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# Fabric Actuator with Embedded Electrodes (FAEE): An integrated System for Active Skin Condition Regulation and ECG Monitoring*

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***Abstract*— This study presents a novel ECG monitoring device named the Fabric Actuator with Embedded Electrode (FAEE) that seamlessly integrates skin condition regulation to improve biosignal acquisition, particularly under dry skin conditions, capable of gentle interaction with the human body. The FAEE incorporates a fabric actuator that actively modulates temperature and humidity, alongside textile-based electrodes for biosignal acquisition, enabling reliable heart rate monitoring. The actuator is constructed with fluidic channels embedded in a fabric engineered to be both waterproof and moisture-permeable, allowing for controlled water circulation and vapor release. By regulating skin moisture levels, the actuator enhances electrode-skin contact, leading to stable and high-quality ECG signal acquisition. The soft, adaptive characteristics of the developed ECG monitoring system offer not only functional monitoring capabilities but also psychological comfort.**

## I. INTRODUCTION

Human skin plays a crucial role in maintaining homeostasis by regulating body temperature and moisture through perspiration and vasodilation. However, individuals with impaired skin functions, such as the elderly or patients with chronic skin conditions often struggle to maintain optimal skin health, which can lead to discomfort or even skin disorders. Decreased skin function, especially during winter, often leads to dryness, which can make it difficult to measure vital signs. Monitoring vital signals such as electrocardiograms (ECG) is essential for assessing the health conditions of elderly individuals and patients[1]. Therefore, it is critically important to measure vital signs while maintaining proper skin conditions.

In this study, we propose a fabric-based ECG monitoring system named the ***Fabric Actuator with Embedded Electrode (FAEE)***, which integrates both vital sign sensing and active thermal-moisture regulation (Fig. 1). The key component of the system is a novel fabric actuator designed to maintain appropriate levels of temperature and humidity (Fig. 2). The fabric actuator incorporates channels made of a material with excellent waterproof and moisture-permeable properties, FX9354 DX (TORAY). By regulating the temperature of the fluid circulating through the channels, we can manage the actuator's surface temperature. More importantly, we can also modulate the amount of vapor released from the actuator by controlling the circulation pressure, which enables adjustment of skin humidity. This functionality emulates the natural behavior of human skin, enabling the system to act as an artificial thermoregulatory layer. By integrating this actuator with fabric-based electrodes (hitoe, TORAY) into a wearable belt system, we achieve gel-free, stable ECG monitoring. This is particularly advantageous in situations where dry skin leads to high contact impedance and disrupts signal acquisition. Our system ensures stable heart rate measurement without the need for conductive gel or skin preparation, enhancing both comfort and practicality.

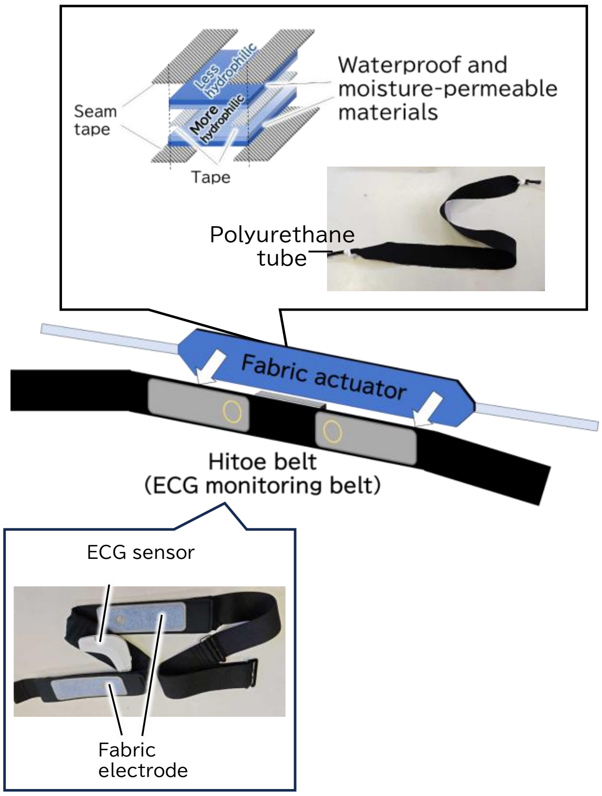

Figure 1. Structure of developed fabric actuator with embedded electrodes (FAEE)

