Like a Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception

Aditya Shekhar Nittala
Saarland University
Saarland Informatics Campus
Saarbrücken, Germany
nittala@cs.uni-saarland.de

Klaus Kruttwig
INM-Leibniz Institute for New Materials
Saarbrücken, Germany
klaus.kruttwig@leibniz-inm.de

Jaeyeon Lee
HCI Lab
School of Computing, KAIST
Daejeon, Republic of Korea
jaeyeonlee@kaist.ac.kr

Roland Bennewitz
INM-Leibniz Institute for New Materials
Saarbrücken, Germany
roland.bennewitz@leibniz-inm.de

Eduard Arzt
INM-Leibniz Institute for New Materials
Saarbrücken, Germany
eduard.arzt@leibniz-inm.de

Jürgen Steimle
Saarland University
Saarland Informatics Campus
Saarbrücken, Germany
steimle@cs.uni-saarland.de

ABSTRACT

The emerging class of epidermal devices opens up new opportunities for skin-based sensing, computing, and interaction. Future design of these devices requires an understanding of how skin-worn devices affect the natural tactile perception. In this study, we approach this research challenge by proposing a novel classification system for epidermal devices based on flexural rigidity and by testing advanced adhesive materials, including tattoo paper and thin films of poly (dimethylsiloxane) (PDMS). We report on the results of three psychophysical experiments that investigated the effect of epidermal devices of different rigidity on passive and active tactile perception. We analyzed human tactile sensitivity thresholds, two-point discrimination thresholds, and roughness discrimination abilities on three different body locations (fingertip, hand, forearm). Generally, a correlation was found between device rigidity and tactile sensitivity thresholds as well as roughness discrimination ability. Surprisingly, thin epidermal devices based on PDMS with a hundred times the rigidity of commonly used tattoo paper resulted in comparable levels of tactile acuity. The material offers the benefit of increased robustness against wear and the option to re-use the device. Based on our findings, we derive design recommendations for epidermal devices that combine tactile perception with device robustness.

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CCS CONCEPTS

• **Human-centered computing → User studies**; **Interaction devices**; **Empirical studies in HCI**; *Haptic devices*.

KEYWORDS

Epidermal devices; skin interfaces; on-body interaction; haptics; tactile perception; psychophysics; materials.

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1 INTRODUCTION

Recent advances in new materials, electronics and human-computer interaction have led to the emergence of electronic devices that reside directly on the user's skin. These conformal devices, referred to as epidermal devices, electronic skin [18], e-tattoo, or interactive skin, have mechanical properties compatible with human skin: they are very thin, often thinner than a human hair; they elastically deform when the body is moving; and they stretch with the user's skin.

This new generation of skin-worn devices opens up opportunities for a broad range of important applications. For use in health and fitness, epidermal sensors can continuously monitor physiological parameters [14, 21, 78] in a device form factor that is ergonomic to wear and compatible with demanding body locations [27, 80]. For use in rehabilitation, electronic skin can add human-like sensory capabilities to flexible membranes, for instance to be integrated with prostheses [11, 52]. For applications in computing, interactive skin devices can augment the skin with interactive input and output capabilities, and hence seamlessly integrate the user interface of a computer system with the human body [28, 42, 49, 72, 74].

Very promising pioneering work has been presented and first devices have been made commercially available [45]. This development makes it very plausible that epidermal devices will soon have a more widespread use. At the same time, materials and fabrication techniques have matured and are now accessible to interface designers through various rapid prototyping platforms [28, 42, 47, 49, 72]. Moving beyond basic technical studies, interface designers and domain experts can now start exploring designs of devices that offer a high usability and user experience.

In this context, envisioning that epidermal devices will be ubiquitous in the near future, one central question that remains is how a skin-worn device affects the natural tactile perception of the skin. An ideal device would leave the user's natural perception undiminished, i.e., the device would be fully transparent to tactile stimuli. Indeed, very slim submicron devices have been presented that may come close to this property [14, 26, 70]. However, the thin form factor comes at the cost of more complicated handling and considerably reduced durability of typically less than one day. This limitation can make thicker devices the preferred choice in many cases. As a consequence, designers are confronted with a complex, multi-factorial design space. Choosing the best material option is a difficult design decision made more difficult because so far very little is known about the impact of epidermal devices on the user's tactile perception.

This paper contributes empirical results from the first systematic psychophysical investigation of the effects of epidermal devices on human tactile perception. Based on our findings, we derive recommendations that can guide designers of epidermal devices and skin-based interfaces in choosing the appropriate device form factor and materials. We start by proposing the metric of flexural rigidity for capturing the mechanical properties of an epidermal device that affect tactile perception. We contribute the first systematic classification of epidermal devices from the literature in material science, mechanical engineering, nanotechnology, biomedical engineering, robotics and HCI based on this metric. Our results allow us to identify common properties and to draw comparisons between devices. We also use the classification to inform our experimental conditions.

The main contribution of this paper are results from three psychophysical experiments that shed new light on the design of epidermal devices. We investigated the effect of device rigidity (mediated by device thickness and elasticity) on human tactile sensitivity thresholds, spatial acuity and roughness discrimination abilities. We also studied the variations across multiple body locations, on fingertip, hand and forearm. Results from our experiments show a significant effect of device rigidity on tactile sensitivity and roughness-discrimination abilities; more rigid devices increased the tactile sensitivity thresholds by up to 390% and roughness-discrimination thresholds by up to 490% compared with bare skin. Device rigidity had a considerably less strong effect on spatial acuity. On the sensitive fingertip, spatial acuity thresholds moderately increased by up to 50%, whereas the thresholds remained fairly unchanged on the less sensitive body locations.

Finally, based on the results of our experiments, we contribute recommendations that can inform the design of future epidermal devices. We also highlight the important trade-offs between material properties, mechanical robustness and tactile perception that designers need to take into consideration when designing epidermal devices.

2 RELATED WORK

Our contribution builds on prior work in new materials, epidermal devices, psychophysics and HCI:

Epidermal Devices. Research in material science and soft-matter electronics has contributed to the development of electronic skin, "an artificial skin with human-like sensory capabilities" [19]. Building on seminal work of Lumelsky et al. [46] and Someya et al. [55], a wide range of epidermal devices with increasingly skin-conformal properties has been developed. This includes devices for skin-mount physiological sensing such as EEG, ECG and EMG [14, 24, 26], skin hydration monitoring [22], blood oximetry [32], characterization of sweat [21] and thermal monitoring [63, 71]. Many of these devices are fully self-contained [30–32]. Inspired by this line of research, the human-computer interaction community has recently started investigating epidermal devices for interaction. Starting with the first interactive skin device [72], increasingly thinner devices have been presented that augment human skin with input and visual or tactile output capabilities [28, 42, 49, 56, 68, 74, 75]. Extrapolating from those rapid advances in design and fabrication strategies [48], it is easy to envision that such devices will be worn on the body for extended durations, for various applications such as health monitoring, sports, entertainment, etc.

Empirical Studies of On-Body Interaction. Previous empirical studies of on-body interaction have focused on input strategies of users. Wagner et al. [64] introduced a body-centric design space to describe, classify and compare different multi-surface interaction techniques. Prior work reported on the various input modalities and user preferences for on-skin input [73], identified user strategies for creating on-body

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gestures [51] and revealed that on-skin input increased the sense of agency [5].

