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Fabrication of a Screen-Printed E-Textile Interdigitated Capacitive Sensor for Measuring Stratum Corneum Hydration †

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Abstract: This work describes the fabrication and testing of an interdigitated capacitive sensor, embedded in a wearable e-textile for non-invasive in vivo monitoring. The sensor is sensitive to moisture changes within the stratum corneum layer (SC) of the skin. Testing is conducted by measuring the hydration state of the skin before and after the application of moisturizing agents to the SC, and the readings are mapped to a commercial gold standard measurement of skin hydration using the Corneometer®. The results confirm that the interdigitated sensor can accurately detect the change in the hydration state of the SC with a sensitivity of 1.29 pF per arbitrary units of hydration.

Keywords: interdigitated sensor; flexible wearable sensor; stratum corneum hydration; screen printing; on-body monitoring

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1. Introduction

In previous work, the authors reported a novel design of an interdigitated capacitor (IDC) sensor for enabling stratum corneum (SC) hydration measurements [1]. The SC is the outermost layer of the skin, and it acts as a natural barrier to prevent skin desiccation and damage from external influences like allergens or viruses. Some common skin conditions, like atopic dermatitis (AD), cause a dysfunction of the barrier by obstructing the production of linking proteins that hold it together [2]. This results in excessive water evaporation from the SC layer as shown in Figure 1. Thus, the hydration level of the SC can serve as an indication of the integrity of this barrier, and therefore, it is an important biomarker that can be used to distinguish AD.

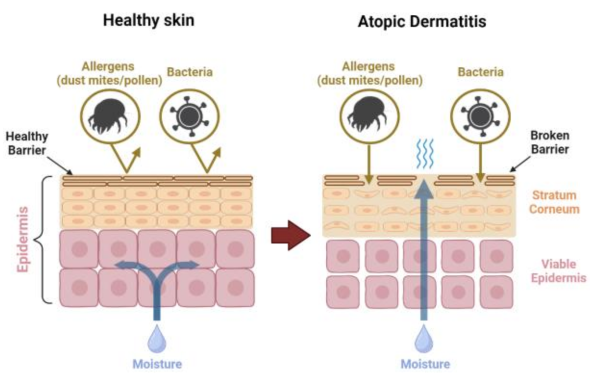

Figure 1. Comparison of cellular structure in healthy skin versus skin with AD. Breaches in the skin barrier result in excessive water evaporation and decrease in cell size.

In this paper, we have presented an e-textile solution for monitoring the hydration of the SC for the purposes of evaluating treatment procedures. A silver-loaded polymer IDC with a specific pattern was printed on the surface of a textile wearable armband to measure the hydration of the forearm using capacitive fringe-field sensing.

2. Materials and Methods

The IDC design and operation is visible in Figure 2—the small gap between adjacent electrode fingers achieves capacitance measurements with high sensitivity towards dielectric changes (water concentration changes) within the SC layer. The gap distance and the width of the electrode fingers are the same—200 µm—which was discovered to be the most optimal design for measuring within the SC layer in our previous publication [1].

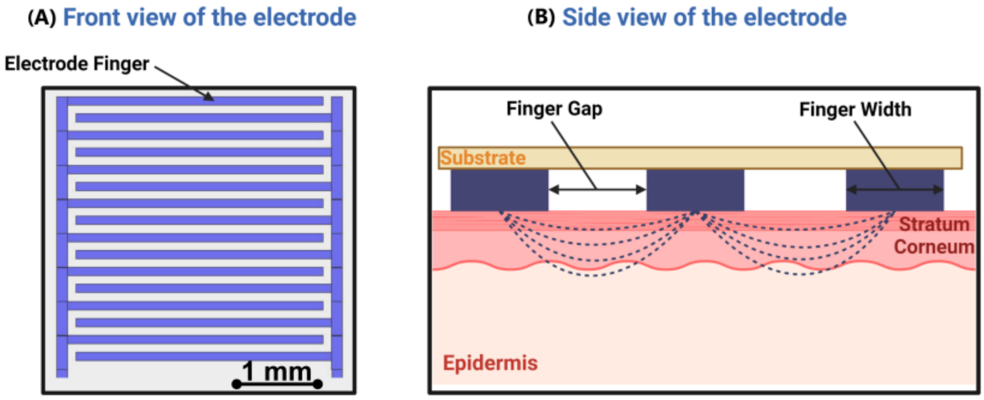

Figure 2. Sensor design and method of operation. Side view is not to scale.