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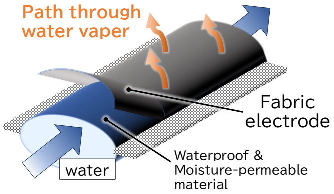

Figure 2. Overview of fabric actuator

### A. *Related works*

Humans regulate their body temperature by balancing metabolic heat with environmental heat loss. To enhance this thermoregulation, various textiles and actuators have been developed utilizing materials that respond to changes in light, heat, and humidity [2][3]. Zhao et al. created a smart fabric with stomata-like functions that open under sunlight to improve ventilation [4]. Fu K et al. designed a material that expands its fibers in the presence of moisture, like sweat, increasing pore size to facilitate the release of heat and sweat [5], [6]. Advanced materials also incorporate actuators that dynamically adjust breathability in response to moisture levels [7]. Wang et al. presented a dual-layer fabric with hydrophilic and hydrophobic properties to optimize moisture transfer and thermal comfort under different conditions [8]. Similar concept is utilized in [9].

Despite these advancements, the studies mentioned above have primarily focused on individuals with normal thermoregulation, overlooking those who require more personalized temperature and humidity control, such as people with dry skin or sensitivity to cold. An active thermal and humidity control system is therefore needed to support individuals with compromised skin function. This study aims to address this issue. Furthermore, localizing this control offers a significant advantage over whole-body systems. This targeted approach allows for the creation of an optimal microenvironment for biosignal acquisition at a specific area of the skin while minimizing whole-body heat stress. This capability is crucial for ensuring stable and comfortable long-term monitoring, particularly for users with compromised skin conditions.

Numerous wearable sensors have been developed to measure biosignals [10], [11], [12], [13], and several of them are now commercially available. For stable biosignal acquisition, low skin impedance is preferable; hence, conductive gels or skin treatments are commonly used to reduce it. However, such skin treatments are typically performed manually by users. To the best of the authors' knowledge, no attempt has been made to automate or integrate this process into a device.

In this paper, we propose an integrated system that combines fabric actuators capable of actively controlling thermal and humidity conditions with fabric electrodes for biosignal measurement, enabling both stable biosignal acquisition and a comfortably warm and gently moist skin interface. This approach offers a proactive alternative to passive systems, particularly for users prone to skin dryness or discomfort.

## II. SYSTEM DESIGN

In this section, we focus on ECG measurement as a representative biosignal and describe the complete design of the proposed wearable sensing system, which integrates temperature and humidity regulation with ECG monitoring. The system is based on a fabric actuator that actively delivers heat, cold, and moisture to the skin via liquid circulation, as shown in Fig. 2. The integration of fabric-based electrodes with the fabric actuator provides not only a warm and soft contact interface but also a suitable physical environment for biosignal acquisition (see Fig. 1). Through this functionality, the system not only supports individuals with impaired skin function but also enhances the reliability and comfort of long-term physiological monitoring.

### A. *Design of fabric actuator and environment control mechanism*

As mentioned above, a waterproof and moisture-permeable fabric (FX9354 DX, TORAY) was used to construct the fluid channel of the actuator, as illustrated in Fig. 2. The fabrication process involves bonding two pieces of this specialized fabric at their edges using adhesive tape. The fabric features a two-layered structure, with the inner layer being more hydrophilic and the outer layer more hydrophobic. The fabrics are joined such that the hydrophilic surface faces the interior of the channel. To prevent leakage during liquid flow, seam tape is additionally applied over the bonded edges. Urethane tubes are attached to the remaining ends of the fabric to serve as the inlet and outlet for the fluid.

