Development of Capacitive Sensor for Diaper Absorption Volume

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Abstract The number of people requiring care in Japan has increased with the increase in number of people aged 65 or more. Thus, the production of disposable diapers for the elderly is also increasing. Two types of diapers; pad-type and tape-type, are generally used in combination in nursing homes. Diaper change is a burden for both the caregiver and the care receiver. To reduce the number of diaper changes, this study aimed to develops electrodes as a capacitive sensor attached to the outer surface of the tape-type diaper. The capacitive sensor evaluates the absorption volume of the pad-type diaper, and consists of electrodes and a converter circuit that converts the capacitance of electrodes into an output voltage. The study used a waist-type torso mannequin wearing a pad-type diaper on the inside and a tape-type diaper on the outside. The inside of the torso was filled with saline, and the weight of the torso including the saline was 8.9 kg in total. The electrodes were made of copper tape fixed to an insulating film, and the copper tape was 500-mm long and 25-mm wide with a 20-mm interelectrode gap. The electrodes were attached to the outside of the tape-type diaper and connected to the circuit. Experiment was conducted with the torso placed in supine and 30° lateral positions. Tap water (100 mL) was introduced via a silicone tube between the pad-type diaper and the torso hip surface at a flow rate of 7.8 mL/s, which is the average urinary flow rate for the elderly. This procedure was repeated six times. The experiment was repeated three times. The output voltage increased linearly with increasing volume of water absorbed by the pad-type diaper, in both torso positions. Therefore, the absorption volume was quantitatively evaluated, and the results suggested that the resolution was at least 100 mL when using this sensor.

Keywords: diaper, absorption volume, capacitance.

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1. Introduction

The number of elderly people aged 65 years and above in Japan has increased from 28 million in 2008 to 35 million in 2018 [1]. Thus, this results in an increase in number of care receivers [2]. Moreover, the production of disposable diapers increased from 5445 million sheets in 2010 to 8384 million sheets in 2018 [3]. In Japan, disposable diapers are commonly used in nursing homes as they are effective for bedridden elderly patients. Skin contamination by excrement causes skin irritation, decubitus ulcer, and urinary tract infection [4, 5]. Ideally, diapers should be changed immediately after urination. However, checking the condition of diaper is a burden for both the caregiver and the care receiver. To solve this issue, diapers of all care receivers are changed at regular intervals regardless of the condition of the diapers in Japanese nursing homes.

Two types of diapers, pad-type and tape-type, are generally used in combination in Japanese nursing homes [6]. To reduce the cost, only pad-type diapers are changed 6–8 times a day, while tape-type diapers are changed once a day. The tape-type diaper must be opened to change the pad-type diaper. However, care receivers sometimes feel uncomfortable with diaper changes [7].

Diaper change is also carried out during midnight, thus interrupting the sleep of the care receiver. In order to improve the quality of sleep of the care receiver, it is imperative that the caregiver does not interrupt the sleep of the care receiver at midnight [8]. Diaper change is not necessary when the absorption capacity of the diaper is sufficient or when there is no incontinence. Although high-performance pad-type diapers can absorb 150 mL of urine ten times [9], these diapers are more expensive than regular diapers. It is economically desirable to change the diaper only when much urine has already
been absorbed. Therefore, a sensor that evaluates the absorption volume of the diaper is useful.

Various urination detection systems for elderly patients have been developed; namely, (1) a thermistor system [10], (2) a radio frequency identification system [11], and (3) a capacitive sensor system [12]. These systems can detect urination but cannot evaluate the volume of urine absorbed by the diaper. On the other hand, urination detection equipment have been available on the Japanese market, such as a paper sensor attached inside the diaper [13], a urine absorption volume-evaluating sensor built inside the diaper [14], and a cloth sensor placed under a bed sheet [15]. These sensors nevertheless involve running costs owing to the disposable sensor, labor and cost of maintenance; in addition, they are not adaptable to position change. This study aimed to develop a system that evaluates the volume of urine absorbed by a pad-type diaper by using a capacitive sensor that is attached on the outside of the tape-type diaper. This diaper sensor system is intended for use by bedridden care receivers.

