Stick&Slip: Altering Fingerpad Friction via Liquid Coatings

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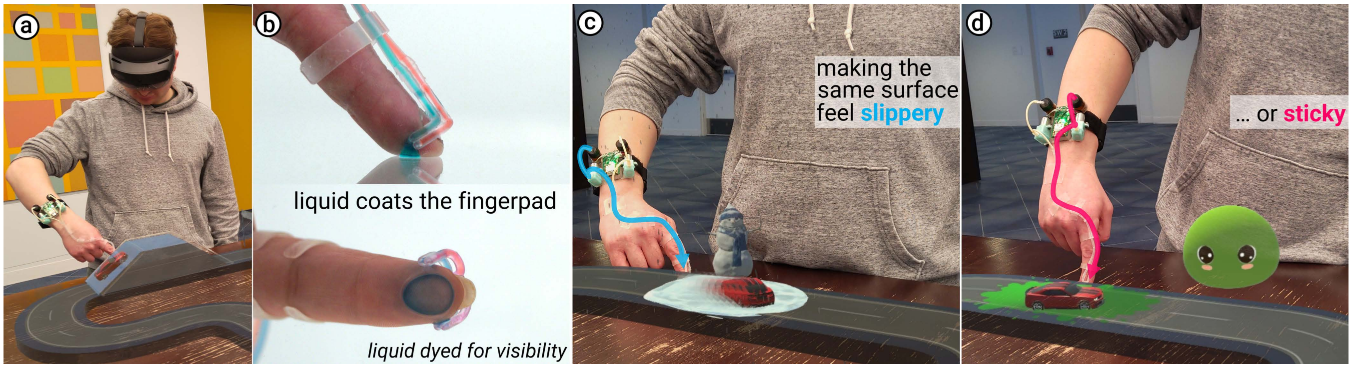

Figure 1: We propose Stick&Slip, an approach to friction modulation that works by coating the user's fingerpads in sticky or slippery liquids, making it possible to alter the friction of nearly any non-absorbent surface, regardless of its geometry. (a) A user plays a racing game in mixed reality, driving the virtual car over real-world surfaces, such as a table and a small ramp. (b) To alter the friction of the user's finger movements on real surfaces, our device deposits liquid droplets onto the user's fingerpad, forming an interfacial layer between the two, which allows us to modulate surface friction corresponding to the virtual events, such as (c) the ice feels slippery to the user's touch, and (d) the green-goo left by the opponent feels sticky while driving the car on the surface.

ABSTRACT

We present Stick&Slip, a novel approach that alters friction between the fingerpad & surfaces by depositing liquid droplets that coat the fingerpad. The liquid coating modifies the finger's coefficient of friction, allowing users to feel surfaces up to ±60% more slippery or sticky. We selected our fluids to rapidly evaporate so that the surface returns to its original friction. Unlike traditional friction-feedback, such as electroadhesion or vibration, our approach: (1) alters friction on a wide range of surfaces and geometries, making it possible to modulate nearly any non-absorbent surface; (2) scales to many objects without requiring instrumenting the target surfaces (e.g., with conductive electrode coatings or vibromotors); and (3) both in/decreases friction via a single device. We identified nine liquids and characterized their practicality by measuring evaporation rates, etc. To illustrate the applicability of our approach, we demonstrate how it enables friction in virtual/mixed-reality or, even, while using everyday objects/tools.

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CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction devices; Haptic devices; • **Hardware** → Emerging technologies.

KEYWORDS

haptics, friction, adhesion, grasp, mixed reality

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1 INTRODUCTION

Touch plays a vital role in our interactions, providing valuable information about the objects we contact [3, 16, 30, 35]. In fact, a crucial tactile property that guides touch and grasping, is perceived *friction* between a surface and fingerpad [75]. When we feel that an object has lower friction, we intuitively know it requires a stronger grasp to prevent slipping [20]. Given the importance of friction to our tactile perception, many researchers have engineered devices that use surface friction as a feedback modality [7, 46, 50].

Unfortunately, while many other haptic cues (e.g., pressure, vibration, or kinesthetics) have seen a plethora of methods developed over the last four decades, this is not the case for friction. For example, to implement pressure rendering, haptic designers can choose from a variety of approaches (e.g., motors [33, 70], pneumatics [79],

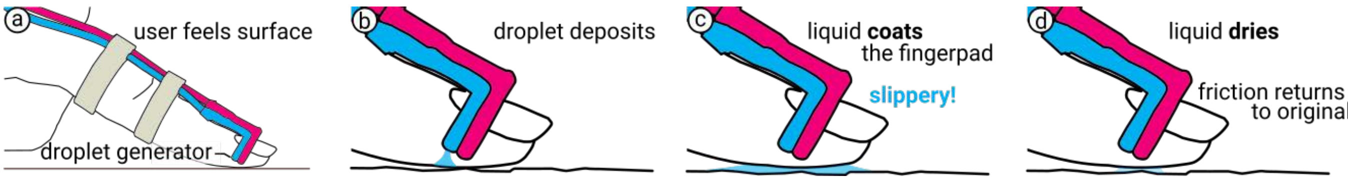

Figure 2: Our approach modulates surface friction via a (a) wearable droplet generator that (b) deposits slippery and/or sticky liquids, which (c) coat the fingerpad to form an interfacial layer that the finger glides on, altering the coefficient of friction. Moreover, (d) these liquids were engineered purposefully to, over time, evaporate and let the surface return to its original friction.

magnets [52, 73], smart materials [11, 56], electrotactile [62, 78], etc.), each offering different pro/cons regarding wearability, power consumption, scalability to real-world objects, etc. However, the haptic domain of friction rendering has not experienced this abundance of research approaches—in fact, only two key approaches to modulating surface friction have been deeply explored: ultrasonic vibration and electrostatic adhesion. Ultrasonic vibrations reduce friction as a finger slides over a surface by vibrating the surface such that it only contacts the finger intermittently [76]. Electrostatic adhesion increases the friction by means of attractive (electrostatic) forces between surface and finger [65]. These two working principles may seem limited in that neither can *both* increase and decrease friction, but this can be overcome by using these techniques in conjunction [29]. Moreover, of greater *conceptual* significance, implementing these approaches requires researchers to *instrument surfaces* around the user—e.g., either adding vibration actuators or coating the surface so that it can be electrically attracted to the user's finger. This need for surface instrumentation prevents achieving the goal that Bau et al. set for the field of augmented reality haptics in their seminal work "[to] only require the augmentation of the user, not the entire environment" [9]. In fact, besides *REVEL* [9] (which requires objects to be electrically grounded to the user and metallic) and a vibrotactile device by Asano et. al [5], the majority of friction devices are implemented on top of touchscreens or tabletops [1, 8, 14, 65, 76], rather than everyday surfaces.

To explore a novel, alternative, technique that circumvents these limitations, we propose Stick&Slip, a wearable device that can modulate the friction between the finger and *many, everyday* objects. We achieve this by depositing liquid droplets onto the finger to form an interfacial layer between the fingerpad and surface. By tuning the lubricating and adhesive properties of the liquid coating, we can either increase *or* decrease the coefficient of friction by up to ±60%. Importantly, we identify liquids that influence friction, yet leave behind only minimal residue (such as alcohol which rapidly evaporates). While we acknowledge that depositing liquids onto the skin is an unconventional approach to haptics, it provides an alternative method that circumvents many of the limitations associated with prior work, enabling friction modulation of a *wide* range of objects and surfaces. To illustrate the applicability of our novel approach, we demonstrate how it adds friction-feedback in virtual/mixed-reality or, even, while using everyday tools. As the first work exploring the use of liquids for interactive friction modulation, we identify not only the benefits of this approach, but also the limitations (e.g., onset times, residues, etc.) via technical evaluations and a user study. Finally, we distill our findings into recommendations based on the benefits and limitations of this approach and discuss areas for future exploration.

Ultimately, we see Stick&Slip as an exploration of alternative approaches for friction haptics—an area that unlike pressure or force-based haptics, has not seen a plethora of technical alternatives.

2 OUR APPROACH: STICK&SLIP

Stick&Slip alters the friction of real-world objects by interactively applying liquid coatings onto the user's fingerpad. We use liquids because they can alter the surface friction of nearly any non-absorbent surface, enabling a wider range of augmented surfaces than possible with prior approaches.