The inner hydrophilic layer consists of a non-porous film that swells upon contact with water. This structure enables water vapor to be released through the hydrophobic outer layer, while preventing the leakage of liquid water from the flow channel. As a result, liquid water remains securely contained within the actuator, while water vapor can effectively diffuse outward. This is the core mechanism by which the actuator provides moisture to the skin without direct liquid contact. Water is circulated through the internal space of the actuator, and the non-porous film facilitates vapor diffusion while maintaining liquid containment.

In addition to its moisture-controlling capabilities, this fabric is characterized by its lightweight and high flexibility, making it ideal for wearable and soft robotic applications. The fabric has a thickness of 0.2 mm, and a mass of 0.0115g/cm$^2$, which supports the actuator's ability to conform closely to surfaces while minimizing added weight.

When warm water flows through the actuator, heat is transferred to the fabric, and water vapor gradually discharged through the fabric. This enables localized heating and humidification at the actuator-skin interface, maintaining high moisture levels for the skin. To prevent skin problems, it is desirable to maintain the humidity level at around 50–60% [14]. The controlled release of vapor helps prevent dryness, which can impair skin-electrode contact for biosignal monitoring. For water circulation, a self-made pump based on a kerosene electric pump was used. The resulting actuator is lightweight, flexible, and suitable for direct skin contact. Its ability to conform to body contours without causing discomfort makes it a promising solution for applications in elderly care, rehabilitation, and temperature-sensitive environments.

### B. Integration with ECG electrode

To realize a skin-interfacing biosensing system, the fabric actuator was integrated with fabric-based electrodes. Specifically, we employed the *hitoe* fabric electrode (TORAY), a flexible and breathable textile capable of detecting bioelectrical signals, such as ECG [15]. To implement this concept, we utilized the commercially available *hitoe belt* (TORAY), a belt-type wearable product that incorporates *hitoe* fabric and ECG sensor terminals (TX02, NTT TechnoCross). The actuator was attached to the backside of the *hitoe belt*, opposite to the surface where the fabric electrodes come into contact with the skin.

A key challenge in fabric-based ECG measurement is maintaining low contact impedance between the electrodes and dry skin. This issue is particularly pronounced in winter, when dryness increases the impedance, leading to signal loss and noise during long-term monitoring. To address this, the FAEE continuously supplies humidity to the skin–electrode interface by diffusing water vapor from circulating warm water. Since the *hitoe belt* is made of a permeable fabric, the water vapor released from the actuator passes through the textile and reaches the contact area between the electrodes and skin surface. Elevated temperature and humidity in the skin microclimate elicit sweat secretion. This mechanism effectively reduces skin impedance without the need for conductive gels or skin treatment, enabling stable signal acquisition in a non-invasive and user-friendly manner. Direct water application to the skin promotes dryness; thus, the proposed steam-mediated approach has the advantage of reducing the risk of exacerbating skin problems.

## III. EVALUATION

### A. Evaluation of Function as a Channel

We investigated whether the part of the developed fabric actuator functions as a channel. Since it is designed to operate while allowing the release of steam, we evaluated its ability to maintain water circulation without a drop in pressure for a certain period of time. As shown in Fig. 3, the experimental setup consisted of the fabric actuator connected to a handmade pump based on kerosene electric pump and a pressure sensor (AP-V80, Keyence) to monitor the internal pressure during operation. Fig. 4 shows the results where the water pressure is almost constant, confirming that the actuator functions as a flow channel.

