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Evaluation of Printed Coplanar Capacitive Sensors for Reliable Quantification of Fluids in Adult Diaper

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Abstract. Advancements in printed technology have led to the development of economical and sustainable electronic solutions for wearable medical devices in the healthcare sector. Printed capacitive sensors in planar geometry are widely used in the development of smart diapers for detecting urination events, quantifying detection, and quantifying voided volumes. However, factors such as the effect of sodium electrolyte variation, body weight effect on a wet diaper and gravitational effect on wet diapers impair the quantification of voided volume with capacitive sensors. In this study, a printed capacitive sensor for quantifying human body fluids in adult diaper was evaluated to analyze these effects. Silver and carbon inks were used to print the parallel-plate capacitive electrodes on a flexible substrate in a coplanar geometry. In-diaper quantification measurements were performed at various concentration levels in pseudo urine with small incremental levels at the adult human urination flow rate. The impact of human body weight on quantification measurements using a wet diaper was studied. The gravitational pull effect of wetness was evaluated for on-human-torso use in both standing and lying positions. It was observed that a printed coplanar capacitive sensor alone is insufficient to reliably quantify the voided volume in diapers.

Keywords: Capacitive sensors · Sodium concentration · Printed sensors · Printed electronics · Voided volume quantification · Smart diapers · Wearable medical devices

1 Introduction

The population is aging globally, and the aging level is on the rise, especially in eastern European and Asian regions, where the share of aged people is larger with lower life expectancy due to dominant health issues [1]. Urinary incontinence – the lack of voluntary control of the bladder – is prevalent in older people with an overactive bladder, causing embarrassment [2, 3]. Disposable diapers

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are one of the most common products used by patients with a loss of bladder control. The global market for absorbent hygiene products such as adult diapers was USD 13.4 billion in 2020, and only USD 0.3 billion in 2016. It is expected to grow to USD 22.7 billion between 2021 and 2028 with a CAGR of 4.5% [4].

A wet diaper, if not replaced at appropriate intervals, may cause infections such as decubitus ulcers, incontinence-associated dermatitis, and lower urinary tract infections in geriatric patients [5]. Care providers continuously check the level of wetness every hour to inspect the need for a diaper change, which not only leads to discomfort for the care receiver but also makes the care provider's job labor-intensive. Moreover, care providers are instructed to fill in urination tracking events and voided volumes in adult diapers of geriatric patients to improve their quality of life. The conventional method of measuring the voided volume and flowrate is by manually weighing diapers or using a container with a stopwatch to maintain the frequency volume charts and paper diaries of patients facing urinary incontinence. This adds an extra burden to healthcare staff and many discrepancies have been noticed in such measurements [6, 7].

Recent advancements in the internet-of-things (IoT) have led to the development of state-of-the-art wearable biomedical solutions for body area sensor networks by enabling the use of healthcare devices not only by healthy individuals but also by the care receiving vulnerable members of society to measure and record their daily routine activity events. The healthcare parameters are continuously ambulatory, measured at sensor nodes, monitored on smart devices, and recorded on the cloud for further investigation of chronic diseases and health performance using deep learning, big data, and artificial intelligence (AI) based algorithms to enhance digital healthcare [8].

The development of smart diapers using various measurement techniques under the umbrella of the Internet-of-Things has brought solutions to several challenges faced by not only absorbent hygiene product users of early age but also the elderly and patients with overactive bladders and lower urinary tract symptoms (LUTS). In literature, various sensors have been developed to detect and quantify the voided volume of body fluids in diapers to maintain the digital voiding diary of geriatric patients. For example, a study in [9] presented the use of a pair of ultra-high-frequency radio frequency identification (RFID) tags inside a diaper as moisture sensors to detect wetness in a diaper.

Capacitive sensors with coplanar geometry have been widely adopted for urination event detection. A planar capacitive sensor development technique was studied in [10], where copper tape was used to implement a coplanar sensor with variation in the inter-electrode distance. The sensor is deployed on the outer surface of the diaper, and discrete components are used to implement the front-end electronic system for data acquisition. Water volume measurements were performed using a sensor on the torso in the supine and lateral positions. Another study [11] presented the development of a portable device to measure the voided volume using coplanar capacitive sensors. A set of three copper-tape-based capacitive sensors was deployed on the outer surface of the urine collection container.

The study in [12] presented the design of a low-cost wireless incontinence sensing system with an array of six capacitive and resistive sensors in planar geometry using conducting polymer in silicon with limited of flexibility and stretchability. The sensor was implemented by sandwiching the absorbing pads of the diaper between several interdigitated electrodes.

