Permeable Skin Patch with Miniaturized Octopus-Like Suckers for Biosignal Monitoring

Aljawharah A. Alsharif, *Member, IEEE* and Nazek El-Atab*, *Senior Member, IEEE*

***Abstract*— Wearable electronics demand high adhesion properties through various skin conditions. Here, 3D-printed porous skin patches with octopus-like suckers of different geometries are presented. Experimental and theoretical studies are investigated to show an enhanced, low-cost 3D-printed bioinspired patches that successfully obtain biosignals comparable to commercial electrodes.**

***Clinical Relevance*— This work establishes low-cost, highly-adhesive skin patches that are irritation- and contamination-free with effortless peel-off technique for biosignal measurement.**

I. Introduction

Miniaturized bioinspired architectures used in diagnostic and therapeutic devices have gained significant amount of attention as they offer improved performance with excellent biocompatibility, breathability, flexibility, and reduced side effects (e.g., skin irritation and painful dermal stress), especially in neonates' and infants' skin or skin with atopic dermatitis [1]. Traditional glue-based adhesives that separate near wet wound areas or wet skin carry the risk of contaminating the skin, causing injury, and severely affecting the biosignal monitoring. Hence, the development of bioinspired, reusable, drainable, and contaminant-free transdermal patches with therapeutic systems or skin- or organ-attachable devices with diagnostic sensing parts is critical for patients who require specialized medical care. Such adhesives are in considerable demand recently to be used for long-term diagnosis, therapy, or rehabilitation [2]. Aquatic creatures have repeatedly developed two primary underwater attachment strategies: pressure-driven (i.e., suction attachment) and glue-like (i.e., bioadhesive secretions) [3]–[5]. To date, bioinspired suction-based adhesives with various multiscale architectures have been reported, including patches mimicking the attachment behavior of octopi [2], [6]–[12], tree frogs [8], beetles [5], [13], leeches [14], snails[15], and gecko [16]. The reported adhesives have demonstrated impressive performances in terms of mechanical enhancements and accurate biosignal monitoring. However, the proposed bioinspired architectures and microfabrication process reported in all these articles were sophisticated, tedious, and expensive. In fact, three-dimensional (3D) printing has grown in favor among academics and researchers due to its ability to provide high-quality signal measurements with optimal performances [17]. Recent advancements in electrode and adhesive printing enabled the replacement of commercial and conventional electrodes and patches with printed devices that are cost-effective, customizable, and fast to manufacture [18]. This study showcases a simple fabrication technique based primarily on Stereolithography (SLA) 3D printing to create a permeable skin patch with miniaturized octopus-like suckers for enhanced mechanics and biosignal monitoring under various skin conditions. However, to limit the scope of this paper we considered testing the patches under dry skin conditions only.

II. Materials and Methods

A. Fabrication of Miniaturized Octopus-Like Suckers and Microgrooves Skin Patch

Resin-based (Phrozen Aqua 8K Resin) negative master molds (25 mm × 25 mm × 0.5 mm) with various microdome patterns (200 µm in diameter; 100 µm in height; 400 µm and 600 µm in spacing; symmetric and asymmetric in arrangement) and embedded serpentine microgrooves (200 µm in width; 100 µm in height) were 3D printed using stereolithography technique (Phrozen Sonic Mini 8K) and post processed with acetone wash and ultraviolet (UV) radiation to cure for 10 min. Finally, the permeable skin patch was obtained by casting the negative master molds with Polydimethylsiloxane (PDMS) (5 wt% mixing ratio) (Sylgard, 184, Dow Corning) of 500 µm thickness. The samples were degassed for 15 min, cured at 70 °C for 1 h. Finally, the permeable skin patches with miniaturized octopus-like suckers were peeled off the molds.