### B. Evaluation of the effects of vapor emission

We examined whether the part of the developed fabric actuator could circulate water while simultaneously releasing vapor. In the experiment, as shown in Fig. 5, the flow channel of the actuator was enclosed within an acrylic box (200 × 145 × 85 mm), and we monitored the humidity inside the box using a DHT22 digital humidity sensor (OSOYOO) while water (19.0 °C) was circulated for five minutes. The pressure during water circulation was set at 1.9 and 2.9 kPa by adjusting the voltage supplied to the pump, which changed the pump's stroke volume and thereby the flow rate. An increase in flow rate led to a corresponding increase in internal pressure within the actuator. Fig. 6 shows the results of increasing humidity over time, indicating that higher water circulation pressures resulted in greater increases in humidity. These results confirm that fabric actuators can release vapor while circulating water and that the amount of vapor increases as the pressure of the circulating water increases. Another important observation is that the resulting humidity varies depending on the circulation pressure. Circulating the fluid at higher pressure leads to a higher level of humidity. In addition, since the increase in humidity tends to constant over time, these results suggest that humidity can be controlled by adjusting the circulation pressure.

We also conducted the experiment where we covered the flow channel part of the fabric actuator with water-absorbing polymer and circulated water for one minute. By examining the change in the weight of the water-absorbing polymer before and after the circulation, the amount of water released was measured. The pressure during water circulation was set at 1 kPa. The weight of the water-absorbing polymer increased by 0.2g, indicating there was no water leakage. The unique characteristic of this fluid channel, which prevents water leakage while allowing the passage of water vapor particles, is notable.