Moreover, previous research has investigated mapping strategies for input elements on the skin. These include salient features on the palm [12, 17, 65], targets placed on the forearm [10], visual and tactile anatomical landmarks [4, 74], as well as mappings between skin and an off-skin display [6].

Psychophysical Studies of Tactile Perception. Classical psychophysical studies identified tactile acuity capabilities of bare skin through a variety of tests such as point-localization, two-point discrimination, tactile sensitivity, roughness discrimination, gap detection etc. [3, 38, 43]. Continuing on this work, previous research also studied how perception is influenced when hands are covered with gloves. This research from various communities such as dentistry and anesthesiology studied the comfort and frictional properties [54], two-point discrimination [7, 69], surface-discrimination [8] and tactile sensitivity [7]. These studies resulted in identification of various properties of gloves that help retain tactile acuity [8] and were followed by material recommendations [34]. We are aware of only one prior study that investigated the effect of a skin-worn overlay on tactile perception [75], which however was limited to only one specific device prototype, to one body location and to a surface discrimination task. In contrast, we contribute the first empirical study that systematically investigates the effect of epidermal devices of various rigidity, worn on various skin sites, on passive and active tactile perception.

3 CLASSIFICATION OF EPIDERMAL DEVICES

We propose to use flexural rigidity as a metric for mechanical characterization of epidermal devices regarding their expected effects on tactile acuity.

This metric allows us to provide the first systematic classification of prior work, to identify common properties and to draw comparisons between devices.

Flexural Rigidity

The key metric reported in prior research in HCI is device thickness (e.g. [28, 42, 42, 47, 72, 74]). Rarely do papers report on material properties such as maximum stretchability [72] or the elastic modulus [41]. The property of device thickness alone is not sufficient to characterize or to compare the tactile performance of devices. For instance, a piece of PET plastic foil is certainly more transmissive to tactile cues than a metal plate of the same thickness. Rather than the device's thickness, it is its resistance to bending that limits how well a tactile cue (i.e. localized mechanical stress applied on its outer side) is transmitted through the device. Let us consider a localized force acting from outside on the device. The thicker the device and the higher the elastic modulus of its material, the lower is the maximum stress on the skin and the larger is the area of stress redistribution [62]. For a less rigid device made of a soft material, the localized force is transmitted as a similarly localized stress on the skin.

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The resistance to bending is formalized in solid mechanics as flexural rigidity and has been previously used for calculating rigidity of thin films [36, 40]

$$FR = \frac{E * h^3}{12(1 - \nu^2)} \tag{1}$$

Flexural rigidity depends on the thickness of the device h, the material's constant Young's modulus E and its Poisson ratio ν. Despite the cubic influence of thickness, the effect of elastic modulus should not be underestimated, as the differences in elastic moduli of commonly used materials span more than four orders of magnitude. This implies that both the thickness and the material properties of a device are key parameters defining its effects on tactile acuity. We recommend reporting on these parameters for future work that contributes novel epidermal devices.

Classification of Prior Work

To provide an overview of the mechanical properties of state-of-the-art epidermal devices, we use the metric of flexural rigidity to systematically classify prior work from material science, mechanical engineering, nanotechnology, biomedical engineering, robotics and HCI. While presenting a fully exhaustive list would be beyond the scope of this paper, we consider the most recent devices (last 7 years) from research groups that are pioneers in the field. This focus allows us to identify common levels of flexural rigidity achieved in prior work and helps us to compare advances in materials with the state-of-the-art in HCI. Figure 1 presents the classification of prior work following its approximate flexural rigidity. For orientation of the reader, we plot in addition the overall thickness of the respective devices.

An epidermal device typically consists of a multi-material sandwich. These materials often have largely different elastic moduli. Elastomers, for instance, which are frequently used as substrate materials, have low elastic moduli (e.g., PDMS: ~ 2-5 MPa), whereas metallic conductors have elastic moduli approximately four orders of magnitude higher (e.g., Copper: 130 GPa). Calculating the exact flexural rigidity of an entire multi-layer epidermal device sandwich requires a complex experimental setup along with FEM (Finite Element Methods) analyses, which is beyond the scope of this work. Also, oftentimes, the prior research does not report on all the parameters required for calculating the flexural rigidity, which makes it even harder to calculate the exact levels of flexural rigidity.

For instance, DuoSkin [28] consists of a layer of tattoo decal substrate covered with a layer of gold leaf (~2 μm, 79

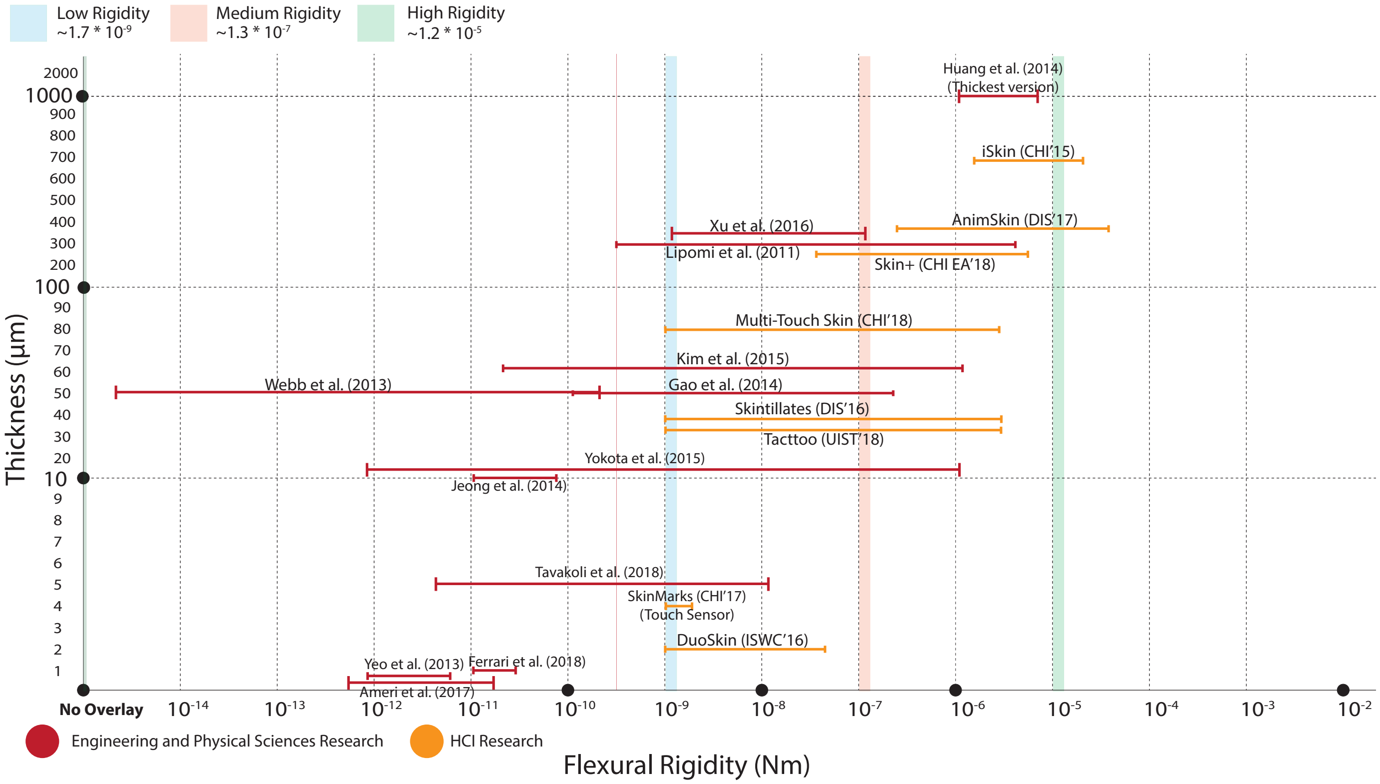

Figure 1: Classification of prior work based on flexural rigidity (ranges shown for devices made of multiple materials). Vertical axis shows total device thickness.