2.1 Working principle of Stick&Slip

Figure 2 shows the working principle of Stick&Slip. When the user's fingerpad contacts a surface, they immediately perceive its surface friction [75], which depends upon surface characteristics like roughness, surface energy, temperature, etc. [10, 54]. To alter the surface friction, we deposit a *thin liquid coating* between the fingerpad and the surface from a nail-worn droplet generator, which acts as a *physical buffer*. We specifically mixed liquids that can decrease friction ("slippery") or increase friction (which we refer to as "sticky"). Our slippery liquids (typically acetone and IPA) decrease the coefficient of friction by forming a lubricating layer that fills the space and irregularities between the skin and the surface, allowing the finger to glide smoothly over the surface with less friction than in a dry condition. In contrast, our sticky liquids (honey mixed with IPA) increase the coefficient of friction by forming an adhesive layer between the skin and the surface, causing the finger to feel more resistance when sliding over the surface.

Notably, for surfaces *coated* with liquids, the friction *is almost independent of surface material* [54]; therefore, the liquid coating influences the user's perceived sense of friction *regardless of the surface* touched by the user. This is a key advantage of our approach: unlike prior approaches (electroadhesion and ultrasonic vibration), our liquid-based approach enables changing the friction of *practically any non-absorbent object* touched by the user. Finally, to fully maximize our novel method of interactively altering surface friction, we selected & evaluated liquids that either evaporate entirely (e.g., mixed with alcohol) or which have residues that can easily be washed away with an antagonist fluid (e.g., sugar dissolved with water). Though our skin naturally leaves behind oil residues on surfaces we touch, our selection of fluid aims to reduce any additional residue (see *Technical Evaluation*).

2.2 Walkthrough: Stick&Slip in a mixed reality application

We demonstrate our concept in a mixed reality (MR) experience where the *friction* of *real* surfaces is altered. As shown in Figure 3, a user is wearing our wearable device in which thin tubes (mounted on the fingernail) deposit liquid droplets onto the fingerpad, which are pumped from reservoirs worn on the user's wrist. Our device is self-contained (i.e., battery-powered, and wireless) and communicates with the HoloLens 2 headset via Bluetooth.

Figure 3: Our user in MR wears our friction modulation device and interacts with real surfaces and objects.

This user experiences a MR racing game where their index finger controls a car driving around a track on their table. Because our wearable does not cover the user's fingerpad, they can feel the texture of their table and the different objects. For example, when the user slides their finger over 3D-printed props corresponding to speedbumps in the game, they feel their ridged texture. As the user drives the virtual car with their finger around the track, in-game events trigger changes in surface friction. As shown in Figure 4 (a) a cloud rains on the track, leaving a virtual puddle. When, (b) driving through the puddle, they *feel* that the table is *slippery* and see their car spin out of control. This change in friction is caused by our device delivering slippery liquid to the user's fingerpad, leading to a better match between virtual & physical sensations (see *User Study*). Our fluids rapidly evaporate and the surface friction returns to normal (e.g., on following laps, the table no longer feels slippery in this location).

Figure 4 (c) depicts as the user rounds a corner, a beehive drips honey onto the track; thus, (d) as the user drives through the virtual honey, they *feel a resistance* to sliding. This increase in surface friction is caused by our device delivering sticky liquid to the user's fingerpad. Like how one feels after getting fruit jelly on one's skin, our sticky liquids use dissolved sugars to increase the friction between the finger and surface via adhesion. However, unlike jelly, our sticky liquids are designed to quickly evaporate. As our liquids evaporate, they leave behind a thin film of adhesive residue. Importantly, this residue is significantly lower in sugar (i.e., ~2-30wt% compared to 70wt% in jelly) and its stickiness decreases over time (dry sugar is not sticky). Moreover, any sugar residue can be

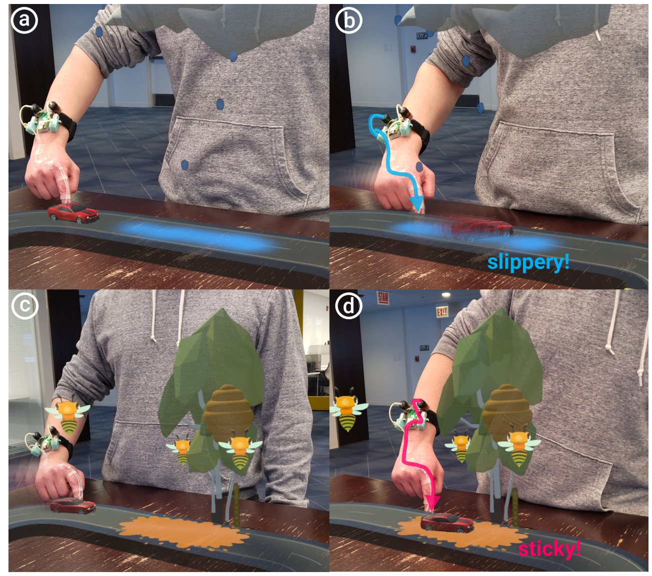

Figure 4: (a) The user drives their car through a rain puddle and (b) our device deposits slippery fluid as their car spins out. (c) The user then quickly rounds a corner, but (d) slows down dramatically sliding through virtual honey as the user feels sticky feedback.

easily dissolved using water, which our device can also deliver (see *Experiments*).

The user keeps racing and experiences more stick & slip effects, as depicted in Figure 5 (a) slowed by an opponent that sprays virtual green goo onto the track, or (b) losing control of their car due to virtual ice on the road.

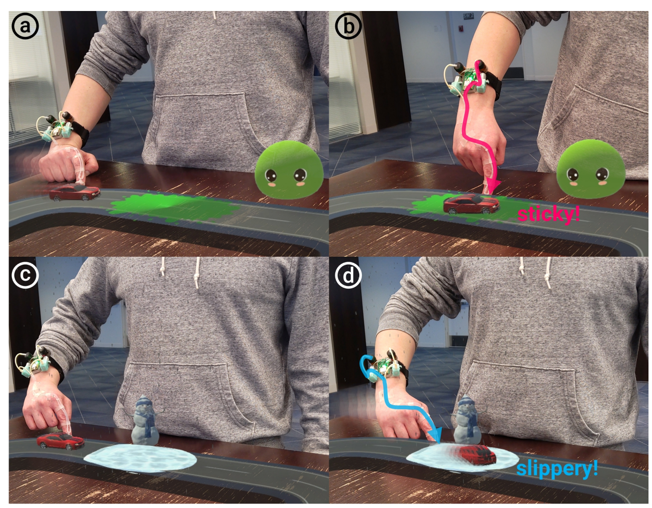

Figure 5: Surface friction effects rendered by our device, e.g., slowed down by resistive slime or losing control on slippery ice.

Importantly, our approach enables friction modulation on nearly any non-absorbent surface, allowing us to alter the friction of everyday objects (without instrumenting them with actuators). Figure 6 depicts this: (a) a virtual boost effect (slippery fluid) makes it feel easier to glide up the physical ramp prop, while (b) a virtual wind effect (sticky fluid) makes the physical speedbump props feel more obstructive.

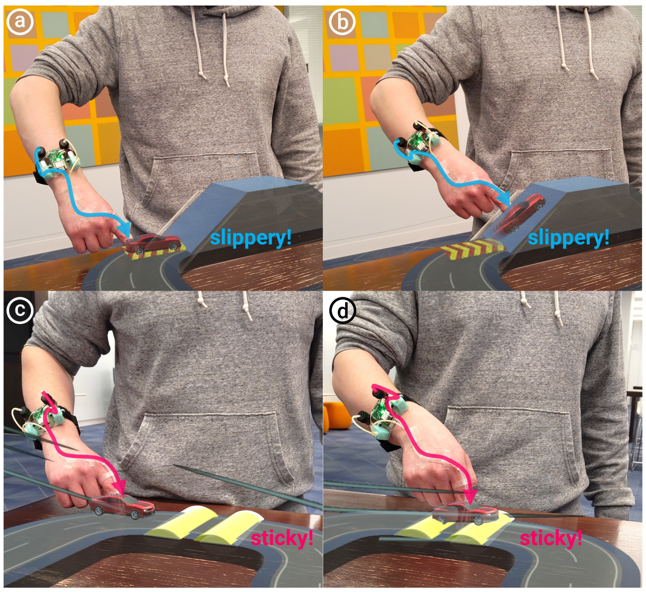

Figure 6: Our device alters the friction of everyday objects, such as on top of this toy ramp or speedbumps.