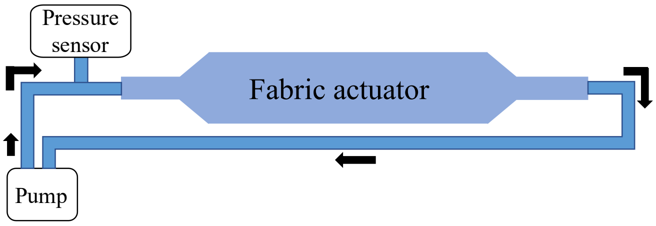

Figure 3. Experiment setup for the evaluation of function as channel

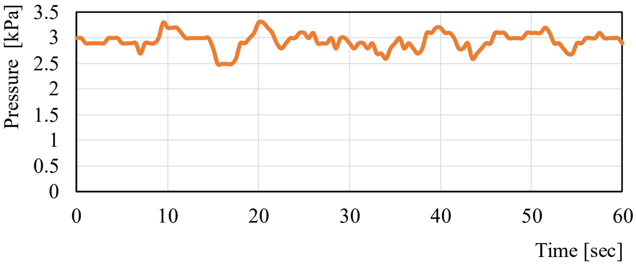

Figure 4. Water pressure during water ciruration

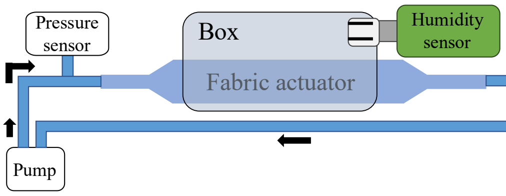

Figure 5. Experinental setup for evaluating vapor release

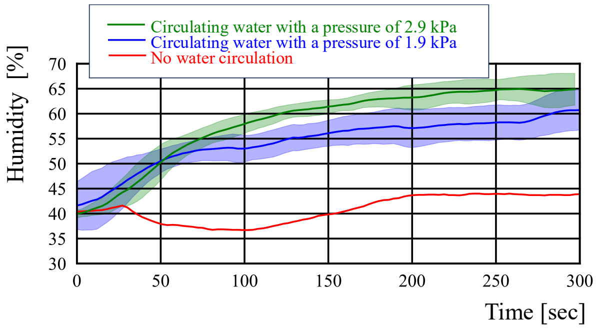

Figure 6. Change in humidity via water (19.0 °C) circulation

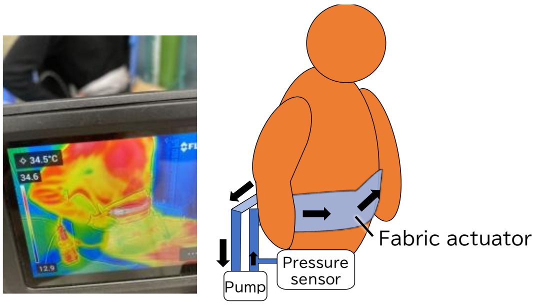

Figure 7. Experiment setup for human trials

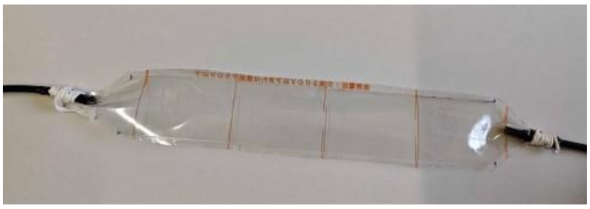

Figure 8. Polyurethane channel used as the control condition in human trials

### *C. Examination of changes in human skin temperature and skin moisture levels*

To evaluate the effect of the fabric actuator on human skin, we conducted an experiment with six participants. Fig. 7 shows the experimental setup. Each participant wore the actuator on their abdomen over an undergarment while warm water was circulated through its fluid channels. The water had an initial temperature of 45 °C. As a control condition, a fluid channel made of polyurethane shown in Fig. 8 was used for comparison under identical experimental setting. The experiment was performed in a controlled environment with room temperature and humidity maintained at 24 °C and 30 %, respectively. Before the experiment, participants remained seated for a stabilization period to ensure that their baseline skin temperature and skin moisture levels were established for use as the baseline condition. During the experiment, warm water was circulated through the actuator for five minutes, and skin temperature and skin moisture level were measured once per minute using thermographic camera (FLIR C5) and skin moisture checker (anyty 3R-MCA01), respectively.

Figs. 9 and 10 illustrate the change in skin moisture levels relative to the baseline conditions. The mean initial skin temperature and skin moisture levels were 32.6 °C and 18.7 %, respectively. When the fabric actuator was used, both skin temperature and moisture levels showed an increase relative to the baseline. In contrast, the polyurethane-based fluid channel demonstrated a comparable increase in skin temperature but a significantly lower increase in moisture levels. A paired t-test was conducted to analyze the differences between the two actuators. The results indicated no statistically significant difference in skin temperature change between the fabric actuator and the polyurethane channel. However, a significant difference ($p < 0.05$) was observed in skin moisture levels, confirming that the fabric actuator was significantly more effective in increasing skin moisture compared to the polyurethane channel.

These findings suggest that the fabric actuator effectively increases both skin temperature and humidity, with a particularly strong effect on skin moisture levels. Unlike conventional polyurethane-based fluid channels, this actuator enables controlled moisture transfer, demonstrating its potential for applications in medical care, healthcare, and sports science, where humidity regulation is crucial.

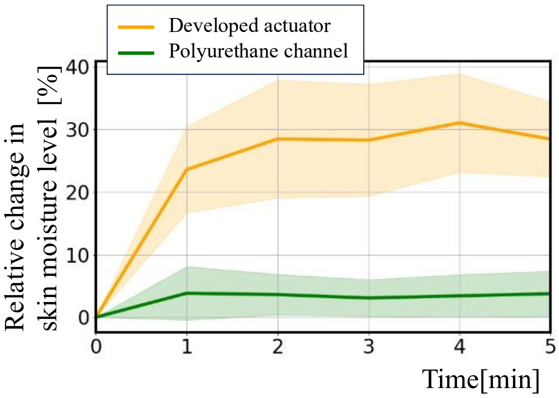

Figure 9. Changes in skin moisture level relative to the baseline without the fabric actuator