Recent developments in printed electronics technology have made it possible to produce sensors and electronic components on flexible, economical, and sustainable substrates [13]. A coplanar capacitive sensor was implemented using various conductive materials to collect the specifications for developing printed capacitive sensors using economical and sustainable materials for human fluid detection and voided volume quantification in adult diapers [14].

To the best of our knowledge, previous works are missing the effect of sodium electrolyte concentration variations in voided volume on the coplanar capacitive sensor model. Secondly, the wet diaper faces a gravitational pull which affects the capacitive sensor measurements. Finally, the wet diaper encounters weight stress owing to body movement, which causes a change in the capacitive sensor readings. All these factors may lead to false quantification of the voided volume if only a capacitive sensor is used for the measurements.

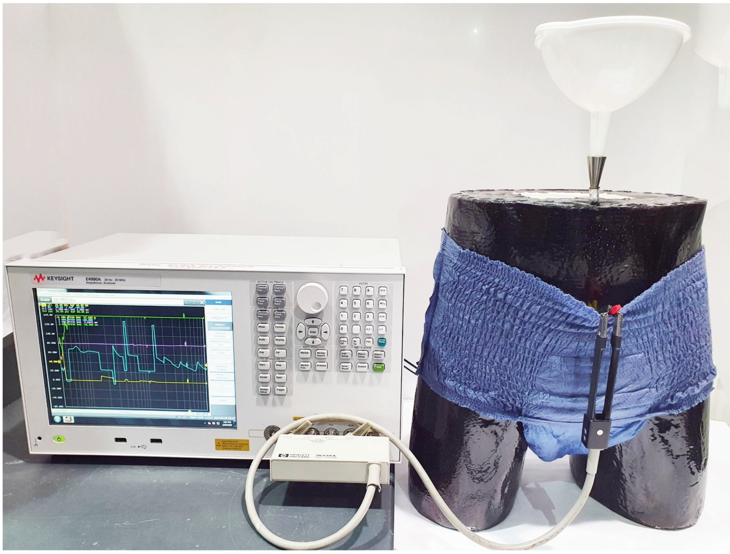

Fig. 1. Voided volume measurement setup with the impedance analyzer using the printed coplanar capacitive sensor.

This study focuses on sensor design and development in biomedical engineering for IoT-based wearable medical devices where screen-printed coplanar capacitive sensors from silver and carbon inks are evaluated for reliable quantification of voided volume in adult diapers. The capacitive sensors of the two electrodes in coplanar geometry were developed based on the specifications provided by [14] to evaluate the aforementioned effects of electrolyte variation, gravity, and weight stress on capacitive sensor measurements while quantifying voided volume in an adult diaper. Figure 1 shows the measurement setup used in this study. The voided volume was imitated using tap water and pseudo-urine with various concentrations of sodium chloride electrolyte. An interesting behavior of the printed capacitive sensors to the variation in electrolyte concentration was observed. Experiments revealed that the precise quantification of voided volume in adult diapers is affected by the variation in the concentration of electrolytes, and measurement with capacitive sensors is insufficient to produce reliable results.

The materials and methods used in this study are discussed in detail in Sect. 2. The results are elaborated in Sect. 3, and the conclusion and future recommendations are provided in Sect. 4. A list of all the abbreviations used in this article is provided in Appendix I.

2 Materials and Methods

Printed capacitive sensors depicted in Fig. 2 were designed with two electrodes in parallel coplanar geometry with dimensions of 10 mm x 200 mm and a 3 mm interelectrode separation. The sensors were fabricated on polyethylene terephthalate (PET, Dupont Teijin Films, Melinex ST506, 125 μm thick) substrate using a flatbed screen printer (EKRA, E2) to pattern silver ink (Asahi LS-411AW, oven-dried at 120 °C for 20 min) or carbon ink (Sun C2171023D1, oven-dried at 130 °C for 30 min), before encapsulation with insulator ink (Loctite EDAG PF 455B E&C, two printed layers, ultraviolet (UV) light cured using a Fusion UV light systems D-bulb for 2 min per layer). Electrically conductive adhesives (Chemtronics CW2400, oven-dried at 90 °C for 5 min) were used to make the connections.