We conducted a preliminary study to investigate the relationship between the absorption area and absorption volume for several pad-type diapers, and the relationship between the absorption volume and capacitance of electrodes [16]. The appropriate electrode width was experimentally determined. In the previous study [17], a balloon waist-type torso mannequin and a subject wore a tape-type diaper outside a pad-type diaper, and the absorption volume of the pad-type diaper was estimated from the capacitance of electrodes attached to the outer surface of the tape-type diaper. The capacitance of electrodes increased in proportion to the increase in absorption volume of the pad-type diaper. Tachibana and Niikawa [19] developed a urine volume estimation system using the change of impedance in the electrode matrix sheet placed on the bed sheet. They used tap water as pseudo-urine. In our study, the electrodes measured the capacitance as the amount of tap water (pseudo-urine) absorbed in the pad-type diaper.

2.2 Electrodes
The electrodes used in this study were made of 0.07-mm-thick copper tape fixed to an insulating polyethylene terephthalate (PET) film. The electrodes were 500 mm in length and 25 mm in width. The width of 25 mm, which is the appropriate electrode width, was experimentally determined in a previous study [17]. To determine the appropriate interelectrode gap, the electrodes were fabricated with 5-, 10-, 15-, 20-, 25-, 30-, 35-, and 40-mm gaps.

Figure 1 presents the measurement principle of the sensor. Since the pad-type diaper is dry before urination, the permittivity between the electrodes is considered to be the permittivity of air. After urination, the pad-type diaper absorbs the urine, and the air in the polymer is replaced with urine. Since the permittivity of urine is higher than that of the air, the permittivity between the electrodes increases. Tachibana and Niikawa [19] developed a urine volume estimation system using the change of impedance in the electrode matrix sheet placed on the bed sheet. They used tap water as pseudo-urine. In our study, the electrodes measured the capacitance as the amount of tap water (pseudo-urine) absorbed in the pad-type diaper.

2.3 Basic characteristics of the sensor
Figure 2 shows a schematic diagram of the basic characteristics of the sensor. First, the frequency responses of dry and wet diapers were evaluated to determine the

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**Fig. 1** Measurement principle of the sensor.

**Fig. 2** Schematic diagram of capacitance measurement.
proper measurement frequency. A dry pad-type diaper was placed onto the electrodes. The electrode capacitance was measured using an impedance analyzer (4294A; Agilent Technologies, CA, USA) from 1 to 100 kHz.

Second, the capacitance of the electrodes was evaluated at 10 kHz using the impedance analyzer to determine the proper interelectrode gap.

Third, to evaluate the effect of the diaper covering the electrodes, the electrode length under the dry pad-type diaper was changed from 0 to 400 mm every 100 mm. Subsequently, a pad-type diaper that had absorbed 600 mL of tap water was placed onto the electrodes. The electrode capacitance of the wet pad-type diaper was measured in the same manner as for the dry pad-type diaper for the above three conditions.

2.4 Torso experiments
This study used a torso made of polyethylene terephthalate glycol-modified (PET-G) with a thickness of 1.5 mm, and was filled with saline. The weight of the torso including the saline was 8.9 kg in total.

Figure 3 presents a schematic diagram of the experimental apparatus. A pad-type diaper was put on the torso first on the inside, followed by a tape-type diaper on the outside. The electrodes were attached to the outside of the tape-type diaper with a protective tape and were connected to the converter circuit. The torso was placed in supine or 30° lateral position. Tap water (100 mL) was introduced via a silicone tube (8-mm inner diameter) between the pad-type diaper and the torso hip surface. This procedure was repeated six times with an interval of 10 min and a flow rate of 7.8 mL/s, which is the average urinary flow rate of the elderly. The output voltage of the converter was recorded using PowerLab 4/26 (ML846, ADInstruments, Sydney, Australia). The experiment was repeated three times.

The CV converter circuit converted the capacitance of the electrodes into output voltage. The converter circuit used in this study consisted of a switched capacitor voltage converter (ICL7660, Intersil, California, USA) and an operational amplifier (TLC27M2CP, Texas Instruments, Texas, USA) (Fig. 4). The oscillator oscillated at a frequency of 10 kHz. A capacitor C1 was connected in parallel with the test terminal to adjust the output voltage to zero with zero water absorption. The supply voltage of the converter was 3.0 V, and the size of the converter was 23 × 65 × 64 mm (H × W × D).