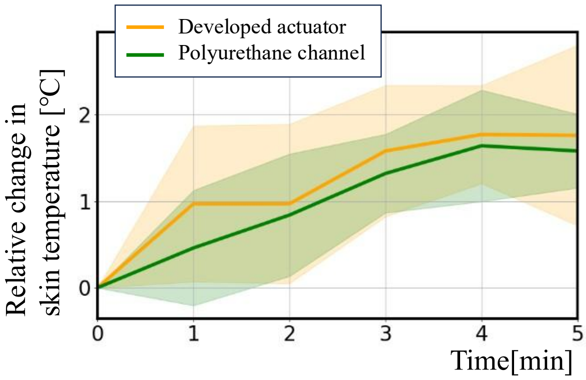

Figure 10. Changes in skin temperature relative to the baseline without the fabric actuator

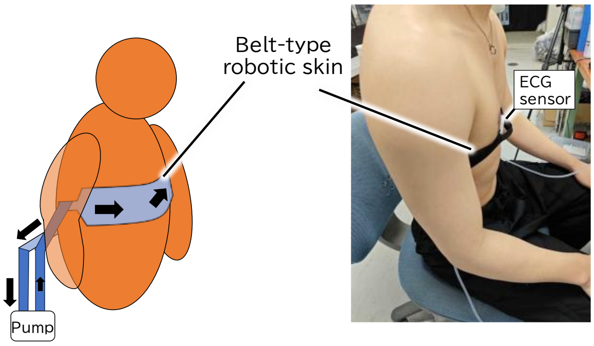

Figure 11. Experimental setup for ECG mesuarment

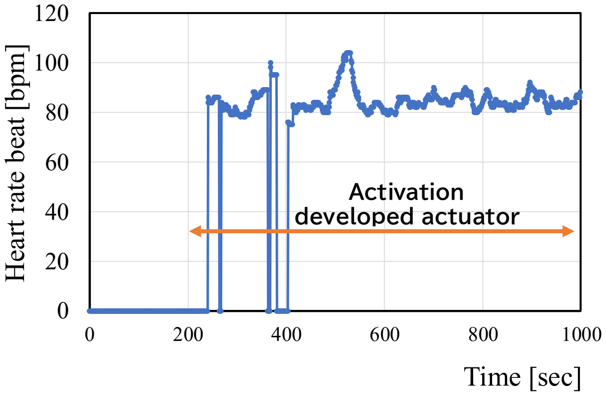

Figure 12. Result of heart rate measurement using FAEE (repsesentative data)

### D. *ECG signal acquisition using developed FAEE*

To evaluate the effectiveness of the for biosignal monitoring, we conducted an experiment in which a developed ECG system, as shown in Fig. 1, was worn during biosignal measurement. The experimental setup is illustrated in Fig. 11. Biosignals were recorded by connecting the fabric electrodes on the FAEE to an ECG sensor (TX02, NTT TechnoCross). Warm water was circulated through the fabric skin using a pump and a pressure sensor connected to the system.

The experiments were performed on human subject(n = 4) in a controlled environment with a room temperature of 23°C and a relative humidity of 42%. Each wore the belt around the chest while seated, and ECG signals were recorded using the ECG sensor. The total duration of the experiment was 1000 seconds. During the first 200 seconds, the actuator remained inactive, and ECG measurements were perfomed under dry conditions. At the 200-second mark, the actuator was activated, initiating the circulation of warm water at 45°C through the system. As representative data, results of the ECG measurements are shown in Fig. 12.

Initially, no clear ECG signals were obtained. However, approximately 40 seconds after activation (240 seconds into the experiment), stable heart rate monitoring became avalabe. Similar results were consistently observed across all subjects, confirming that the fabric actuator improved skin–electrode contact by increasing the local humidity at the contact area, thereby enabling effective ECG measurement even when the skin condition is otherwise unsuitable for such measurement. It should be noted that the signal disturbance observed around 400 seconds was caused by the subject adjusting the belt they were wearing.