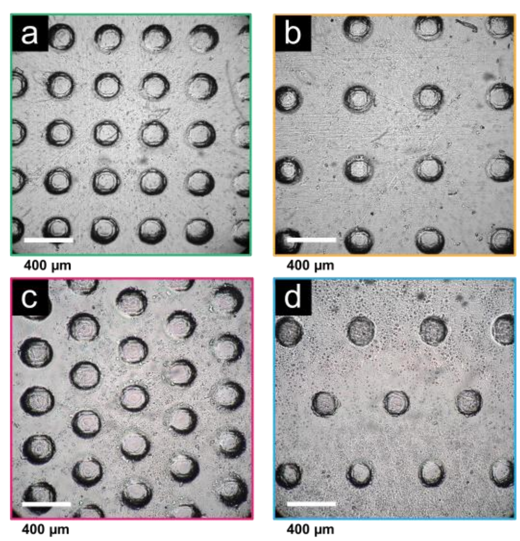

Figure 1. Microscopic images of miniaturized octopus-like suckers. (a-b) Symmetric arrangement. (c-d) Asymmetric arrangement.

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*Prof. Nazek El-Atab is with the SAMA Lab, Electrical Engineering, Computer Electrical Mathematical Scienceand Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia (00966 544 701 844; e-mail: nazek.elatab@kaust.edu.sa).

Aljawharah Alsharif is with the SAMA Lab, Electrical Engineering, Computer Electrical Mathematical Scienceand Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia (e-mail: Aljawharah.alsharif@kaust.edu.sa).

B. Fabrication of Dry Electrode

The permeable skin patches were treated with oxygen plasma to enable stable attachment of a medical grade silver ink onto the microstructures. Electrically conductive silver-based ink (Creative Materials 113-09, Ag/AgCl, thickness ≈ 80 µm) were syringe printed (Hyrel Hydra 16A, SDS10) on the microstructures and cured at 80 °C for 10 min to fabricate stretchable electrodes that monitor ECG signals.

C. Performance Assessment

Permeable skin patches (25 mm × 25 mm) of various microstructural patterns were attached onto a glass substrate to measure the pull-off force in a dry (relative humidity ≈ 50%) condition. Adhesion tests were carried out using a universal testing system (Instron 5944). The pull-off force and normal adhesion of patches were measured with respect to time, and maximum magnitudes of pull-off forces were obtained demonstrating the adhesion strength of the 3D printed permeable skin patches.

III. Attachment and Detachment Mechanism of Miniaturized Suckers

In this study, we predicted the suction forces as in (1). After pressing the patch to a flat substrate, the theoretical suction force of the suction cup array is

$$F = P \cdot \left(1 - \frac{V_1}{V_0}\right) \cdot A \cdot n \tag{1}$$

where P is the atmospheric pressure and A is the base area of a single suction cup, V_0 is the volume of the air inside the suction cup before the pressing load, and V_1 is the volume of the air inside the suction cup after the pressing load (ideally, 0). The normal adhesion can be predicted as well by removing the area's effect in (1) so that σ represents the stress (2).

$$\sigma = \frac{F}{A} \tag{2}$$

IV. Results and Discussion

A. Investigation of Enhanced Mechanical Strengths of Various Microstructures

In Fig. 1(a-d), we investigated the adhesion performances of patches with various miniaturized octopus-like suckers' arrangements. The pull-off forces and equivalent normal adhesion of patches were measured on a dry glass substrate using a universal testing system and compared against a flat patch with no microstructures, as shown in Fig. 2(a-b). The miniaturized octopus-like suckers have an aspect ratio of ≈ 0.5 (AR: ratio between height and width) and a spacing ratio of ≈ 2 and ≈ 3 (SR: width divided by distance between structures). We further revealed that controlling the geometries of the microstructures (e.g., AR, SR, and arrangement) can enhance the pull-off resistance. In our measurements (Fig. 2), the asymmetric arrangement with SR of ≈ 2 had the highest force and equivalent normal adhesion among all samples and the asymmetric arrangement in specific.