The IDC sensor is produced using a DEK 248 Screen printer using a 280UTC ultra-fine stainless-steel mesh. A single layer of Fabinks® TC-C4007 silver is patterned onto Elecrom Stretch HC® laminating film with a printing gap of 0.5 mm. The deposited pattern is then cured in a Carbolite oven at 120° for 15 min. Once the pattern has been cured on the laminate, it is laminated on the inside of a commercial arm band with a strap (Ionocore®, Wistaston, UK) using a hot press at 160° for 1 min. The arm band has an internal EVA cushion that ensures constant pressure being exerted onto the skin. Several IDCs were laminated on the same band as a contingency plan in the event of one of them being damaged. The e-textile IDC sensor is visible in Figure 3—the adjacent IDC electrodes are electrically insulated from each other, and their measurements are not affected by the presence of the other IDCs.

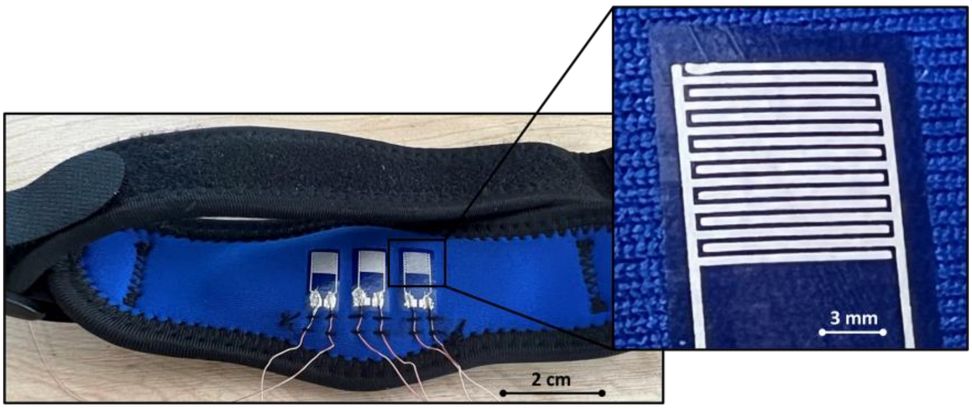

Figure 3. Photograph of the E-textile IDC sensor for SC hydration along with an inset photograph of just the IDC sensor arrangement.

Measurements were performed with a Wayne Kerr 6500B Impedance analyzer. Three healthy young adults were used as volunteers to test the device. The testing was performed on both volar forearms after the participants rested for 30 min. A commercial humectant cream (Eucerin®, Birmingham, UK) was applied to strengthen the SC barrier properties. Testing was repeated 15 min after application of cream. The measurements were mapped to the Corneometer® (Courage+Khazaka, Cologne, Germany)—a gold standard commercial device for skin hydration measurement [3]. The same procedure was repeated when obtaining the Corneometer® measurements.

3. Results and Discussion

3.1. Varying Hydration States

The selected volunteers had no history of skin conditions that may cause extreme dehydration. The applied moisturizing cream is used to treat such skin conditions by strengthening the SC barrier properties. The IDC reading across the frequency range increased for all volunteers after the application of the cream, indicating improvement in the SC's ability to retain water. At specific frequencies, this effect is more prominent, e.g., 1 kHz, but even at 1 MHz, there is a significant difference between the two hydration states. The findings are presented in Figure 4.

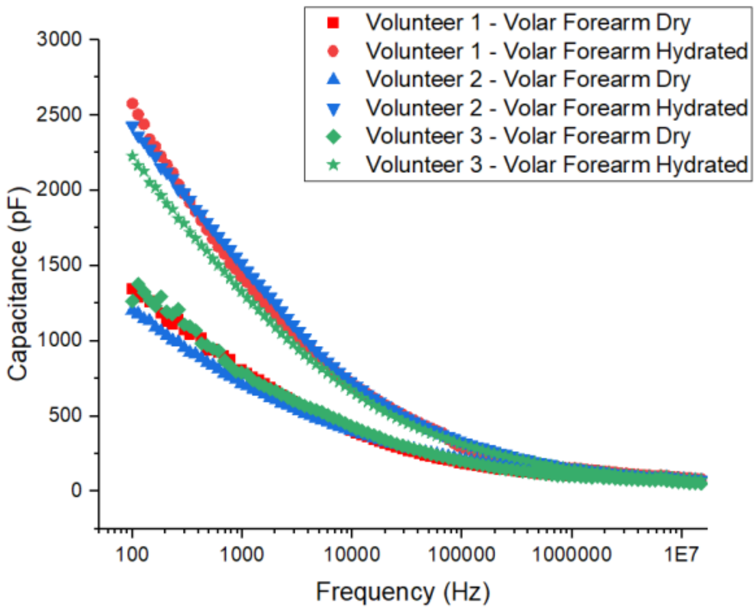

Figure 4. Capacitance measurement against frequency (100 Hz to 15 MHz) for 3 volunteers across two hydration states. Plots are color-coded for each volunteer.