3 RELATED WORK

Our work builds upon devices that provide friction feedback. With a goal of haptic ubiquity, we focus on wearable approaches, especially those that can overlay haptics on real-world surfaces (e.g., [4, 72, 77]). Additionally, we reflect on recent alternatives to traditional actuators (e.g., liquid chemicals), which aligns with Stick&Slip's ethos.

3.1 Non-wearable Friction Devices

The most traditional approach to achieving friction feedback is by adding actuators to surfaces. There are four methods that have been commonly used.

Mechanical devices have long been used to generate resistive forces like those presented by friction. For example, the Haptic Tabletop Puck presented a tangible with a retractable rubber stopper that increased friction when dragged on a surface [42].

Vibration devices are commonly used for tactile feedback and simulating surface properties, typically integrated into flat surfaces and tablets. By vibrating the surface at high frequencies, the finger only intermittently contacts the surface, leading to a reduced coefficient of friction [37, 76].

Electroadhesion devices increase friction by electrostatic adhesion [44, 64, 65]. TeslaTouch [8] popularized this approach, using an electrostatic charge on a touch panel to increase attraction between the surface and finger. Others combined electroadhesion with ultrasonic vibration to achieve both increasing and decreasing friction [29]. Haptidrag [45] used a novel electrode arrangement to augment tangibles with electroadhesion friction feedback on real surfaces, although its underlying principle limits the surface materials, e.g., no metals or plastics.

Temperature-triggered mechanisms for friction changes have recently been explored. StickyTouch [28] is a surface with variable stickiness from temperature-sensitive tape that undergoes a dramatic increase in adhesion above a transition temperature. Others found that the friction between skin and glass can be controlled by simply heating certain regions, due to the skin's temperature dependent viscoelasticity and moisture content [14].

Considering the goal of ubiquitous haptics, non-wearable approaches face a particular challenge: *adding actuators* onto every object is impractical due to cost, size, and power consumption [43]. While these approaches lend themselves well for use in tablets and other standalone devices, they do not easily scale to the demands of haptics for mixed reality. As such, a more pragmatic solution to scaling haptics may be to instrument the user (rather than the environment) so that the actuator accompanies the user *anywhere* that haptics is needed.

3.2 Wearable Friction Devices

Wearables offer a solution to providing haptics at scale because they are always with the user and do not require further instrumentation. The common approaches use similar actuators to their non-wearable counterparts.

Mechanical wearables include devices like Frictio [25], a ring with motor-controlled rotational resistance as an eyes-free information display. Similarly, FrictShoes [71] proposed wheeled shoes with brakes for simulating the sensation of walking on surfaces with different frictions in VR. Some have simulated the sense of friction via skin stretch on the fingerpad by placing motors around the finger and end effectors on the pad [55, 61, 63].

Vibration wearables include devices like HapCube [32], which generates tangential pseudo-forces (that can be interpreted as friction to users) by means of asymmetric vibrations [48, 57].

We take inspiration from wearable approaches to rendering friction but identify a key challenge: in most cases, the body is instrumented with actuators that impair interactions with real-world objects. While these approaches work well in VR, these cannot *overlay* friction onto real-world objects, a key goal in MR haptics [6] and also our focus. To solve this, we need devices that leave the fingerpad free to feel *both* physical *and* virtual sensations.

3.3 Fingerpad-free Friction Devices

REVEL [9] laid out the vision for friction modulation in MR by expanding electroadhesion to be applicable to everyday applications outside of using tablets (e.g., mixed reality, tangibles, etc.). REVEL proposed reverse electrovibration, where rather than charging the surface, charge is applied to the user, enabling feeling friction changes when interacting with metallic, grounded objects.

REVEL scales to objects in one's surroundings, as long as the objects have been coated in layers of conductive electrode and insulation. We draw inspiration from REVEL's approach while aspiring to eliminate all object-side instrumentations.

Alternatively, Asano et. al [5] developed a vibrotactile device that leaves the fingerpad free and modulates roughness of real surfaces, which is related to surface friction. Because this approach is based on tactile masking of the real-world, the technique requires *strong* vibrations that the authors note to interfere with the "natural fusion of real and artificial stimuli" [5]. Our work is motivated by this challenge and aims to build upon wearable and scalable haptic devices by improving upon the sensory consistency between real and artificial stimuli.

Both REVEL and Asano et. al made great conceptual strides towards friction modulation anywhere. However, we speculate that to go beyond the capabilities of conventional actuators, a less conventional route may be needed. Thus, we explore friction modulation on a wide range of surfaces via *coating the user's fingerpad with liquids*.

3.4 Chemicals as Alternatives to Traditional Actuators

In recent years, there has been a push to experiment with different approaches to influencing perception, such as with chemicals, to overcome challenges of traditional actuators [12, 24, 31]. For example, Chemical Haptics proposed using liquid stimulants as an alternative to Peltiers, vibromotors, and electrotactile stimulation [40]. We draw inspiration from the ethos of these works when we explore using liquids as opposed to traditional actuators for friction modulation.

Water as a touch medium has been investigated in HCI [23, 53, 59]. However, to the best of our knowledge, liquid *lubricants* and *adhesives* have not been investigated within an interactive context. While unconventional, we demonstrate that carefully chosen liquids can circumvent many of the limitations associated with prior approaches to variable friction, enabling friction modulation of a *wide* range of objects and surfaces.

4 BENEFITS, CONTRIBUTIONS, AND LIMITATIONS

Our key contribution is that we propose, explore, and engineer a new approach to friction modulation based on liquid droplets that coat the fingerpad. Our approach provides three key benefits: (1) It enables altering friction on a wide range of surfaces and geometries, making it possible to modulate *nearly* any non-absorbent surface; (2) Since our device is a wearable, friction modulation easily scales to *many* objects in the environment; (3) It can *both* increase and decrease surface friction using a single hardware device. Ultimately, we see Stick&Slip as an exploration of alternative approaches for friction haptics, an area that unlike pressure or vibrotactile haptics, has not seen many alternatives.

Our approach is not without limitations: (1) Liquids are ineffective in absorbent materials (e.g., fabric); similarly, there are edge case materials that resist our approach (e.g., "non-stick" surfaces such as PTFE onto which not even a gecko can adhere [27]) or are incompatible with solvents (e.g., acetone can strip some surface finishes [58]); (2) Because our sticky fluids are diluted to enable faster evaporation, they first feel slightly slippery to the user before increasing in friction as their solvent evaporates; (3) While our approach delivers small droplets, their wetness can be noticed in some use cases. That said, we strive to characterize these limitations so that we can reduce them and improve the overall interaction experience. Further insights into understanding these limitations, best practices, and areas for ongoing investigation are detailed in our *Recommendations and Future Work* section.

Finally, we are not proposing to replace existing friction modulation techniques such as electrostatics and vibration, but rather we aim to widen the range of objects and surfaces that can be modulated with a new approach.

5 IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. To accelerate replication, we provide all the source code of our implementation[1]. The key components of our haptic device are the finger-worn droplet generator, the pumps, and the control electronics, as shown in Figure 7. Our wearable device uses its pumps to draw liquids from their reservoirs (worn as a bracelet around the wrist), through tubing, and then to the holes that generate droplets on the skin.

5.1 Finger-worn Droplet Generator

We wrap y-split channels around the sides of the finger, there the channels narrow from 1mm to a 0.5mm nozzle that pinches the fluid into a droplet (droplet size: ~15uL). These droplets run down the side of the finger and coat the fingerpad. The nozzle diameter is small enough such that shaking the device or touching a surface does not cause leakage. Importantly, our droplet generator keeps the user's fingerpad free to feel real surfaces—even if fingers are slightly wetted from friction modulation, they still feel some of the surface's texture [22]. The droplet generator weighs 0.35 grams and is adhered to the fingernail with double-sided tape. We use silicone tubing for sticky liquids and PTFE tubes for slippery liquids (to prevent evaporating through silicone).

5.2 Pumps, Sensors, and Microcontroller

At the core of our device is an ESP32C3 microcontroller (Seeeduino Xiao), which communicates with external applications (e.g., MR experiences) via Bluetooth LE and is responsible for controlling the micropumps. Our entire wearable device weighs 60 grams including filled liquids. We also piloted a three-channel version by adding another pump, tubing, and y-split in the droplet generator to include a channel for depositing water to wash away sugar (as shown in Figure 7a). For the sake of miniaturization, our final device uses just two channels (sticky/slippery).