### E. *Investigation of the relationship between vapor release and changes in conductivity*

For reliable biophysical measurements, it is desirable for the electrodes to exhibit low impedance or resistance. Here, we investigate how the resistance of the electrodes changes when exposed to vapor generated by the actuator, and whether the resulting increase in humidity contributes to stable biosignal acquisition.

Fig. 13 illustrates the setup of the experiment. In this experiment, we fabricated a small-scale test system consisting of a fabric actuator with *hitoe* electrode attached to its surface and a lead wire connected for electrical measurement. The FAEE (the fabric actuator with embedded electrodes) was inserted into a plastic bag (100 ×70 mm) along with a humidity sensor (DHT22, Waveshare), and warm water (55°C) was circulated through the internal fabric actuator. By monitoring resistance and humidity levels over time, we observed whether as humidity increased due to vapor emission from the actuator, the resistance between the electrodes decreased. The experiment was conducted four times, each over a duration of 300 seconds. Fig. 14 shows the result of the experiment. Initially, the resistance was approximately 25 kΩ. Around 150 seconds, when the humidity level had risen to about 70 %, the resistance had decreased to approximately 15 kΩ. By the end of the experiment, it had further dropped to around 10 kΩ. These results indicate that the resistance consistently dropped to below 15 kΩ over the course of the experiment, indicating that vapor release from the actuator increases electrode conductivity.

