms might dominate the dynamics, such as Marangoni flows induced by evaporation-driven gradients in surface tension, complex geometrical interactions between the compliant film and the droplet surface, and the shape and chemistry of the film edge. Therefore, explaining nontrivial measurements may benefit from connecting these to existing models on these topics to understand the dynamics of the solid film over the droplet surface, and thereby provide a foundation for predictive engineering of the system. Post-impact, the authors have already shown the importance of the droplet size and contact angle in controlling the final deposition location of the film. It is well-known that the properties of micro-objects placed on the surface of a sessile droplet may affect the flow, and even whether they deposit as a coffee-ring or as a homogeneous film.[3] Therefore, to drive the film either to the center or the contact line of the sessile droplet, control over the film orientation and electrode placement would greatly benefit from a better understanding of the underlying mechanisms.

New manufacturing strategies may be needed to scale the proposed "drop printing" method. We see three challenges of particular interest, related to the stages of the process. First, the "pick-up" of the film should be controlled. Here, a lithography- or surface-based method could control the precise pick-up position of multiple films, enabling their pick-up by multiple droplets gently impacting at specific locations when multiple nozzles run in parallel (Figure 1D). Subsequently, the pendant droplet hanging onto the moving needle may detach by gravity, especially for larger droplets for which the acceleration-induced forces exceed the surface tension binding the drop to the nozzle. One solution would be to only use small droplets, for which surface tension is dominant and the droplet is stably connected to the nozzle tip. Alternatively, droplets could be coated by mechanically depositing one or more thin films onto their surface after ejection but before impact. For example, a conveyor belt loaded with dry film, moving with a velocity that matches that of the fast-moving droplet could provide a practical solution to achieve this (Figure 1D). Although perhaps at the expense of some control, such on-the-fly coating of droplets with a dry film would represent an exciting new method to address outstanding challenges for solvent-free coating or wrapping small droplets with thin films. This would constitute a variety of "In-Air Microfluidics",[4] a strategy to manipulate fluids (such as droplets or bubbles) prior to impact on a surface. The surface energy of the belt and the impact angle of the droplet must ensure that the droplet bounces off the belt and lands on the desired surface. Finally, after deposition of the droplet, the motion of the film over the surface may change when depositing multiple droplets. For example, it is known that the evaporation of sessile droplets strongly depends on the presence or absence of adjacent droplets that affect the local humidity. A detailed understanding of the mechanical properties of the film may also be important to understand its conformability to the surface, its sensitivity to tearing, and the fashion by which the film changes the liquid interface.

In conclusion, the proposed drop-printing technique effectively resolves the long-standing trade-off between device fragility and conformal integration in the transfer and wrapping of bioelectronics. It opens new opportunities for constructing a new generation of high-fidelity, mechanically gentle bioelectronic devices, including advanced health monitors, neural prosthetics, and precise in vivo therapeutic tools. We believe that the method could further benefit from integration with advanced microdroplet technologies, such as inkjet printing, on which the authors are experts.[5] This integration would provide new means to achieve greater controllability in assembling microscale objects and enable deeper insight into microscale transport phenomena.

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DECLARATION OF INTERESTS

The authors declare no competing interests.