Pumps. We use peristaltic micropumps (Takasago RP-Q) to pump our liquids from their reservoirs to the droplet generator. These specific pumps were chosen for their siphon prevention (i.e., liquid cannot be shaken or sucked out preventing accidental fluid discharge, unlike piezoelectric diaphragm pumps). We run our pumps at 3.7V via DRV8837 H-Bridges and control fluid volume based on timing (adding thermistors or flow meters to close the loop

[1] http://lab.plopes.org/#stickslip

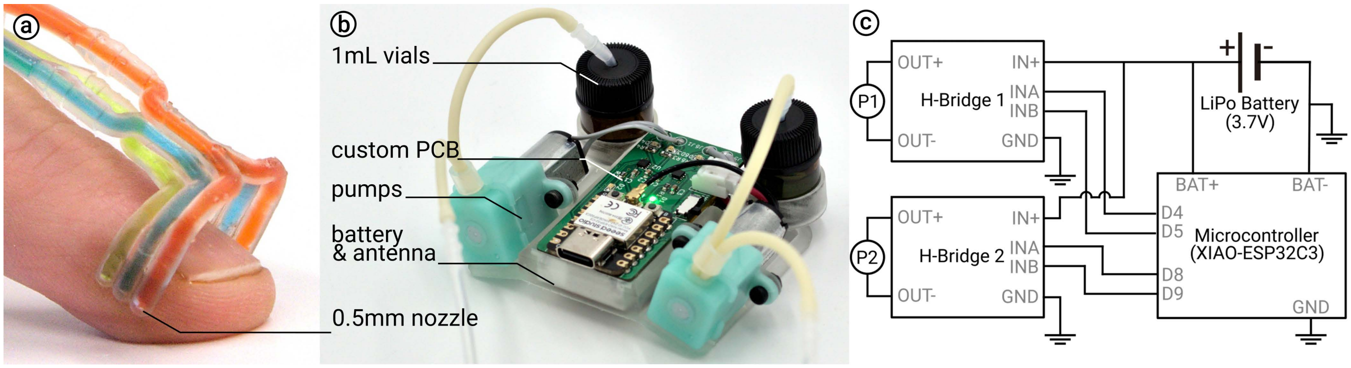

Figure 7: (a) Our nail-worn droplet generator. (b) Our bracelet device and its components. (c) Electronics schematic of our PCB.

is possible, but we found in pilots that these pumps are consistent even in open loop). We found that 1 second of pumping is sufficient to coat the fingerpad, which is what we use in typical interactions. Given our 1mL fluid reservoirs and our pump flow rate of 1mL/min, our device enables 120 interactions (60 droplets x 2 channels). This number is proportional to the reservoir size (e.g., a 2mL reservoir will double interactions).

Battery life. Our 350mAh battery fits directly under our custom PCB. Since our pumps are low-power (3.7V x 80mA = 0.3W), the battery life is >4 hours of continuous pumping. However, as outlined above, we only need to pump fluid for ~1 second to coat the fingerpad. Therefore, our battery tends to last a full day of on-demand use.

Latency. The total latency of our device is ~200ms as measured by a highspeed camera, i.e., from a keyboard trigger in Unity to a droplet beginning to dispense. This overall latency includes Unity/OSC/BLE communication (~40ms), microcontroller (<10ms), and pump (~150ms).

6 DEVELOPING OUR FRICTION-MODULATING LIQUIDS

There are two primary factors that influence a fluid's frictional characteristics: viscosity and surface energy. Increased viscosity leads to greater resistance to flow, while increased surface energy leads to greater adhesion and cohesion [18, 67]. As such, we experimented and selected a set of liquids with various viscosities and surface energies aiming to find fluids that induce sticking and slipping. As a subgoal, we uniquely want fluids that can either *quickly evaporate away* or whose effects can *be negated by another fluid*, so that we may interactively switch between frictions. As this is a first work in using liquids for interactive friction modulation, we detail the rationale for selecting candidate fluids: (1) We chose only from fluids deemed skin-safe (i.e., found in commercially-available healthcare products), which ruled out UV-curable resins and chemically corrosive fluids. (2) We selected only fluids that are relatively clean to deposit into environments, which eliminates fluids that cause miscoloring such as liquid metals—all our fluids are clear and were colored only for visibility in photos. (3) We chose only from fluids that can be easily pumped, which rules out very viscous fluids like pure honey or silicone damping fluids. (4) We did not choose fluids that require hardware beyond pumps (e.g., skin-safe super glue requires a closing mechanism to protect it from curing in air). (5) We did not choose liquids that are not liquid at room temperature (e.g., hot glue). This yielded the following set of initial fluids that we evaluate later:

Isopropyl Alcohol. While not commonly regarded or studied as a lubricant, isopropyl alcohol (IPA: 99.9% v/v) acts as a slippery liquid while also offering a rapid rate of evaporation. This is highly desirable for our use case—IPA can lubricate a surface to make it feel slippery and then evaporate away without a trace. If the user touches the surface after the liquid has evaporated, it will feel as though it had never been lubricated. IPA is skin-safe under normal use [26, 34], but can lead to dry skin when the skin is exposed to high volumes of fluid for a long time (e.g., 20mL for 1 hour [34]); this exposure level required for extreme dryness is considerably higher (>1000x the volume) and longer than that of our droplets, which evaporate in minutes as shown in *Experiment 2.* Moreover, widespread clinical studies have found IPA to be *less irritating* to the skin than hand washing with detergents [38, 68]. Thus, it is commonly found in hand sanitizers, cosmetics, and household cleaning products. Similarly, isopropyl alcohol is compatible with a wide range of surfaces spanning metals, glass, electronics, and most plastics. It should be noted that some plastics and surface finishes are degraded by alcohol and are thus incompatible with IPA [39].

Acetone. Acetone is a solvent that can act as a lubricant, but with a faster rate of evaporation than IPA. This makes it a great candidate for interactive applications in which the friction must only be briefly reduced. Acetone, like IPA, is skin-safe under normal use. While acetone is commonly thought to lead to dry skin [41, 80], studies in dermatology have found that it does not disrupt the skin barrier, even when exposure is much greater and longer than used in our application (e.g., a cotton ball soaked in acetone applied for >12 mins continuously) [2, 60]. It is commonly found in nail polish remover, often accompanied by additives such as glycerin to ensure skin moisturization [13, 49]. While acetone has the advantage of rapid evaporation, it should be noted that it is a stronger solvent than IPA [58]. Thus, if a material is incompatible with acetone, IPA may be used as an alternative.

Honey-IPA Solution. Honey is well-known for its viscosity and stickiness owing to sugar's hydrogen bonds with water [74]. Unfortunately, honey's viscosity makes it difficult to pump. Therefore, to create a sticky liquid, we dilute honey with IPA to reduce its viscosity. Importantly, honey's stickiness remains despite being diluted (as we show in our *Technical Evaluation*, just 2wt% honey can cause a 50% increase in static friction). Because we dilute honey with a solvent, the honey can effectively coat the fingerpad. As the IPA evaporates, it leaves behind a thin, adhesive film on the fingerpad. Importantly, we chose honey because it is water-soluble; thus, it can simply be washed away with water after use, returning the fingerpad and surface to their original friction. Note, we chose IPA (IPA: 70% v/v, water: 30% v/v) as the solvent rather than acetone because sugar water is insoluble in acetone. This is beneficial: slippery liquids that do not rehydrate sugar residue prevent accidental stickiness.

Thickened Water. Water can be made into a viscous gel with a very small amount of thickening agent (e.g., 1 wt% of Xanthan gum, a food-grade polysaccharide). Despite the small concentration of thickening additive, it feels adhesive to the touch while very little residue behind.

Additional safety measures. We exclusively applied our liquids in small droplets (~15 uL) to the fingerpad, with brief exposure times enabled by rapid evaporation. This approach mitigates potential side effects, notably dry skin. Moreover, the small volumes employed, coupled with the direct delivery of droplets to the side of the fingerpad, not only ensures immediate coating but also minimizes the risk of inhalation or application to other skin areas.

7 EXPERIMENTS 1-4: FLUID FRICTION & PRACTICALITY

To understand the effects of our candidate liquids on friction as well as their practicality (i.e., how long do their frictional effects last?), we performed four technical experiments. We then apply these findings to our user study where participants experienced our approach in an interactive context. To our knowledge, these experiments have not been performed in related work. Thus, we designed these to focus on our specific application of temporary friction modulation between a finger and surface.