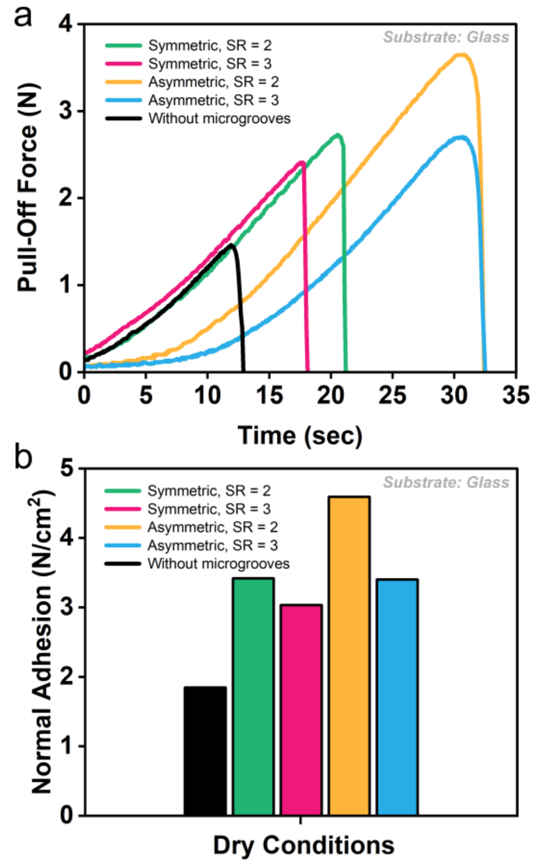

Figure 2. (a) Pull-off force and ;(b) normal adhesion of different geometries of miniaturized octopus-like suckers.

The air propagation underneath the patch depends on the suckers' arrangements. Therefore, the asymmetric arrangement significantly reduced the air propagation, prohibiting the air from progressing smoothly while splitting the airflow into smaller trajectories. After embedding the serpentine microgrooves (AR ≈ 0.5) in the octopus-like suckers' pattern (Fig. 3), we investigated the adhesion performances.

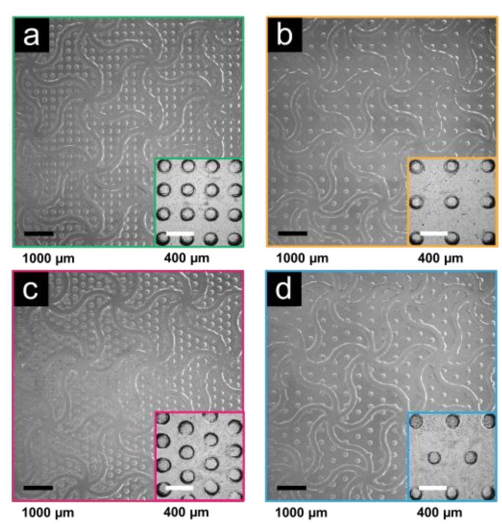

Figure 3. Microscopic images of miniaturized octopus-like suckers and embedded serpentine microgrooves.

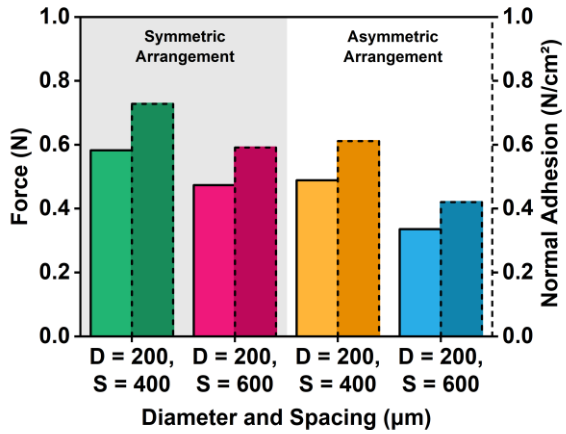

Figure 4. Pull-off forces and normal adhesions of permeable skin patch.

In Fig. 4, the pull-of forces reduced significantly for all samples after adding the drainage microchannel system. However, the patches of asymmetric and symmetric arrangements with SR of ≈ 2 had the highest force and equivalent normal adhesion values among the asymmetric and symmetric arrangements, respectively, due to the large number of miniaturized suckers they contain with respect to other samples. In fact, the arrangement of the microstructures tends to have a lower impact on the patch adhesion as the air propagation is now interrupted by the microgrooves design.