GPa). This combination leads to flexural rigidity ranging from ~[1 ×10^{-10} - 6×10^{-8}]Nm. Typically, the most rigid layer of the material sandwich has the strongest influence on the transmission of tactile stimuli. Hence, it is the upper end of the denoted range that is qualitatively capturing the behavior expected from a given device.

Figure 1 shows that the flexural rigidity of epidermal devices ranges between [$\sim 10^{-5}$–10^{-15}] Nm. The majority of work, including all work from the HCI community, is situated in the area of [$\sim 10^{-5}$–10^{-9}] Nm. Some pioneering work from materials science extends further to extremely soft devices of down to $\sim 10^{-15}$ Nm. The total thickness of devices ranges from less than 1 μm up to $\sim$ 1000μm, while the vast majority of devices are 1 μm – 100μm thick.

By clustering devices using their upper end of flexural rigidity (which has the strongest effect on tactile acuity), we identified three main clusters:

- **Flexible Devices ([10^{-5}, 10^{-7}] Nm):** Most of the current day epidermal devices in HCI and some work from material science fall into this category [21, 67, 68, 72]. These devices are made of elastomers of considerable thickness (e.g. ~240-700 μm in [67, 68, 72]) or contain layers of metallic conductors that are relatively thick (e.g., 20–30 μm in [42, 49, 74, 75]).
- **Highly-Flexible Devices ([10^{-7}, 10^{-9}] Nm):** Devices in this region are highly flexible, conforming well even to smaller wrinkles on the skin. They are typically thinner than 5 μm. The limitation of these devices comes from their using functional materials of high moduli that are still fairly thick (e.g., DuoSkin [28] uses ~2μm thick gold-leaf) or their use of a substrate material with a high elastic modulus, e.g., [28, 74], which use a temporary tattoo paper substrate with a high elastic modulus ($\sim 0.8 - 1GPa$) that can be a few micron thick.
- **Ultra-Flexible Devices (≤ 10^{-9} Nm)**: Devices in this category possess very low flexural rigidity levels and hence are very stretchable and flexible. Typically, these devices use polymers (e.g. PEDOT:PSS) or very thin metallic layers (<1μm) as functional materials [14, 26, 79]. It is interesting to note that though the devices reported by Webb et al. [70] have a high thickness ($\sim$ 50μm), they have very low flexural rigidity. This is because they use low-elastic modulus substrate ($\sim 30kPa$), which is roughly 30 times less than the elastic modulus of a commercial temporary tattoo paper used in [28, 42, 74, 75]. The functional materials used in Webb et al. [70] are also elastomeric in nature (Silicon nanomembranes), due to which the overall flexural rigidity is very low. This examples proves that thickness should not be the only metric considered when evaluating

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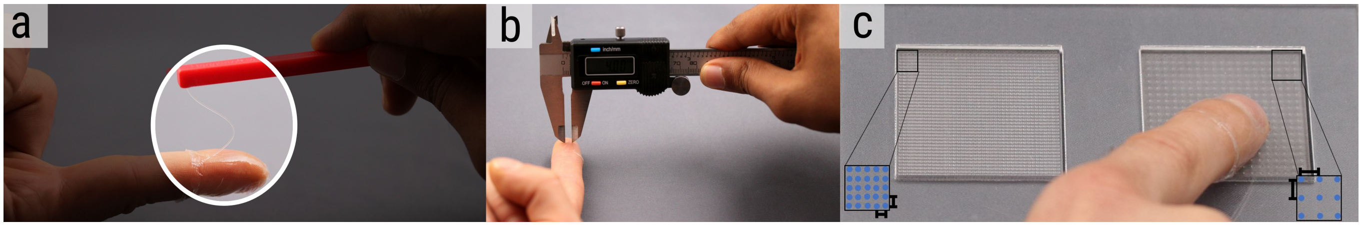

Figure 2: Overview of the three experiments. (a) Von-Frey monofilaments applied to measure sensitivity, (b) tips of the digital calipers for Two-Point Orientation Discrimination Task, (c) Participants performed the roughness discrimination experiment by exploring two surfaces with different spacing between "dots" (the surface on the left is the baseline).

the overall flexibility of an epidermal device. The material conditions for our experiments were informed from these clusters.

4 EXPERIMENT OVERVIEW

To investigate how epidermal devices affect a user's natural tactile perception abilities, we conducted a series of three psychophysical experiments. We designed the experiments to measure three specific aspects of tactile perception and to involve both active and passive tasks: (1) tactile sensitivity to a single stimulus (passive), (2) distance threshold (spatial acuity) between two stimuli (passive), and (3) tactile-roughness discrimination capability (active). We compared the results from bare skin with skin-worn patches of different flexural rigidity to quantify the effects of the flexural rigidity of an epidermal device.

Rigidity Levels and Materials

We chose three conditions of flexural rigidity to be tested in our experiments based on the representative levels of flexural rigidity we identified in the classification of state-of-the-art epidermal devices shown in Figure 1. These conditions are: **High Rigidity** Material: $\sim 10^{-5}\ Nm$, **Medium Rigidity** Material: $\sim 10^{-7}\ Nm$, **Low Rigidity** Material: $\sim 10^{-9}\ Nm$, and Baseline condition: **Bare Skin**.

Material Choice and Fabrication. To represent epidermal devices of those levels of flexural rigidity, we engineered passive patches of elastomers to exhibit the respective rigidity levels. As materials, we chose the most commonly used substrate materials for epidermal devices in the HCI and materials science communities. These materials are temporary tattoo decal paper (Silhouette Inkjet Printable Tattoo paper, Young's modulus of $\sim 1GPa$ and thickness of $\sim 2.5\mu$m) used for electronic rub-on tattoos in [14, 26, 28, 42, 57, 74, 75]) and poly(dimethylsiloxane) (PDMS), which is a bio-compatible, elastic material actively used for the design of epidermal devices [15, 21, 31, 47, 66, 70, 72]. We intentionally opted for using passive patches rather than functional epidermal devices, as this allowed us to more carefully control the rigidity properties of the material.