To aid the reader in understanding the four technical experiments we conducted, we present an overview of their results: **In experiment 1, we measured the fluid effects on friction coefficients**: we found the greatest friction reduction from oil, IPA, and acetone, and the greatest friction increase from sugar water, 30wt%, and 2wt% honey in IPA**; In experiment 2, we measured the fluid evaporation rates**: we found that acetone, IPA, 2wt%, and 30wt% honey in IPA evaporated the fastest, and we eliminated oil, water-based lube, water, and sugar water for their poor evaporation; **In experiment 3, we measured friction over repeated trials**: we found that acetone and IPA initially decreased friction, then returned to the baseline. We found that 2wt% and 30wt% honey in IPA caused stickiness faster than thickened water**; finally, in experiment 4, we measured washing away residue**: we found that water washes away sugar residues, where effectiveness increases with water volume.

7.1 Experiment 1: fluid effects on friction coefficients

To determine the extent to which each of our candidate fluids impacts the coefficient of friction between surfaces, we built a mass-pulley tribometer, as illustrated in Figure 8. By increasing the load of the hanging mass, a sliding mass approximating the finger's frictional properties slides across the surface. The coefficient of friction can be calculated by measuring the block's acceleration along with the hanging mass. For each fluid, 10uL of liquid was pipetted between the testbed surface and the sliding block. We evaluated both the static and kinetic friction coefficients for nine potential liquids: (1) sugar water (66.6wt% sugar), (2) 30wt% honey in IPA, (3) 2wt% honey in IPA, (4) thickened water (1wt% xanthan gum), (5) water, (6) water-based lubricant (*Shibari*), (7) acetone, (8) IPA, and (9) oil (*3-IN-ONE Multi-purpose*).

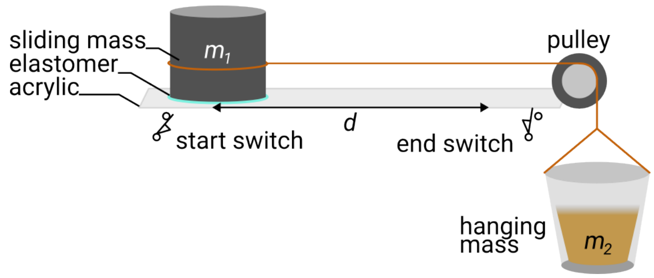

Figure 8: We built a mass-pulley tribometer to mechanically evaluate the effect of our liquids on coefficient of friction.

Our sliding mass approximated the finger's frictional properties during a light, exploratory touch. The sliding mass weighed 25g. To approximate skin, the bottom of the sliding mass was coated in polyurethane (commonly used in mechanical approximations of the skin [15], *Smooth-On KX Flex 40*). The surface area of the block was 20mm^2 to approximate the contact area of a fingerpad under 25g of compression [17]. The testbed was made from smooth acrylic (note that for well-lubricated surfaces, the friction coefficient is nearly independent of the material [54]). Prior work in contact mechanics indicates that the friction coefficient for an index fingerpad on acrylic under 25g and sliding at low velocity is ~1.60 [3, 36]. In our testing, we found our sliding mass to be a reasonable approximation for a finger because its kinetic coefficient of friction on acrylic measured 1.6±0.125 over 25 trials.

Static friction procedure. First, we tested the effect of liquids on the coefficient of static friction, determined by finding the minimum force required to initiate sliding. To do so, the hanging mass was slowly increased by pouring sand into a suspended cup (~1.5grams/sec). Once the mass began to slide, a hardware limit-switch was released, and no more sand was added. The hanging mass was then weighed. The static coefficient of friction is calculated by taking the ratio of the hanging mass to the sliding mass. For each liquid, five trials were performed, and the apparatus was cleaned between trials; we confirmed the cleaning effectiveness by measuring and comparing it to the no-liquid baseline value.

Static friction results. Figure 9 (a) shows change in static friction coefficient that fluids achieved (relative to a no liquid baseline, the surfaces' original friction). We found greatest reductions in static friction from oil (-62.9±3.3%), IPA (-59.7±2.9%) and acetone (-59.2±4.3%), while the greatest increases in static friction were found from sugar water (83.0±15.7%), 30wt% honey in IPA (78.3±16.1%) and 2wt% honey in IPA (56.1±9.5%). Note that because there is

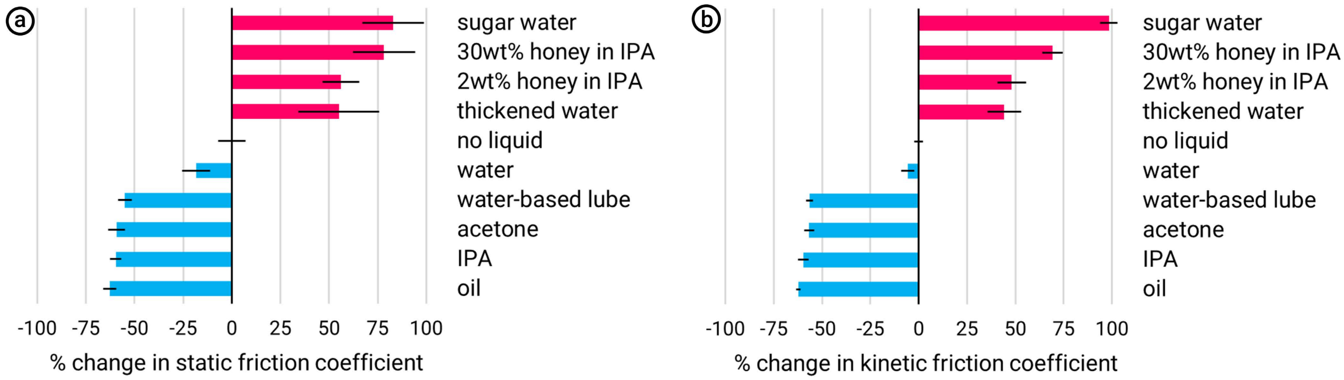

Figure 9: Relative changes in: (a) static friction, and (b) kinetic friction for each fluid.

an onset time for sticky liquids, we depicted maximal values (see *Repeated Trials* for a characterization of this onset).

Kinetic friction procedure. As we are interested in sliding interactions, we measured the kinetic friction coefficient, which can be determined by finding the acceleration of the sliding block. To do so, we apply a hanging mass equal to the average mass that initiated sliding for each fluid in our earlier static experiment. When the mass begins sliding, the start limit switch is released and the block slides into the end limit switch. The distance (6cm) and time difference between triggering the switches is used to calculate the block's acceleration ($a = d/t^2$). The kinetic friction coefficient is then calculated using: $\mu_k = (m_2 g - (m_1 + m_2)a)/m_1 g$.

Kinetic friction results. Figure 8 (b) shows the relative change in kinetic friction coefficient for each liquid. As shown, the overall trend held between the static and kinetic friction tests. Considering that friction coefficients span a small range (i.e., typically from 0.0 to 4.0), even a ±30% change is dramatic.

7.2 Experiment 2: evaluating fluid evaporation

With a goal of using liquids to alter friction interactively, we aim to choose liquids that not only alter sensation, but are also *practical*, i.e., evaporate quickly and leave minimal residue so that we may design applications that can switch easily between sensations. Thus, we measure the weight of a fluid droplet over time, to characterize its evaporation.

Procedure. To measure the rate of evaporation, we pipetted a 10uL droplet onto a plastic weigh tray and placed it inside a lab-grade scale (Mettler Toledo, 0.0001g precision). The droplet weight was recorded every 30 seconds.

Evaporation results. Figure 10 shows the relative remaining droplet mass after five and 60 minutes (only two points depicted for clarity, measurements taken at 30s intervals).

We found that solvents like acetone and IPA evaporated the fastest and left behind no residue. The second fastest evaporating group of fluids were solvents containing honey, where a lower concentration of honey resulted in faster evaporation. Notably, the solvents evaporated out of these mixtures leaving behind residue of approximately the mass of the honey contained within the mixture along with retained water (after 60 mins, 2wt% honey had 3.4% remaining mass and 30wt% honey had 32.4% remaining mass). Water-based liquids evaporated slower than solvent-based liquids, where thickened water evaporated faster than water, which itself evaporated faster than water-based lubricant. Finally, oil showed no signs of evaporation in 60 minutes.