3.2. Corneometer® Validation and Treatment Monitoring

The Corneometer® takes singular readings at a pre-defined frequency of 1 MHz and outputs values in arbitrary units. When testing between dry and hydrated skin using the device, the arbitrary readings also increase with higher hydration states. Therefore, the E-textile IDC and Corneometer® are positively correlated. The IDC measurements at 1 MHz were mapped to the Corneometer® readings, to match the internal measurement frequency of the device (Table 1).

To test the utility of the E-textile IDC sensor, a time course reading of the effect of commercial humectant cream is recorded. Measurements were taken just before and after the application of the cream and then every 20 min for a period of 4 h. The results are presented in Figure 5.

Both sensors can effectively track the hydration decay after the application of the cream. In both cases, there is an initial fast decay of the capacitance, attributed to the absorption of the cream's molecules within the skin. Between minutes 50 and 200, there is slight stabilization in the readings, indicating that the cream has absorbed fully and is now exerting its effect to improve the barrier properties of the SC. After minute 240, again, an increase decay in capacitance readings is evident, meaning that the effect of the humectant is declining. Thus, the IDC sensor can not only be used to estimate severity but to also monitor treatment procedures and rank their efficacy.

Table 1. Capacitance measurements mapped against Corneometer® arbitrary units (A.U.) readings with the following typical results: <30 A.U. = Very dry; 30–50 A.U. = Dry; 50 + A.U. = Sufficiently hydrated.

Location and Hydration State	E-Textile IDC Measurement (pF)	Corneometer® Reading (A.U.)
Left forearm; dry	95	43
Right forearm; dry	89	40
Left forearm; hydrated	151	89
Right forearm; hydrated	159	94

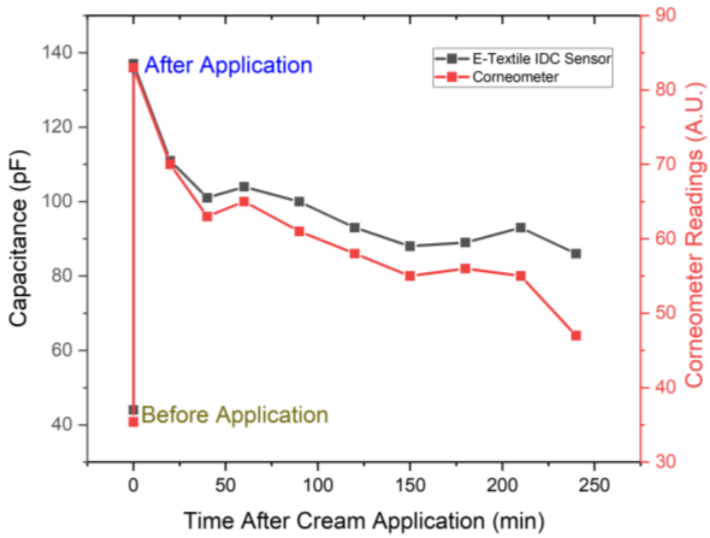

Figure 5. Time course measurement of humectant cream effect using an E-textile IDC sensor and a Corneometer® for a period of 4 h.

4. Conclusions

The non-invasive and mobile packaging of e-textile technologies make them a perfect environment for medical applications, such as the one presented here. The textile IDC sensor can assist in estimating the barrier properties of the SC and thus determining the severity of skin desiccation in conditions such as atopic dermatitis or psoriasis. Furthermore, the effectiveness of any subsequent treatments can be estimated, as demonstrated here by the impact of adding a humectant to the skin. The E-textile IDC sensor is a low-cost and accurate way of measuring the hydration state of the outermost layer of skin, comparable to the expensive commercial devices.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of University of Southampton (70980, approved on 27/06/2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are available upon request to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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