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Polymer films were manufactured by a doctor blade technique with an automatic film applicator (AFA-IV, MTI Corp, USA). For fabricating the Medium Rigidity patch Sylgard 184 was used (2.7MPa, Dow Corning, USA), and OE-6550 (5.1MPa, Dow Corning) was used for the High Rigidity patch. The silicone layer was deposited on polyethylenterephthalat (PET) films and cured at 95°C for 1 hour. Previous work in HCI [28, 42, 49, 72] used external adhesives such as mastic or temporary tattoo paper adhesive. Here, we chose to use commercially available soft-skin adhesive (MG7-1010, Dow Corning), a subclass of PDMS. It was deposited on top of the first layer and cured again for 1 hour at 95 °C. The thickness of the patches was determined with an optical microscope (Olympus). The thickness values were 40±9μm for the Medium Rigidity patch and 390±70μm for the High Rigidity patch. The thickness values for the SSA layer were 144±27μm for the Medium Rigidity patch and 177±58μm for the High Rigidity patch.

Experimental Verification of Flexural Rigidity. The material characteristics of commercially available Temporary Tattoo Paper have been reported in previous literature [14, 44], giving a flexural rigidity of $\sim 1.7 \times 10^{-9}$Nm. In contrast, as the PDMS-based patches were custom-fabricated and composed of two different layers for this experiment, we analyzed their flexural rigidity, experimentally determined by measuring deflection under their own weight. Samples with a constant width have been excised and placed at the edge of a microscope slide. The length L and deflection angle α of the films were determined from photographs, as shown in Figure 3. The entire thickness h for each individual sample has been analyzed with optical microscopy. The flexural rigidity was then calculated as: $FR = \frac{\rho * g * L^3 * h}{6(1-\upsilon^2)\tan\alpha}$ with density $\rho = 1000$ kg m^{-3} (Sylgard 184 = 936 kg m^{-3}; OE6550 = 1109 kg m^{-3}; MG7-1010 = 994 kg m^{-3}); υ(Poisson's ratio)=0.48; g = 9.81 m s^{-2}. The experimental values obtained for the Medium Rigidity and High Rigidity version of the PDMS substrates, including the adhesive SSA layer, were $1.3 \pm 0.62 \times 10^{-7}$ Nm and $1.2 \pm 0.5 \times 10^{-5}$ Nm respectively.

Body Locations

For the Two-Point Orientation Discrimination and Tactile Sensitivity experiments we chose three locations: the tip of the index finger (***Fingertip***) (Figure 4 (a, b, c)), the dorsal side of the hand (***Hand***), and the volar side of the forearm (***Forearm***), as shown in Figure 4(d & e). The main reason for choosing three body locations was to understand how tactile perception with epidermal devices varies depending on the natural sensitivity and acuity of skin sites. The locations have varying levels of cutaneous receptors (fingertip > hand > forearm) [43], which allows us to study epidermal devices for varied inherent sensitivity levels of the human body.

We chose locations on the upper limb because this body part is commonly used in prior work on epidermal devices [9, 21, 32, 39, 49, 72, 74]. Apart from this, hand and forearm are very commonly used for various activities where unimpaired tactile perception is essential. As an input and output space, the hands and forearm have been considered as promising candidates in HCI. Researchers used the dorsal side of the hand and the forearm as an extended input space for smartwatches [77] and explored the potential of expressive input using skin deformation on the forearm [50, 74]. We expected that not only proprioception but also the cutaneous sensation generated when tapping at a certain position, drawing gestures on skin, or squeezing skin would play an important role for the usability of epidermal interfaces. As an output space, hands and forearm have been considered as preferable target locations for wearable interfaces, as they have a relatively high sensory capacity and provide large and flat surfaces on which a display can be mounted [23, 53].

For the roughness discrimination task, we chose only one body location, the Fingertip, because this task is typically performed with the fingertip [33, 35]. We conducted the experiment on the fingertip of the dominant hand.

Participants

We recruited 16 participants (9 female, mean age: 27.4, SD: 3.1) from the local university. Participation was voluntary. Each participant received a compensation of $30 for completing the three experiments.

Experiment Design

All experiments were performed in a silent room with participants blind-folded (Figure 4 (f)). To eliminate any potential auditory cues, the participants were wearing noise-canceling headphones. The patch dimensions (4.5 x 4.5 cm) were kept constant for all materials. Responses for all the experiments were logged on a laptop computer.

We randomized the order of three experiments and the body locations across all participants. For experiments 1 and 2, which were administered on three different skin sites, the order of skin sites was randomized. There were a total of 4 (material) × 3 (skin sites) = 12 conditions for experiments 1 and 2. For experiment 3, which was administered only on the *Fingertip*, there were a total of 4 (material) conditions. The series of three experiments took 3-3.5 hours in total (~70-90 minutes each for experiments 1 and 2 and ~45-60 minutes for experiment 3). To avoid fatigue, the experiments were conducted in three independent sessions, on separate days. For all the experiments, the participants were free to take breaks in between. After every experiment, we conducted a semi-structured interview to gather qualitative feedback. The interviews were audio-recorded.

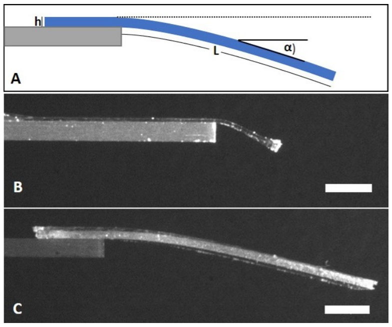

Figure 3: Experimental determination of the flexural rigidity of composite films: (A) Schematic representation of the experimental analysis of the flexible rigidity of composite PDMS films. L indicates the length of the film and h the thickness. (B) Medium Rigidity and (C) High Rigidity patches were investigated. The scale bar represents 2.5 mm. N = 3 independent manufactured films with a total of 9 samples for each condition were analyzed.

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Analysis

To counter the inherent interpersonal variation of tactile perception abilities between participants, we established the Bare Skin condition as the baseline. For each participant, we calculated the thresholds of all patch conditions on the same body site relative to this personal baseline. This resulted in a normalized measure for the relative increase of tactile thresholds generated by a material condition.

Since our data did not have a normal distribution, we performed the Aligned Ranked Transform from Wobbrock et al. [76]. For each experiment, the normalized data were first ranked and aligned by the ART tool [76] followed by a repeated-measures ANOVA, after which the Tukey HSD (Honestly Significant Difference) post-hoc test was run, with 95% confidence level. Mauchly's test showed no sphericity.

5 EXPERIMENT 1: TACTILE SENSITIVITY

Experiment 1 identified threshold force detection levels on three skin sites using patches with three different levels of flexural rigidity and bare skin as a baseline.

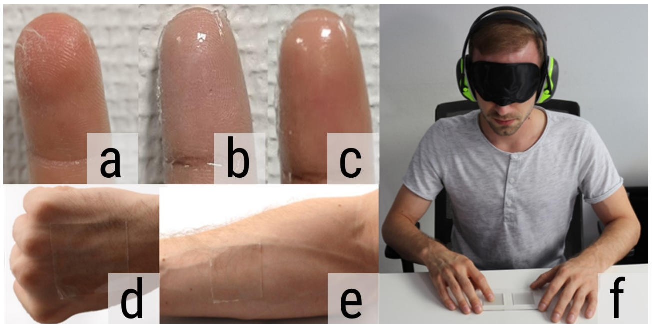

Figure 4: Three patch conditions with varying levels of flexural rigidity: (a) Patch with low rigidity level ($\sim 1.7 \times 10^{-9}$), (b) medium rigidity ($\sim 1.3 \times 10^{-7}$), (c) high rigidity ($\sim 1.7 \times 10^{-5}$). Patches were applied on (a) the *Fingertip*, (d) *Hand* and (e) *Forearm*. (f) Participant performing roughness-discrimination task.