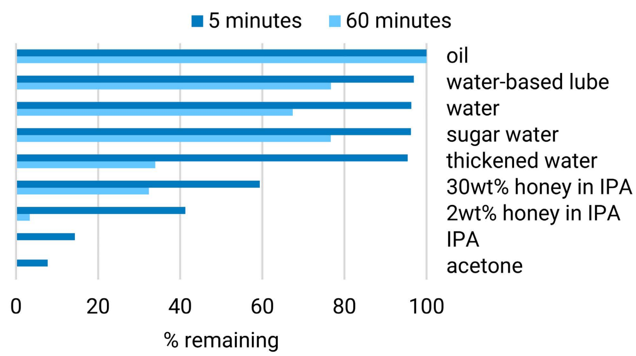

Figure 10: Fluid evaporation at two points (5 and 60 minutes).

Eliminating unsuitable fluids. At this point, we found that oil, water-based lube, water, and sugar-water do not evaporate rapidly (i.e., the four slowest evaporations in Figure 10). Moreover, given that we found that solvents had comparable lubricating properties in our previous experiment and that these solvents evaporate rapidly, we deem oil, water-based lube, water, and sugar-water as no longer fluids of interest. That said, these may still have niche use cases, which we elaborate upon in *Recommendations and Future Work*.

7.3 Experiment 3: fluid friction over repeated trials

Having characterized each fluid's maximal effects on friction along with their evaporation rates, we now look to characterize friction and evaporation in conjunction over multiple sliding motions. Additionally, we aim to shed light on the timing (onset and offset) of each fluid's effects.

Procedure. We used the same apparatus and procedure described in *Static Friction*. However, instead of cleaning the testbed and sliding block after a single trial, we placed the sliding block back on the starting position and tested the static friction again. After a droplet was placed on the block, sliding was repeated 10 times. Each time, the block slid 6cm, for a total distance of 54cm.

Repeated trial results. Figure 6 shows the relative change in friction for each fluid over the sliding distance (each point represents the average of 5 trials). We found that all our fluids cause an

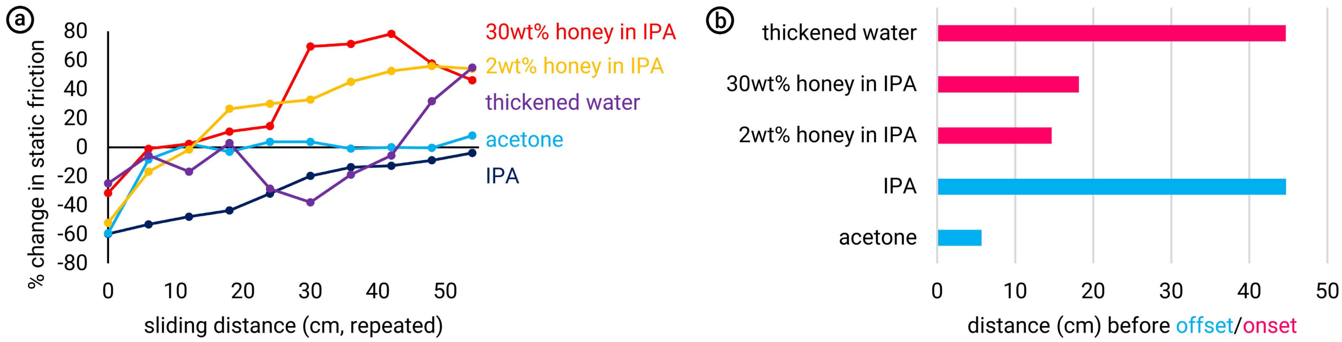

Figure 11: (a) Fluid friction over repeated trials (distance in cm); and (b) offset/onset distance (i.e., the sliding distance required for a slippery sensation to disappear or a sticky sensation to appear).

initial reduction in the static friction, with solvent-based fluids being the most lubricating. Acetone and IPA return to approximately the no-liquid baseline as the fluid evaporates. The fluids containing honey and xanthan gum result in increased friction after sufficient spreading of the fluid during sliding and evaporation.

On/offset results. To understand how the onset/offset times of friction changes affect perception, we contextualize them within psychophysics literature by comparing to established just-noticeable-difference (JND) values. Specifically, the Weber fraction for surface friction is known to be ~11% [19]. Therefore, we can determine the sliding distance required for a change in friction to be felt, as depicted in Figure 11 (b). All tested liquids initially reduce friction greater than 11% and thus immediately feel slippery. In the case of liquids that intentionally are slippery, we aim to select for those that can quickly return to within 11% of the baseline friction coefficient (determined with linear interpolation), i.e., the slippery effect has disappeared, and the surface feels unaltered. In the case of IPA, we found that after 44.7cm, the change in static friction returns to within 11% of the original. Acetone exhibited a faster return to baseline friction, at just 5.7cm. This suggests that acetone is better for brief lubrication, while IPA can provide a sustained sensation for the same dispensed volume (while still disappearing over time). While sticky liquids initially reduce friction by a small amount, after some sliding and evaporation, they dramatically increase friction. Therefore, we are interested in how long it takes for sticky liquids to perceivably increase the friction by more than the 11% JND. We found that 2wt% honey in IPA took the shortest distance (14.7cm), followed by 30wt% honey in IPA (18.2cm) and thickened water (44.7cm).

These are conservative estimates. We discuss the implications of these timings in *Recommendations* but it is important to note that mechanical analysis results in very conservative estimates of performance: (1) we slid the block repeatedly over the same path as opposed to one continuous long slide (worst-case scenario); (2) our elastomer skin does not absorb any fluid unlike actual skin [40]; and (3) our sliding block is at room temperature, while our skin is significantly warmer which aids in fluid evaporation [47].

Eliminating unsuitable fluids. Because thickened water has a long onset time to increasing friction, we eliminate it, but discuss other potential uses for it in *Recommendations*.

7.4 Experiment 4: washing away sticky residue

As we found in our second experiment (Figure 10), sticky liquids leave residue behind due to sugar content. Moreover, our third experiment (Figure 11) found that, in the short-term, this residue increases friction as long as it retains water (dry sugar is not sticky). While waiting for this stickiness to naturally dry might fit some applications, we argue that understanding whether this process can be sped up is of value for a wider interactive application of our concept. To tackle this, we propose using water to dilute and dissolve away sugar residue. To this end, we conducted an experiment.

Procedure. On sticky liquids, we performed static friction tests until the friction reached within 5% of the peak reported in our first experiment (Figure 9). Then, we added 10uL or 20uL of water and continued performing static friction tests.

Washing stickiness results. We found that without washing, the friction decreases over time for both 30wt% and 2wt% honey in IPA. Adding water causes an initial decrease due to lubrication. Then, the water dissolves the sugars, and the friction decreases toward the baseline condition, where more water led to greater reduction in friction. Moreover, we also confirmed that using acetone and IPA as wash fluids also reduced the stickiness immediately, but the stickiness eventually rises back to peak values as the solvents evaporate without having diluted the sugars.

7.5 Summary of findings and narrowing the best liquids

Our four experiments characterized fluids based on their ability to modulate friction and their practicality. While all fluids we investigated offer unique properties which we discuss in *Recommendations*, we optimize for our applications (requiring strong modulation changes while being easily removed). As such, we selected **30wt% honey in IPA as our sticky** fluid and **acetone as our slippery** fluid for all our interactive applications.

8 EXPERIMENT 5: USER-STUDY ON INTERACTIVE USE

While our first experiments examined our fluids' effects on friction along with their evaporative properties, our final experiment focused on observing our approach in an interactive application.

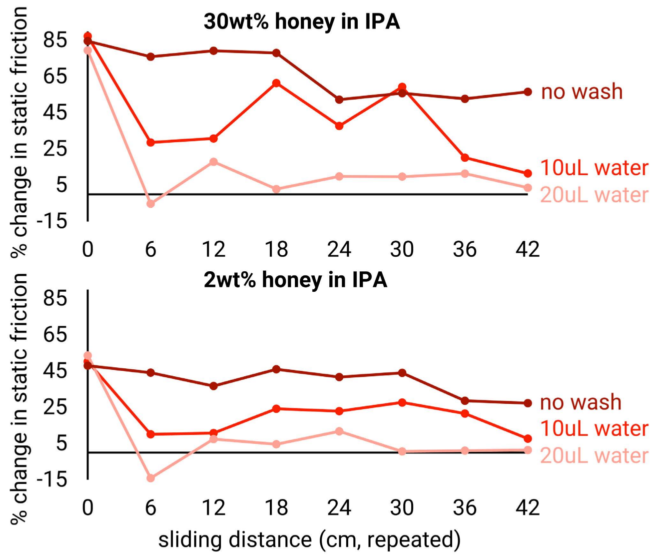

Figure 12: Applying water to sticky surfaces reduces friction.