B. *Investigation of Effective Microgrooves Breathability*

In this work, we observed the left edge of a 2 cm × 2 cm sample to verify the enhanced drainage effect (Fig. 5). A liquid composed of 100g of Fluorescein Disodium diluted in distilled water was injected to the microchannels of the sample. The liquid was mainly evaporating from the edges due to the interference with outer air. In Fig. 5, the non-patterned flat design did not show any enhancement over time. The DI water and intensity were constant among all different captures. However, the serpentine microgrooves showed significant evaporation over time. The DI water and intensity were reduced over 1.5 h, indicating the breathability of the patch.

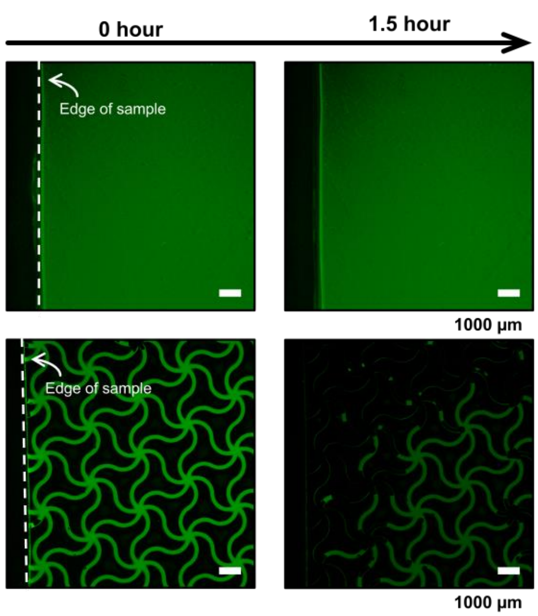

Figure 5. Demonstration of flat and patterned patches breathability.

C. *Investigation of Reduced Skin Irritation*

The proposed permeable skin patches were analyzed in terms of biocompatibility through qualitative analysis of skin irritation. The normalized intensity values ($\Delta I/I_{before}$) were observed using red, green, blue, and grayscale color channels. Skin images were taken before and after the attachment of a commercial adhesive patch, including our permeable skin patch. The difference ratio of the colorimetric intensities indicates the degree of color change (i.e., irritation) on the skin surface as shown in Fig. 6(a-b).

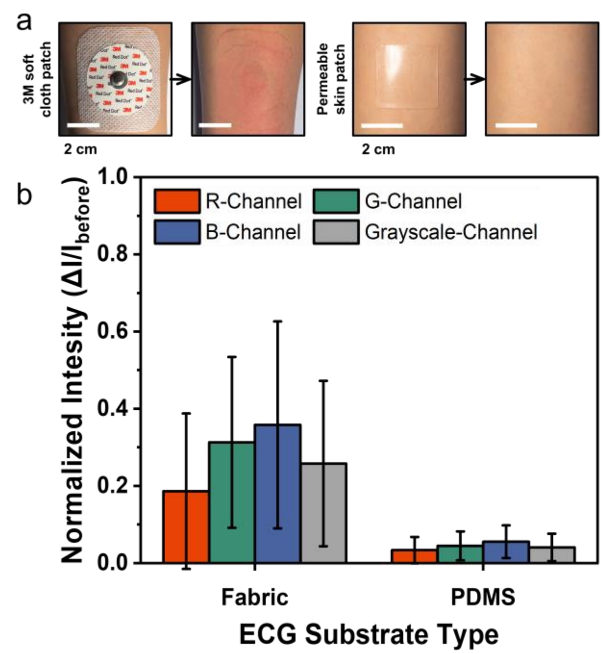

Figure 6. (a) Demonstration of skin irritation using commercial adhesives and our fabricated permeable skin patch (attached to the forearm of a female volunteer for 6 h). (b) The normalized intensity was measured for each patch before and after attachment, so the difference ratio of colorimetric intensities indicates the level of skin irritation to the corresponding patch.