Apparatus

The tactile sensitivity measurements are used to get an estimate of how well we can perceive the minutest of the deformations that the human skin undergoes. Traditionally, this is done through Von-Frey filaments, which measure the sensitivity at given skin sites. This method is widely used in reseach literature, is easily reproducible, and is a quick and easy way for measuring tactile sensitivity [1, 3].

Commercially available Von-Frey filaments[1] were used for delivering constant force stimuli [1, 3]. A total of eleven calibrated monofilaments was chosen for all locations: 0.008g, 0.02g, 0.04g, 0.07g, 0.16g, 0.4, 0.6g, 1g, 1.4 g, 2.0g,and 4.0g (1 gram force = 9.8 mN).

Design and Procedure

We used the Method of Limit [3, 16, 25] with Yes/No paradigm. Each condition consisted of 4 series of trials with alternating ascending or descending forces. The starting series (ascending or descending) was chosen randomly. Since the participants are administered very low force levels, before each trial the experimenter gently tapped with a finger on the test location to indicate the start of the trial. This helped the participants to focus and accurately count the number of stimuli.

For each trial, a monofilament of the respective force value to be tested was pressed five times against the selected skin site, for approximately 1 s with a 1 s gap between presses. After administering five stimuli, the experimenter asked the participant how many presses she had felt. The force level was deemed to be detected if the participant reported having felt at least four of the five stimuli.

Results

The average Tactile Sensitivity thresholds for all skin locations and rigidity conditions are shown in Figure 5. The results from the Bare Skin condition on the fingertip are inline with sensitivity thresholds reported in previous research (0.06g ±0.09) [7]. As expected, the thresholds increased with increasing rigidity of the patch, on all skin locations.

Figure 6 depicts the normalized tactile sensitivity for each patch condition. The results show that the average increase in intensity for all body locations was 34.76% for the Low Rigidity patch, 97.6% for the Medium Rigidity patch and 221.6% for the High Rigidity patch. *Hand* showed the highest and lowest levels of increase (26.3% for the low rigidity patch and 392% for the high rigidity patch).

One-way repeated measures ANOVA showed a significant effect of Flexural Rigidity on tactile sensitivity for all skin sites ($F_{3,60} = 26.31$, $p = 5.48 \times 10^{-11}$, $F_{3,60} = 18.85$, $p = 9.09 \times 10^{-9}$, $F_{3,60} = 13.9$, $p = 5.45 \times 10^{-7}$ for *Fingertip*, *Hand*, *Forearm* respectively). For the *Fingertip*, the Tukey HSD post-hoc test showed significant difference among all the patch pairs ($p < 0.012$) except for the Bare Skin-Low Rigidity pair ($p = 0.26$). For the *Hand* condition, the Tukey HSD post-hoc test showed significant difference between all patch pairs ($p < 0.006$) except for the Bare Skin-Low Rigidity and the Medium Rigidity-Low Rigidity pairs ($p = 0.36$ and $p = 0.28$ respectively). For the *Forearm* condition, the Tukey HSD post-hoc test showed significant difference between all patch pairs ($p < 0.032$) except for the Medium Rigidity-Low Rigidity and the Medium Rigidity-High Rigidity pairs ($p = 0.46$ and $p = 0.52$ respectively).

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On the most sensitive skin site, the *Fingertip*, the Low Rigidity patch showed an increase of 30.3% compared to Bare Skin. The relative difference in thresholds between Low Rigidity and Medium Rigidity conditions was 87.3% while the difference between the Medium Rigidity and High Rigidity patches was 71.5%. It is worth noting that the relative difference between the Low Rigidity and the Medium Rigidity patch is always of the order to 50%, which is acceptable given that the Medium Rigidity patch has a 100x higher flexural rigidity.

Discussion

Results from Experiment 1 show that epidermal devices of different rigidity considerably affect tactile sensitivity levels. While the Low Rigidity tattoo patch had a comparably small effect on tactile thresholds, with less than 50% increase on all body locations, the most rigid patch showed increases of up to almost 400%. The results further show that the skin site is a major influencing factor. For example, on the *Fingertip*, it can be observed that there is significant difference

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[1] http://www.danmicglobal.com/semmesweinsteinmonofilament.aspx

between the Low Rigidity and both Medium and High Rigidity patches. For the less sensitive regions, however, our results show a considerably lower relative increase in thresholds, which was statistically not significant. One of the key implications of this observation is that on less sensitive body locations, a more rigid and robust PDMS overlay can be used without overly compromising on tactile sensitivity. The range of tactile sensitivity between participants varied from 0.011 to 0.07g for the Bare Skin condition. Compared to this, the maximum difference in intensity thresholds between the Bare Skin and the Low Rigidity conditions for all the participants was lower (0.02g).

It is very interesting to note that the intensity thresholds we have identified with our most rigid patch condition $\sim$ 0.12g (SD=0.032) are more than three times lower than values reported in prior work for surgical gloves $\sim 0.4g(SD = 0.6)$ [7]. Those gloves are used by surgeons for high-precision activities during surgeries. We conclude that epidermal devices with flexural rigidity levels corresponding to our most rigid patch condition retain a superb level of tactile sensitivity sufficient for high-precision manual activities.

Furthermore, these findings confirm our initial hypothesis that thickness alone is not a sufficient parameter for predicting an effect on tactile sensation, as the surgical gloves tested in [7] were considerably thinner ($\sim$ 260μm [2]) than our most rigid patch condition ($\sim$ 390μm). This highlights the relevance of other material properties. The E modulus of natural rubber latex is [0.01-0.1] GPa, multiple times higher than our thickest sample. One additional factor contributing to the inferior behavior of gloves might also be that they enclose small air gaps, whereas our patches had conformal skin contact.

6 EXPERIMENT 2: TWO-POINT ORIENTATION DISCRIMINATION

This experiment tested spatial acuity levels using a 2-point orientation discrimination [61] with two-interval forced choice (2IFC) paradigm on three skin sites using patches with three different levels of flexural rigidity and bare skin as a baseline.

Apparatus

We used a standard, commercially available two-point discriminator (Digital Vernier Calipers, Mitutoyo Corp). The tactile stimuli were the tips of the two-point discriminator. The width of each tip was 1 mm and the thickness was approximately 1 mm. The stimulus was manually applied by the experimenter [43, 61]. The spacing intervals were adopted from previous literature [61]. Based on pilot tests, we used 10 tip separations from 0 to 5mm (0, 0.5, 1.0, ...) for the *Fingertip*. For *Hand* and *Forearm*, we used 2.5 mm spacing intervals (0, 2.5mm, 5mm, 7.5mm .. 45mm). The upper limit was determined from literature [43, 61] and pilot tests.