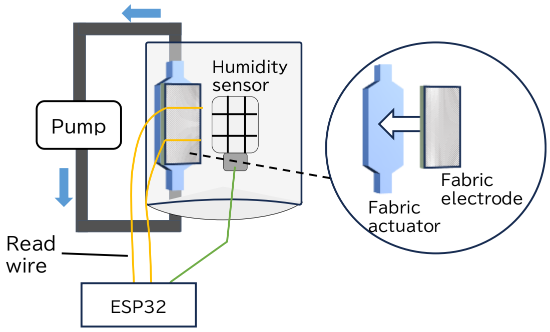

Figure 13. Setup of conductivity change evaluation

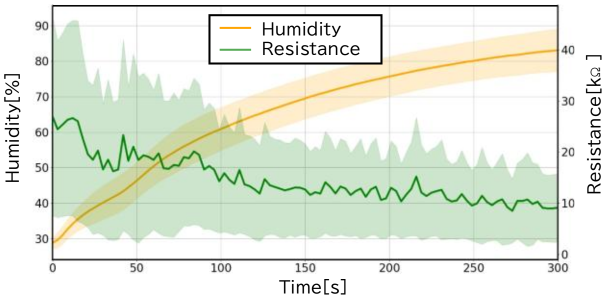

Figure 14. Result of conductivity change evaluation

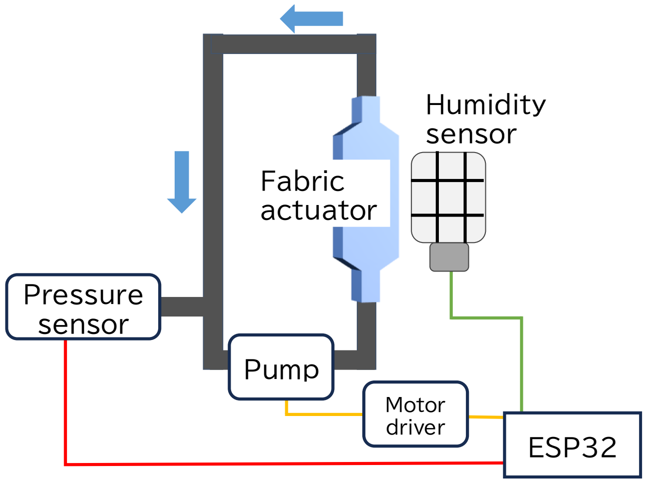

Figure 15. Setup of humidity regulation evaluation

### F. *Feasibility of a pressure-based humidity control system*

Building upon the findings in Section III-B, where it was confirmed that the amount of water vapor released by the fabric actuator increases with internal water pressure, we conducted an experiment to evaluate the feasibility of maintaining a target humidity level by controlling the water pressure within the fabric actuator. Fig. 15 shows the setup of the experiment. In the experiment, the fabric actuator was equipped, and a humidity sensor was positioned at a fixed distance from the actuator outer to monitor ambient humidity. Warm water was circulated through the actuator, and the internal pressure was dynamically adjusted using a micro pump and motor driver system under the control of microcomputer (ESP32-WROOM-DA, Espressif Systems).

The control goal was to maintain a target humidity of 55 %, which is within the comfortable range for human skin (50 %~ 60 %) [14]. The pressure control logic was designed as follows.

- If humidity < 50%, the pump pressure was increased to 8 kPa.
- If humidity was between 50-55 %, the pressure was held at 3 kPa.
- If humidity > 55 %, circulation was stopped (0 kPa)

These control parameters were carefully tuned to account for variations in environmental conditions such as background humidity and airflow. The system successfully demonstrated real-time humidity regulation by modulating the actuator's vapor release rate, validating the potential of this approach for maintaining a stable microclimate around the fabric actuator.

The experiment was conducted in an environment with an ambient temperature of 24 ℃ and a relative humidity of 32 %. During the first 180 seconds, the actuator remained inactive to establish a baseline condition. After this initial phase, the actuator was activated, and the water circulation began in accordance with the humidity control algorithm. Fig. 18 shows the result of the experiment. The humidity near the outlet of the actuator gradually increased. Around 500 seconds into the experiment, the target humidity level of 55 % was successfully reached. Following this, the system maintained the humidity within a ± 5 % range around the target humidity, demonstrating stable and responsive humidity control. This performance highlights the effectiveness of pressure-based modulation in maintaining a desired microclimate, even under initially dry conditions.

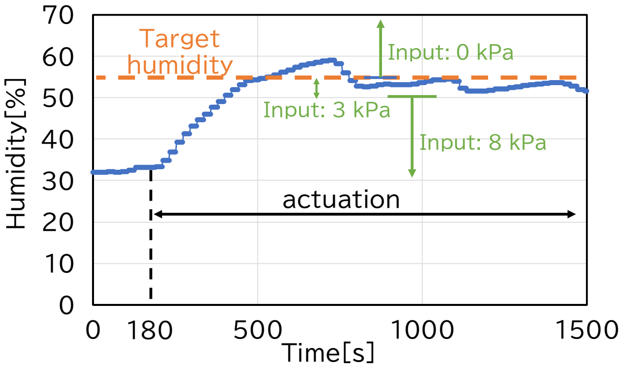

Figure 16. Result of humidity regulation

## IV. CONCLUSION

This study presented a novel device capable of controlling temperature and humidity and sensing biosignals. The device is composed of a novel fabric actuator for regulating skin temperature and humidity, as well as a fabric electrode. The fabric actuator features fluid channels within a specially constructed fabric that possesses both waterproof and moisture-permeable properties, facilitating water circulation and vapor release. The fundamental test demonstrated that warm water circulation increases not only temperature but also humidity of human skin. An experiment measuring ECG under dry conditions showed that stable ECG signals were obtained only after the actuator was activated. This confirms that increased local humidity significantly improves skin-electrode contact and signal quality. This integrated approach offers a proactive solution for non-invasive biosignal monitoring, and provides particular benefits for individuals with dry or sensitive skin. Future work will focus on improving the system to enable continuous, long-term monitoring, as well as implementing real-time logic to automatically regulate the microclimate based on measured vital signs. These improvements will maximize the system's potential in real applications. Ultimately, the results of this research will contribute to the development of more effective, comfortable and adaptable health monitoring systems that provide new solutions for the non-invasive remote care of patients and the elderly.

## ACKNOWLEDGMENT

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