D. *Application for Biosignal Monitoring*

Snap connectors were attached to the proposed permeable skin patch from the outer side to match the electrode buttons in the ECG monitor device (Wellue ECG Recorder, Viatom) as shown in Fig. 7(a-d). The patches were tested to demonstrate ECG signal through various skin conditions (i.e., dry hairy chest skin). Two identical permeable skin patches and two commercial wet Ag/AgCl electrodes (Red Dot Electrodes, 3M) were attached to a male volunteer's dry, hairy chest skin as in Fig. 7(e-f). ECG patterns of the heart were recorded under static conditions from the fabricated and commercial patches, as shown in Fig. 7(g). The identified P wave, QRS complex, and T wave indicate the permeable skin patches' potential for biosignal monitoring.

V. Conclusion

We developed a permeable skin patch with miniaturized octopus-like suckers and serpentine microgrooves using a simple fabrication technique based primarily on SLA 3D printing. This study investigated the pull-off forces behavior

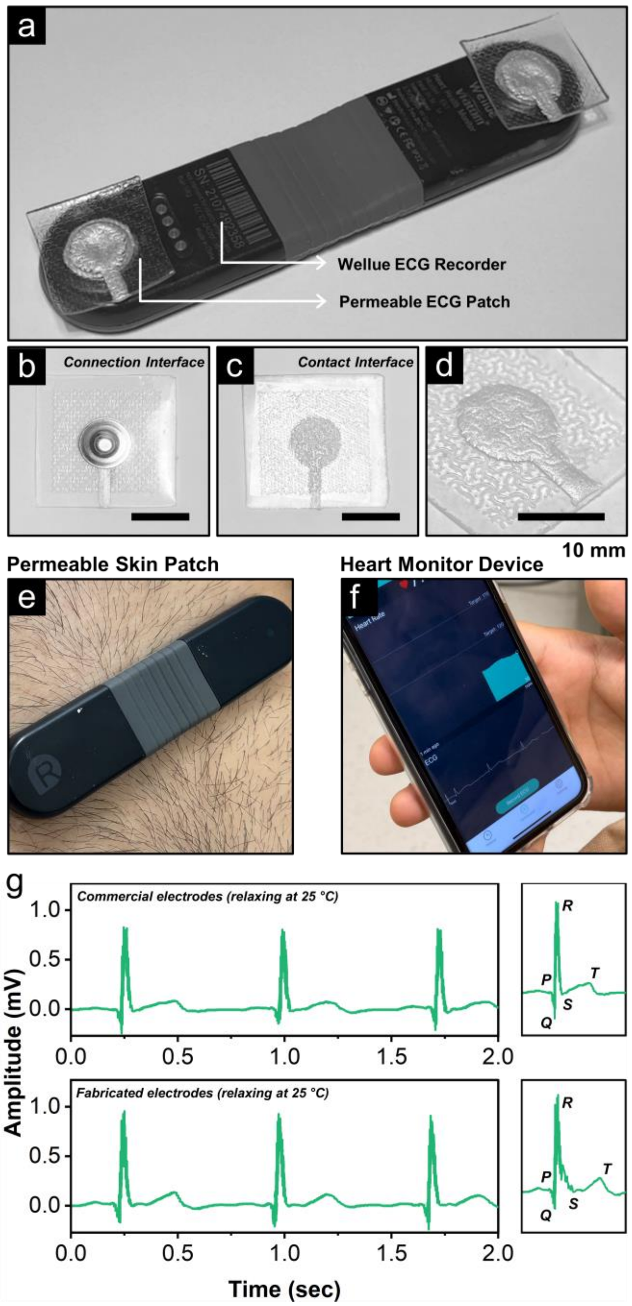

Figure 7. (a-d) Complete patch demonstration. (e-f) ECG signal measurement on a dry hairy chest skin of a male volunteer. (g) The ECG signal recording of both commercial and fabricated permeable skin patch in static mode at room temperature.

of the fabricated patches for enhanced mechanics and biosignal monitoring under various skin conditions. The simplified fabrication technique of our permeable skin patches may pave the way for developing low-cost, high-volume smart skin or organ-attachable medical devices.

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