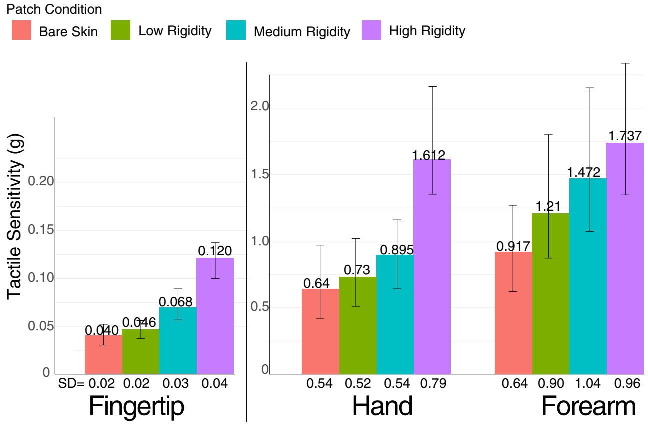

Figure 5: Tactile Sensitivity thresholds for all skin sites and all the patch conditions, with 95% confidence intervals. Lower thresholds mean higher sensitivity.

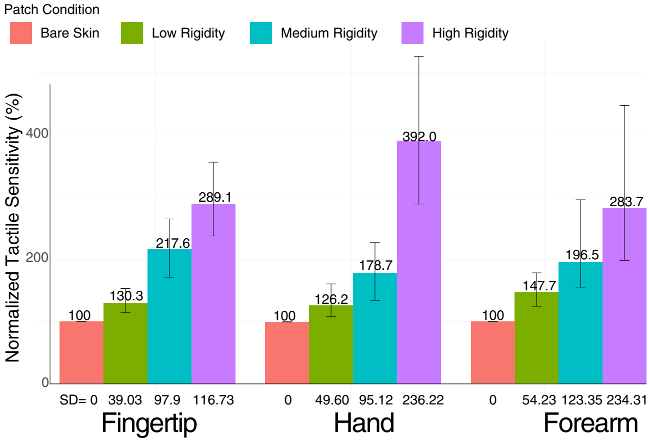

Figure 6: Normalized Tactile Sensitivity levels relative to the Bare Skin condition, with 95% confidence intervals. Lower thresholds mean higher sensitivity.

Design and Procedure

We used the Method of Limits [25] to determine the thresholds. A total of four alternating ascending or descending series was administered. The starting series (ascending or descending) was chosen randomly. To reduce the cognitive load on the participants, the experimenter informed them of the location where the stimulus was to be applied so that the participant could concentrate on the stimuli being presented at the specified site.

For each trial, the stimuli were presented consecutively in randomized order, once with the two points oriented along the arm and once oriented perpendicular to the arm. The

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[2] https://www.molnlycke.ca/SysSiteAssets/master-and-local-markets/documents/canada/biogel-surgeons.pdf

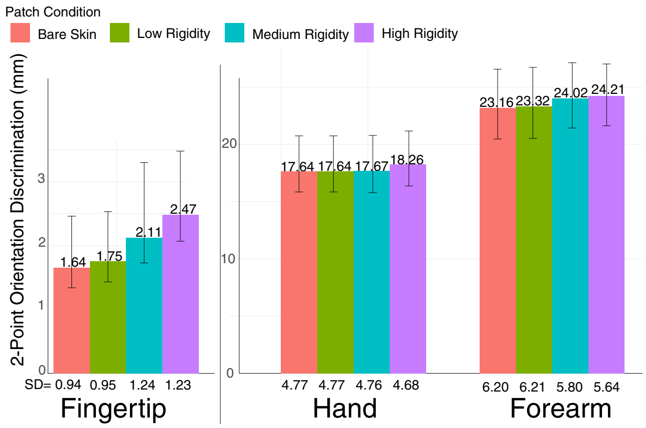

Figure 7: Two-Point Orientation Discrimination thresholds (in mm) for all skin sites and patch conditions, with 95% confidence intervals. Lower thresholds mean higher spatial acuity.

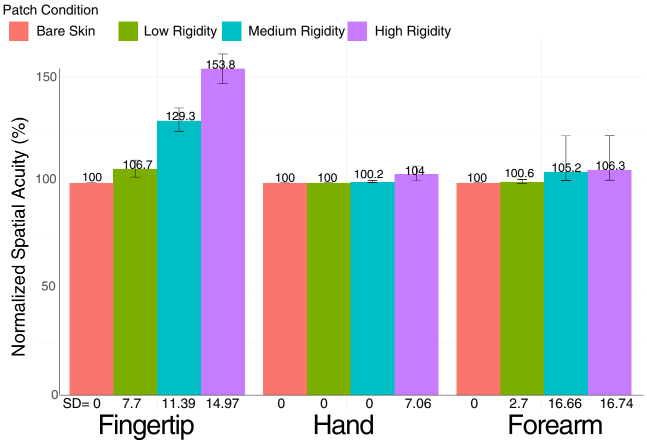

Figure 8: Normalized Two-Point Orientation Discrimination thresholds (in mm) for all skin sites and patch conditions, with 95% confidence intervals. Lower thresholds mean higher spatial acuity.

stimuli were applied for one second; the inter-stimuli interval between horizontal and vertical stimuli was 3 seconds. Then the participant was asked to report whether she had perceived the points that were oriented along the arm before or after the perpendicularly oriented points.

Before the actual experiment, there was a training phase wherein the experimenter provided stimuli multiple times against the three skin sites, allowing the participant to become familiar with the experiment and ensuring that the stimuli were non-nociceptive.

Results

The average two-point orientation discrimination thresholds for all skin locations and rigidity conditions are shown in Figure 7. The thresholds from the Bare Skin condition are inline with the literature [43, 61]. For the normalized thresholds (Figure 8), the average increase in spatial acuity thresholds for all body locations was 2.43% for the Low Rigidity patch, 11.56% for the Medium Rigidity patch and 21.36% for the High Rigidity patch.

Fingertip (Figure 7 and Figure 8) showed the highest increase in the spatial acuity thresholds. The Low Rigidity patch showed a relatively small increase of 6.7 %, while the most rigid patch showed the highest difference when compared to Bare Skin (increase of 53.8 %).

The less sensitive skin sites, *Hand* and *Forearm*, showed only small increases in thresholds. Even the most rigid patch (which is four orders of magnitude more rigid than the Low Rigidity patch) showed only a 4.0% increase for *Hand* and 6.3% for the *Forearm* when compared to bare skin.

This is also evidenced by one of the comments from a participant: “It does not make a difference between the patches, as long the distance between the needles is the same." [P14].

One-way repeated measures ANOVA showed significant effect of Flexural Rigidity on tactile acuity for *Fingertip* ($F_{3,58} = 5.649$, $p = 0.00187$). The Tukey HSD post-hoc test did not show any significant difference between all patch pairs ($p < 0.36$) except for the Bare Skin-High Rigidity pair ($p = 0.0008$). However, the difference was noticeable for Bare Skin-Medium Rigidity pair, yet not significant ($p = 0.081$). For *Hand* and *Forearm* one-way repeated measures ANOVA did not show any significant effect of Flexural Rigidity on spatial acuity ($F_{3,56} = 1.25$, $p = 0.3$ and $F_{3,56} = 1.269$, $p = 0.294$ respectively).