3. Results
3.1 Basic characteristics of the sensor
First, Fig. 5 presents the frequency responses of the electrodes with 25-mm interelectrode gap. For both dry and wet pad-type diapers placed onto the electrodes, the capacitance remained almost flat as the frequency changed. The capacitance of the wet pad-type diaper was approximately ten times larger than that of the dry pad-type diaper. Measurement frequency did not affect the capacitance measurement in this frequency range.

Second, Fig. 6 presents the relationship between the capacitance of the electrodes and interelectrode gap. For each interelectrode gap, the capacitance of the wet pad-type diaper was larger than that of the dry pad-type dia-

![Fig. 3 Schematic diagram of the torso experimental apparatus.](image1)

![Fig. 4 Circuit diagram of capacitance to voltage converter.](image2)

![Fig. 5 Frequency response of electrode capacitance.](image3)
For the dry pad-type diaper, the capacitance decreased slightly with the increase in interelectrode gap. For the wet pad-type diaper, the capacitance increased up to an interelectrode gap of 20 mm, and then decreased with the increase in interelectrode gap. The greatest difference in capacitance between the dry pad-type and wet pad-type diapers was observed at a 20-mm interelectrode gap. Therefore, a 20-mm gap between electrodes was used in the following experiments.

Third, Fig. 7 presents the relationship between the capacitance of the electrodes and the overlapping distance. The capacitance remained almost flat as the overlapping distance changed for the dry pad-type diaper. For the wet pad-type diaper, however, the capacitance increased linearly as the overlapping distance increased.

3.2 Torso experiments

Figure 8 shows the relationship between the output voltage and absorption volume in the torso measurement. For both positions of the torso, i.e., supine and 30° lateral, the output voltage increased linearly with the increase in water absorption volume of the pad-type diaper. The capacitance of the electrodes was lower when the torso was in 30° lateral position than in supine position.

4. Discussion

When the width of the electrodes was 25 mm, the difference in capacitance between the dry pad-type diaper and wet pad-type diaper was the largest at an interelectrode gap of 20 mm. Therefore, this study shows that the 25-mm electrode width and the 20-mm interelectrode gap are optimal to evaluate diaper absorption volume.

Figure 7 shows that the capacitance increases in proportion to the area where the wet pad-type diaper and the electrode face each other. In the torso experiments, the water absorption area of the pad-type diaper increased as the amount of water absorbed by the pad-type diaper increased. The CV converter circuit converted the capacitance of the electrodes into an output voltage. The linear relationship obtained between the volume of water absorbed and the output voltage, as shown in Fig. 8, is probably due to the increase in area of the water absorption surface facing the electrodes. We previously reported that care receivers in a nursing home urinated between 170 g and 300 g [12]. In this study, the capacitance measured by the capacitive sensor showed linearity with the volume of water absorption between 0 mL and 600 mL or even more. Therefore, the absorption volume can be measured quantitatively, and our data suggest that the resolution is at least 100 mL (Fig. 8). The output voltage in the supine position was higher than the output voltage in the 30° lateral position. When the position of the torso was 30° lateral, the pressure exerted by the buttock of the torso on the electrodes was less than that in the supine position, and the water flowed in the direction of the lower thigh while being absorbed by the pad-type diaper.
The capacitance decreased because the absorption area detected by both electrodes was reduced. Tachibana and Niikawa [19] reported the possibility of quantitative estimation by an electrode matrix sheet using simulated urine and a plastic torso in supine position. However, since the electrode matrix sheet is separated from the pad-type diaper in the lateral position, it is difficult to estimate the amount of urine absorbed in the lateral position using the electrode matrix sheet. In this study, the output at the 30º lateral position was small relative to the supine position, but a linear output voltage change with respect to the amount of absorption was obtained.

To avoid skin contamination by excrement which may cause skin irritation, decubitus ulcer, and urinary tract infection, the diaper sensor may be also have to detect defecation. A method to distinguish between urination and defecation using a gas sensor has been reported [20].

The task for the next work is to achieve higher accuracy to evaluate the absorption volume and examine the electrode shape in order to reduce the capacitance change related to position change. Gender difference will be one of the parameters to set the optimal detection of urination in diapers. In addition, a defecation detection function would be realized. The next step is to improve the sensor system and evaluate care receivers in nursing homes.

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