Specifically, we assess the extent to which our approach influences the sense of immersion and enjoyment in a mixed-reality experience with physical surfaces and props. Our main hypothesis for this study was that the MR experience with Stick&Slip would feel more immersive and enjoyable than a baseline without our device because of the haptic experience.

8.1 Conditions

Participants experienced two interface conditions in counterbalanced order: (1) Stick&Slip (worn on the right-hand index finger and wrist) and (2) a no-haptics baseline in which participants did not wear our device. We chose this baseline rather than depositing a "neutral" fluid because any fluid, even water, still causes changes in friction, as found in our experiments and literature [51]. Additionally, the baseline depicts the current state of MR with passive props. Wearable devices offer the benefit of always-available haptics, often at the expense of, to some extent, encumbering the user. To assess whether adding our liquid-based friction haptics to mixed reality justified this encumbrance, we compared between *our device* and a *no-haptics* baseline.

8.2 Participants

We recruited twelve participants (seven identified as female, five as male, average age of 23.4 years old, SD=3.3). Participants received $10 for their time.

8.3 Apparatus

We built a prop-based MR experience to evaluate our device as shown in Figure 13. Specifically, as informed by our prior experiments, we tested this experience using **acetone** as a slippery liquid and **30wt% honey in IPA** as a sticky liquid. In the experience, participants wore a Microsoft Hololens 2 MR headset. The table was made of acrylic to minimize issues with the Hololens' hand-tracking.

We designed the timings of pumping our liquids based on the results of Experiment 3: (1) **Slippery sensations produced by acetone:** Because there is no onset time for slippery liquids to reduce friction, we pump for one second immediately when a user's finger enters a slippery zone. (2) **Sticky sensations produced by 30wt% honey in IPA:** Sticky liquids have an onset distance due to time required for fluid to evaporate and leave behind a sticky film. Informed by Figure 11, we designed our experience to begin pumping 30wt% honey in IPA approximately 18cm before the effect appears so that it feels sticky when the user reaches it.

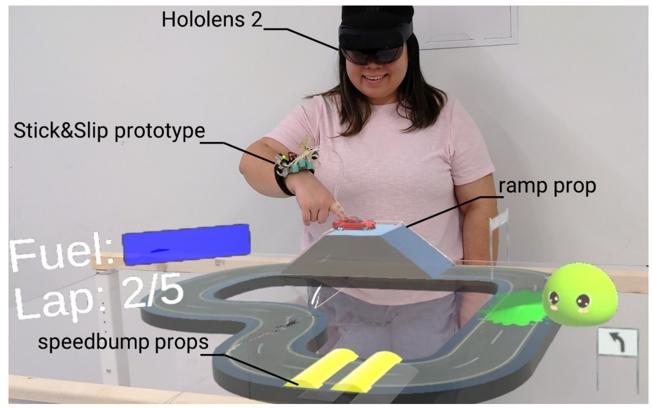

Figure 13: Study 2's apparatus: a mixed reality experience with physical props (image taken from 3rd person perspective).

8.4 Procedure

We utilized our MR racing experience, in which participants drive a virtual car on a track by dragging their finger (the same application described in our *Walkthrough*). In this version of the MR racing game, participants experienced eight surface haptic events (rainfall, ice, slime, and honey—each was presented twice). Each trial took ~10 minutes and participants were interviewed between trials. Interviews consisted of Likert ratings (1-7 scale) of the experience (immersion, enjoyment, sensory engagement [66, 69]) along with open-ended questions regarding what contributed to their experience. Participants' fingers were cleaned with soap and water before each trial. Finally, besides these virtual effects, participants also experienced physical props, such as the texture of the table, 3D-printed speedbump props and an acrylic ramp prop.

8.5 Results

Figure 14 presents our main findings. After testing the Likert data for normality, we used a Mann-Whitney test (two-tailed) to test our hypothesis that Stick&Slip leads to improved experience. We found significant differences between the two interface conditions, where Stick&Slip received greater ratings than the baseline for immersion ($p<0.001$), enjoyment ($p<0.001$), and sensory engagement ($p<0.001$). Moreover, all twelve participants indicated that they preferred the Stick&Slip condition over the no-haptics baseline. Altogether, this supports our main hypothesis that Stick&Slip improves the experience.

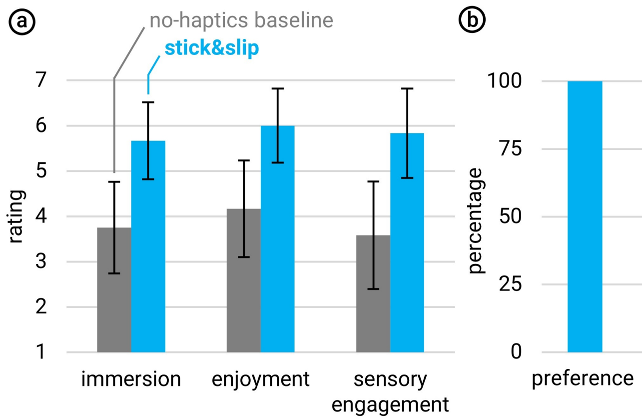

Figure 14: (a) Participants' ratings for both conditions. Error bars show standard deviation. (b) Participants' preference.

8.6 Qualitative Feedback

We analyzed all responses to our questionnaire. First, all participants felt that friction haptics added to the experience. To illustrate this, P10 stated "when touching one single surface, you don't feel much but now with different road situations its quite interesting." P2 & P6 both stated that the device made them want to explore tactilely and P9 expressed that it "sparked more childish excitement." While one may expect some potential novelty effect, all participants preferring Stick&Slip gives some indication that participants felt the fluids were not unpleasant and added to the experience; for example, the liquids "added a whole other dimension to the game through sensations" (P6 & P4). This suggests that the gain in immersion was worth the cost of wearing our device.

Beyond adding haptics, five participants expressed a desire for "the digital and physical to correspond" (P11). P5 explained "seeing the visuals line up with the feeling led to better immersion". P7 noted that "the ice felt slippery" and that their "finger went faster than expected". Similarly, P9 stated, "if I were driving through ice, it's how I'd expect it to be". Along this line, P8 recalled that "[I] felt a sense of traction going through honey effect".

Our haptics also influenced how participants experienced props on the track. For example, P1 felt that it was harder to go up the ramp after going through slime. Similarly, P3 & P9 felt going down the ramp was more slippery after it had rained.

Finally, our approach is not without limitations and participants' responses also indicate opportunities for further research. First, two participants (P1 & P9) noted feeling that the ice and rain felt cold, likely either from acetone's evaporative cooling or from a pseudo-haptic effect driven by the visual suggestion (P1 noted the ice felt colder than the rain, despite identical actuation parameters). Second, three participants noted that they felt a delay between the sticky visuals and the sticky sensation. Third, only two participants noted feeling any residue, despite us opting not to use any wash fluid during the MR experiment, suggesting that the once the sugar has dehydrated, it is no longer perceived as sticky. No participants commented on any odors originating from the fluids, which suggests that no odors were perceivable (e.g., from possible vapors of the liquids as they evaporate). Finally, no participants reported any dry skin or irritation.

9 FURTHER APPLICATIONS FOR STICK&SLIP

To illustrate the versatility of our approach, we implemented two additional and unique applications in which we use Stick&Slip to enhance user experience via variable friction.

9.1 VR using static props with dynamic friction

Figure 15 depicts a VR escape room experience in which the user needs to repair three pipes to open the next door. When a pipe cracks and sprays water, the user must place their hand on the crack to stop the water, which will now feel slippery via our device rendering the virtual water with real water droplets. To patch the pipe, the user turns around, dips their finger into virtual sealant putty, and returns to rub it over the crack. The user then discovers that another pipe has rusted and feels the rust's roughness rendered by our sticky fluid. To remove the rust, the user sprays a dissolver and rubs the pipe until the rust sheds off, feeling the pipe's surface return to its smooth texture as our device washes this stickiness with water.