Discussion

Our results show that the skin site is a key influencing factor for the effect of epidermal devices on spatial acuity. On the *Fingertip*, more rigid patches resulted in a moderate increase of thresholds by up to 54%. This result is in line with the previous research, which showed significant difference in tactile acuity on the fingertip for surgical gloves with ~ 100μm thickness. On the less sensitive skin sites, however, the rigidity of the patch had only a very little effect. This is because, for tip distances as large as ~ 20 mm, patches with the rigidities considered here do not reduce the separation of the stress maxima transferred from the tips to the skin. For tip distances of ~ 1.5 mm, which are perceived as separated by bare skin, the more rigid patches blur the stress maxima such that only larger distances are perceived as separated. The spatial acuity thresholds varied from 1mm to 5mm among our participants. Considering this large interpersonal variation, the difference in the thresholds between Bare Skin-Low Rigidity condition are much smaller (avg=6.7%) with an increase of [0-16.7%].

Since our results for the fingertip showed a significant difference in spatial acuity between both the PDMS patches and bare skin, we recommended using Low Rigidity devices

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on the fingertip if exquisite spatial discrimination abilities are desired. On less sensitive skin sites with spatial acuity thresholds similar to the *Hand* or below, a more rigid and mechanically robust patch of any of our rigidity levels can be used without generating any practically relevant decrease in spatial acuity.

7 EXPERIMENT 3: TACTILE DISCRIMINATION OF TEXTURED SURFACES

The purpose of Experiment 3 is to analyze how the human sensory information processing varies with different patch conditions for varying surface textures. This test is administered only on the fingertip since it has the largest concentration of cutaneous receptors and is typically used for active tactile perception tasks. We adopted this task from the classical roughness discrimination experiment [35].

Apparatus

Square surfaces of 4x4cm with grids of raised “dots" were fabricated using a 3D printer (Objet Connex 260). The baseline surface had a center-to-center spacing of dots of 1.0mm. The modified surfaces had increasing dot spacing in intervals of 5% up to 100%. These intervals are similar to those used in previous work [35], while extending to larger intervals to account for the effect of the patch conditions. The dots were 0.65mm high and the diameter was one-third of the spacing. This design of surfaces was based on previous work, which showed that spacing of dots plays a larger role than dot size in the roughness discrimination task [35, 38, 58]. An acrylic plate was laser cut to form a frame for holding both the surfaces, as shown in Figure 2 (c).

Design and Procedure

The patches were administered on the *Fingertip* of the dominant hand. We used the method of limits [25] to determine the surface offset threshold. Each patch condition had a total of 4 sets (2 ascending and 2 descending) of trials with alternating ascending or descending forces. The starting series was randomly chosen.

For each trial, a two-alternative discrimination paradigm was used. Surfaces were presented in pairs (one of them baseline) and the participants were asked to respond whether the surfaces were similar or different after consecutively feeling the two surfaces with the fingertip of the dominant hand. Participants were free to explore the surfaces in any pattern (horizontal, vertical, diagonal, random, etc.) of their choice. There was no time limit for performing each trial.

Since the patches might tear or rip off the skin, visual inspection of the patch was carried out before each trial. If a patch was damaged, a photo of the torn patch was captured (Fig.10), a new patch was applied and the trial was repeated.

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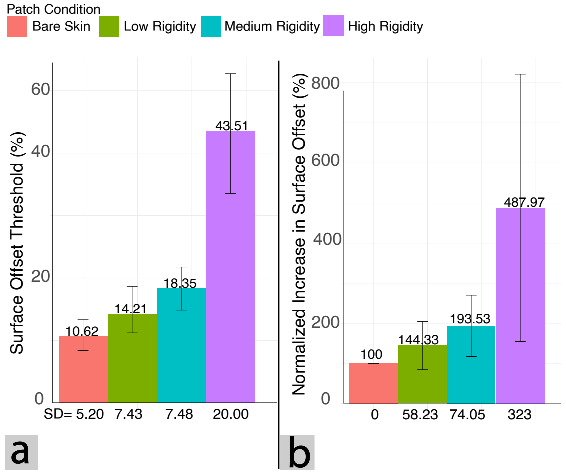

Figure 9: (a) Absolute Surface Offset Thresholds of tactile roughness discrimination task for all patch conditions, with 95% confidence intervals. (b) Normalized Tactile Roughness Discrimination levels relative to the Bare Skin condition, with 95% confidence intervals. Lower thresholds mean higher capability to discriminate surfaces.

Results

The average surface offset threshold that the participants could discriminate relative to the baseline surface is shown in Figure 9 a. As expected, the threshold increased with increasing rigidity of the patch. The relative increase compared to the bare skin performance, normalized per participant, is shown in Figure 9 b. The results revealed a 44.3% increase in the surface offset threshold for the LOW RIGIDITY device and 93.5% increase for the MEDIUM RIGIDITY patch. The HIGH RIGIDITY performed the worst with an average increase of 487.7%. This is the highest relative increase found in all our experiments.

One-Way repeated measures ANOVA ($F_{3,60} = 36.69$, $p = 1.35 \times 10^{-13}$) revealed significant difference between the patch conditions. The Tukey HSD post-hoc test showed significant differences between all patch-pairs ($p < 0.01$) except the LOW-RIGIDITY AND MEDIUM-RIGIDITY pair.

Discussion

One of the key material properties of epidermal devices required for the tactile roughness discrimination task is high tactile transfer capability, i.e, the capability of material to transmit the underlying tactile roughness information to the cutaneous receptors. This is specifically more important for the roughness discrimination task since there is high-frequency tactile information resulting from lateral exploration of the surface that needs to be transmitted to the cutaneous receptors. For devices with high flexural rigidity the area of stress distribution is larger [2]. Hence the detailed information of the surface is not transmitted accurately to the underlying receptors.

Figure 10: (a) Patches of the Low Rigidity condition were damaged during the surface discrimination task for 10 participants. (b) 4 patches of the Medium Rigidity condition were damaged.

Results from the roughness discrimination task indicate that there is significant reduction in the tactile roughness perception with both the PDMS patches, while the Low-Rigidity patch condition only showed a moderate effect. Particularly the most rigid patch showed a very strong increase with an almost five times higher offset than bare skin. This suggests that the flexible patch is not an appropriate choice for performing activities that require high-resolution exploration of surfaces. As the difference between the Low Rigidity patch and Medium Rigidity patch is not very large, the latter is a good trade-off between active tactile perception and mechanical robustness.

8 OVERALL DISCUSSION AND DESIGN IMPLICATIONS

Effect of Epidermal Devices on Tactile Perception

The results of all three experiments have shown that the rigidity of epidermal devices has a significant effect on human tactile perception abilities. It is hence a critical factor that needs to be considered in the design of epidermal devices.

As expected, tactile perception abilities decrease with increasing rigidity of the epidermal device. The most flexible patch condition resulted in comparably small effects on tactile sensitivity, tactile acuity, and surface roughness perception on all skin sites, with relative increase of thresholds ranging between 6.7–47.7 %. In contrast, our most rigid device condition resulted in considerably larger increases of up to almost four times for intensity thresholds and almost five times for roughness discrimination offsets. In consequence, we can recommend *ultra-flexible* devices for all tactile tasks and all body locations if tactile perception abilities are key.

The results further revealed that skin location is a major influencing factor. On the highly sensitive fingertip, the Low Rigidity patch performed significantly better for tactile intensity perception than the more rigid patches. In contrast, on the less sensitive *Hand* and *Forearm*, we identified a less pronounced effect. On these skin sites, a more rigid device can be chosen, offering a good trade-off between tactile perception and mechanical robustness. This contrast is even more pronounced for spatial acuity, where we did not identify any practically relevant difference between our device conditions on the hand and forearm. This implies that a device of any rigidity level amongst the ones tested in our experiment can be used in situations where spatial discrimination abilities are required on less sensitive skin sites, while tactile intensity is less relevant. For instance, this finding can be relevant for tactile output devices that spatially encode information, for instance using a matrix of taxels.

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For active tactile perception, more rigid devices should be avoided if possible, as they considerably increase perception thresholds. However, *highly flexible* devices perform almost as well as *ultra-flexible* ones, presenting an attractive trade-off between roughness discrimination and mechanical robustness.

It is worth highlighting that our most rigid device condition yields considerably better results for tactile sensitivity and tactile acuity than thin surgical gloves studied in related work [7]. This finding suggests that despite the considerable increase in thresholds identified in our experiment, devices of this rigidity might still retain superb performance for high-precision manual tasks, such as surgeries.

Mechanical Robustness of Materials

One of the key observations we made during the roughness discrimination task was that the mechanical robustness of the patch varied considerably based on its rigidity. The lateral movements required for the active roughness discrimination task caused mechanical damage to the patches. The damage was more pronounced for the Low-Rigidity patch. The tattoo patch ripped off for 10 participants (once for 8 users and 4 times for 2 users). Figure10 shows the structural damage before the patch was replaced. It can be seen that the level of damage varied from small cracks to complete damage of the patch. In contrast, the Medium Rigidity patch, which had higher flexural rigidity compared to the *Low Rigidity* patch, showed considerably higher durability, ripping off for 4 participants. Our most rigid patch was the most mechanically durable and was not damaged for any participant.

Re-Usability and Adhesion

Flexural rigidity of the device also determines its re-usability. In our case, the overlay with the highest rigidity was the most re-usable. In contrast, the Low Rigidity tattoo material is usually a single-use device. Once applied on the skin, it is very hard to remove from the skin without damaging the patch. Moreover, in some cases removing the tattoo material caused participants discomfort when it was applied on a non-glabrous area on the forearm or hand.

Qualitative observations from our experiments further highlight the relevance of the adhesive. We found that adhesive properties of the epidermal devices are important criteria for re-usability. In general, silicones are a versatile class of polymeric materials exhibiting a low surface energy, high flexibility of the silicone network and a high permeability to water vapor [59, 60]. SSAs differ from analogous silicone elastomers by the absence of reinforcing silica filler and the exhibition of a minimal viscous component [60]. After the application of deformation pressure, only minimal energy dissipation occurs, resulting in a rapid debonding process [60]. In conjunction, these properties allow a sensitive, less traumatic removal of skin adhesives, which is particularly important for the attachment to the sensitive skin of neonates or the skin of elderly people [29, 37]. Hence, it was very easy for the participant to remove the patch without discomfort even on skin sites with body hair and without any visible residues. Designers should take these aspects into account while realizing epidermal devices. For example, for long-term physiological monitoring that might require expensive and re-usable sensors to be placed on the body, a device with higher flexural rigidity can be developed. However, for an inexpensive device such as touch sensors [28, 42, 74], which can be easily fabricated with off-the-shelf materials, the flexural rigidity can be very low and the device dispensable.

9 LIMITATIONS

Flexural Rigidity Classification: Our classification of epidermal devices from prior work indicates ranges of flexural rigidity rather than absolute points. Calculating the latter would require FEM-based modeling of the material sandwich of a device including the exact coverage of functional material for each layer, which is rarely reported. We take a conservative approach by assuming that the entire layer is covered by the functional material. The effective flexural rigidity is hence within the limits of the range indicated in our classification.

Rigidity Levels: We tested three levels of flexural rigidity representative of today's devices. As materials and fabrication techniques have matured, we believe it is safe to expect that these levels will also be appropriate representatives for devices we may see in the future. Moreover, even if future devices were to reach considerably lower levels of flexural rigidity, our results provide some close indication of their performance, which would be situated between our baseline and low rigidity conditions.

Cutaneous Stimuli: Our experiments investigated the types of tactile stimuli most commonly chosen in psychophysical studies. Future work should investigate the effect of epidermal devices on other cutaneous modalities, such as vibrotactile or thermal cues.

Participants and Body Location: We have conducted our experiments with healthy adults in their twenties. It remains to be studied how epidermal devices affect the tactile perception abilities of people with lower sensitivity, such as the elderly. Our findings are limited to locations on the upper limb. Future work should address additional skin sites.

Analytical Model: We have not developed a generalized model of how flexural rigidity affects human thresholds of perception. While our work provides the first empirical results that can be used in future work to inform or validate an analytical model, deriving such a model is beyond the scope of this paper. Modeling the flexural rigidity of layered patches with no-slip conditions at the interfaces requires finite-element numerical modeling [62]. Simplified analytical models would then have to be parameterized based on numerical results.

Flexural Rigidity vs Thickness: In our experiments, we modified thickness and elastic modulus to fabricate patches of varying rigidity levels. However, it would also be interesting to explore independent variation of flexural rigidity at constant thickness. For this, the elastic modulus needs to be scaled drastically and would require fabrication of multi-layer patches, which in turn risks affecting other properties (e.g. adhesion, friction coefficient) of the samples.

Duplex Model for Tactile Perception: The perception of textures is duplex in nature, influenced by two components of stimulation: vibrational and spatial stimuli [20]. For discriminating very fine surfaces (particle sizes $<\sim 20\mu$m) with lateral exploration of the surface, vibrational cues resulting from the friction of the surface play a vital role. The surfaces used in our experiments had larger particle sizes ($\sim 300\mu$m in radius); hence the experiments focused on the spatial cues, with vibrational cues having a lesser impact. Future experiments should test the vibrational component of texture perception, as done for instance by Fagiani et al. [13].

10 CONCLUSION

In this work we presented the results from the first set of psychophysical experiments conducted on epidermal devices. We presented the first classification of epidermal devices based on their thickness and flexural rigidity. Results from our experiments show a significant effect of device rigidity on tactile sensitivity and roughness-discrimination abilities; more rigid devices increased the tactile sensitivity thresholds by up to 390% and roughness-discrimination thresholds by up to 490% compared with bare skin. Device rigidity had a considerably less strong effect on spatial acuity. On the sensitive fingertip, spatial discrimination thresholds moderately increased by up to 50%, whereas the thresholds remained fairly unchanged on less sensitive body locations. Our results offer the opportunity for an informed choice of device materials when a compromise between tactile performance and mechanical durability is to be found.

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Future work should investigate how epidermal devices affect other natural functions of skin (e.g. body movement, thermal management) and their effect on other cutaneous stimuli. It will also be important to study the usability and durability of epidermal devices during long-term user deployments.

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