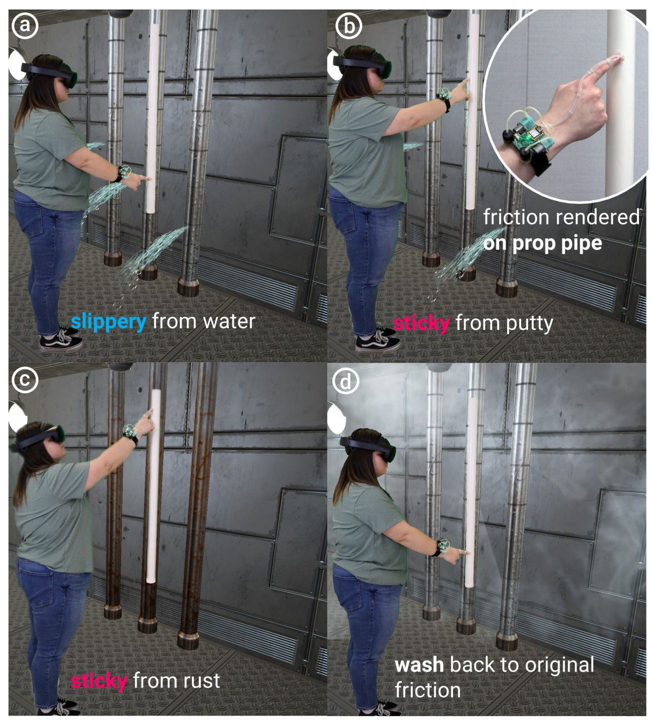

Figure 15: Stick&Slip adds friction feedback to VR with props.

We use this example of enhancing VR with props to demonstrate a key benefit of Stick&Slip: no existing technique can *both* increase or decrease surface friction on a prop of this size and material (not electrically conductive).

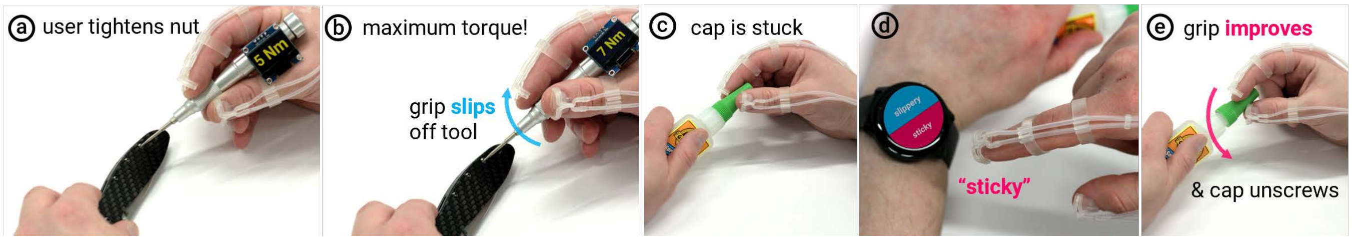

Figure 16: Stick&Slip with tools: (a) A user tightens a nut via a digital torque screwdriver. (b) At the maximum torque, our device pumps slippery liquid to provide an additional haptic cue. (c) A user unsuccessfully tries to open their glue. (d) The user activates on-demand stickiness, which increases friction and improves grip, (e) which assists the user to unscrew the cap.

9.2 Augmenting friction of everyday tools

We leverage liquid lubricants and adhesives because they modulate the friction of nearly any non-absorbent surface without the need for any surface instrumentation. Therefore, our approach can alter the friction of everyday objects and tools. Figure 16 (a-b) demonstrates our first example of how Stick&Slip can alter friction while interacting with everyday tools. Here, a user is tightening a nut with a digital torque screwdriver (Figure 16a). When they reach the maximum allowable torque, our device deposits slippery liquid, causing the user's fingers to slip off the tool and stop tightening (Figure 16b). This provides an additional haptic cue when maximum torque is reached.

Figure 16 (c-e) depicts a second example of altering the friction of everyday tools. Here, our device can improve users' grip. The user tries to unscrew a stuck glue cap but is unable (Figure 16c). They activate Stick&Slip on-demand via their smartwatch, which coats both their index and thumb's fingerpads (Figure 16d). This improves their grip on the cap, assisting them to ultimately unscrew the cap with less effort Figure 16e).

Each of these examples demonstrate that our device can augment everyday tools with variable friction, providing cues and aid to the user. This highlights another benefit of Stick&Slip: it would be impractical to augment these tools with any other existing approach (i.e., coating/grounding every tool for electroadhesion).

10 RECOMMENDATIONS AND FUTURE WORK

We now condense our recommendations based on the benefits and limitations of our approach, as informed by both our technical evaluation, user study, and pilots.

Timing. Because our sticky fluids are diluted with solvents like IPA to enable greater evaporation, they first feel slightly slippery to the user before their dramatic increase in friction as the solvent evaporates. Therefore, it is important to design with this in mind. We conservatively characterized this delay in our *Experiments* and used it to design our MR experience. For example, depositing sticky fluid on top of the ramp prop in anticipation of an upcoming sticky event did not interfere with immersion because participants felt that the initial slipperiness corresponded to sliding down the ramp. Similarly, we investigated liquids with a range of evaporation rates. While we implemented further studies and applications using fluids with rapid evaporation, there is opportunity considering liquids that *intentionally* leave a trail of liquid as a feature of the interaction.

Residue. Sticky liquids may leave residue in proportion to the added sugar. Once water has evaporated from this sugar, it is no longer sticky, but this is slower than desired for most interactions. Thus, based on our technical experiments, performance can be improved by either adding a third channel or opting to use a water-based liquid as the slippery liquid, which can also serve the dual purpose of acting as a washing fluid.

Wetness. Our approach to friction modulation might also be accompanied by a sensation of wetness. Surprisingly, only two participants mentioned this (and could be due to pseudo-haptics from visual suggestions of ice/water puddle). Still, we recommend designing with this user expectation in mind. For example, in our user study, we used visual effects that would not feel out of place if the participant experienced wetness.

Mixing liquids. As the first exploration of interactive liquid friction, we selected liquids that both alter friction and are *practical* to use, which yielded simple mixtures. It is likely possible to synthesize more advanced liquids. Because this is an early exploration, it is likely that future works may identify liquids that alter friction with fast onset and offset times but are entirely inert when interacting with skin and sensitive materials (e.g., surface lacquers). In the meantime, we can draw inspiration from products that contain our liquids (nail polish remover, hand sanitizer, etc.), but also include common additives like glycerin for improved practical long-term use [13, 49]. Moreover, liquids offer a wider design space than just friction, such as affective responses (e.g., pleasantness), which offers opportunity for further investigation [21, 22].

11 CONCLUSION

We proposed, engineered, and validated Stick&Slip, a new approach to altering everyday surface friction by coating the user's fingerpads with liquid. Unlike traditional actuators such as vibromotors or electroadhesion, which are confined to specific surfaces, our method uses liquid lubricants and adhesives. These substances can modulate the friction of nearly any non-absorbent surface without requiring specific surface instrumentation, resulting in a more universally applicable friction modulation.

We demonstrated the versatility of our technique in various applications, including mixed reality, virtual reality with props, and everyday objects. Our approach was validated through four technical experiments and a user study.

Stick&Slip points towards a new direction in HCI, in which engineered materials/chemicals offer alternative methods to achieve haptic sensations. Having shown that liquids can both modulate friction and be improved in their practicality, we hope to inspire future research exploring the use of liquids for haptics beyond friction modulation. Ultimately, we hope to provoke alternative strategies in areas of haptics that may otherwise be limited by traditional approaches.

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We would like to acknowledge that the ACM CHI 2024 conference has decided to take place in Hawaii, offering extremely limited options for remote participation. While some authors have chosen to present their work in person or bring its physical prototype to the CHI community, they have done so with compassion towards Native Hawaiians and with a heavy heart. We urge that the ACM's process for conference selection should more carefully consider the impact our conferences have on local communities. We especially want to acknowledge Prof. Josiah Hester, a Kānaka Maoli Professor in Computing, who organized comprehensive resources that educated us about the negative impacts of over-tourism and climate degradation in Hawaii[2]. Finally, the decision of some authors to participate in this conference does not represent the views of other members of our lab, who have chosen not to engage with this edition of the CHI conference due to its impact on Native Hawaiians.

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