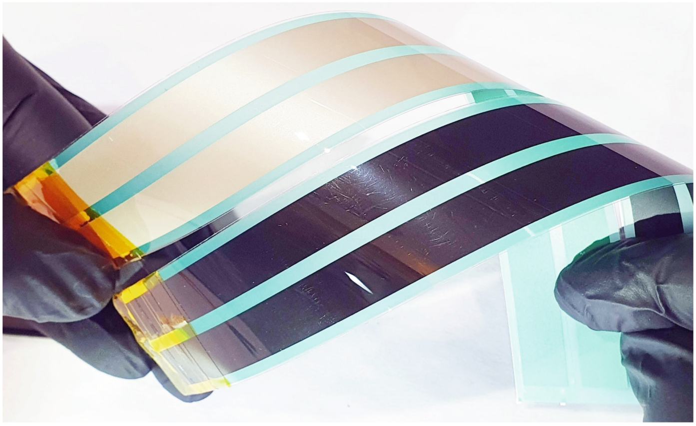

Fig. 2. Screen-printed capacitive sensors in a coplanar geometry using silver and carbon inks.

Sodium electrolyte concentration varies in urine from 30 to 140 mmol/l for children below the age of 16 years and from 80 to 240 mmol/l for adults, according to the Laboratory of Helsinki University Hospital. Pseudo urine is prepared for this study with different concentrations of electrolytes to analyze the effect on the quantification measurements with printed capacitive sensors in coplanar geometry. Sodium chloride solution was prepared as pseudo-urine using table salt and tap water. Solution with concentration of 0, 10, 30, 60, and 90 mmol/l were used to evaluate the behavior of the printed coplanar capacitive sensors inside the adult diapers.

Capacitance measurements of the printed sensors were performed using an impedance analyzer E4990A (Keysight Technologies Inc. with fixture HP16664A), and the recorded data were processed to compile the results using MATLAB software. Commercially available adult diapers by Caroli (W. Pelz GmbH & Co. KG) were used to conduct in-diaper sensor measurements in this study.

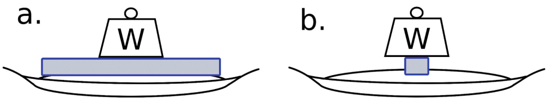

Fig. 3. The figure depicts the weight load on the entire diaper and partial diaper for voided volume quantification on the test bench.

The experimental setup involved three scenarios of measurements using the impedance analyzer: (i) sodium electrolyte concentration effect, (ii) weight effect on wet diaper, and (iii) gravitational effect on measurement using a humanoid torso.

In the first scenario, the effect of sodium electrolyte concentration on the printed silver and carbon sensors was measured using diaper pads on the test bench. Pseudo-urine is poured into the diaper with an incremental volume of 50 ml for each measurement. All measurements were recorded with a delay of 30 s after the introduction of the liquid to the diaper to ensure stable readings. Pseudo urine (300 ml) was used as the total voided volume to measure each concentration level of 0, 10, 30, 60, and 90 mmol/l.

Fig. 4. Measurement setup to analyze the gravitational pull effect with on-torso diapers in both standing and lying positions.

The second scenario assessed the effect of weight on a wet diaper. An incremental weight from 1 kg to 10 kg was applied to the entire pad and partial section diaper to analyze the impact on the capacitive sensor measurements. Figure 3a depicts the measurement setup with a weight load on the entire pad, and Fig. 3b shows the partially loaded diaper pad.

In the third scenario the gravitational impact of a wet diaper on a capacitive sensor was measured using a human torso in both the standing and lying positions. The measurements were recorded at 1, 5, and 10 min after introducing voided volume to the diaper worn by a human torso. Figure 4 shows the measurement setup of the torso in the standing and lying positions for measuring the gravitational effect of the wet diaper position on the capacitive sensors.

3 Results

The variation in the electrolyte concentration of human fluid affects the sensing capabilities of coplanar capacitive sensors, leading to incorrect measurements of the voided volume. The silver- and carbon-printed sensors show incremental capacitive behavior with the addition of every 100 ml fluid introduction to the diaper for all sodium concentration levels in pseudo urine. However, readings at the same volume with different concentrations present meaningful changes in the capacitance for both the carbon and silver sensors. The capacitance reading of the silver sensor is twice for 100 ml fluid when the concentration increases from 0 mmol/l to 10 mmol/l, and it is four times higher with concentration levels of 60 mmol/l and 90 mmol/l. Figure 5 shows the measurement of the behavior of silver and carbon capacitive sensors for the concentration change of sodium electrolytes in pseudo-urine. The change in the sensor capacitance is even higher for higher voided volumes when the concentration is greater.

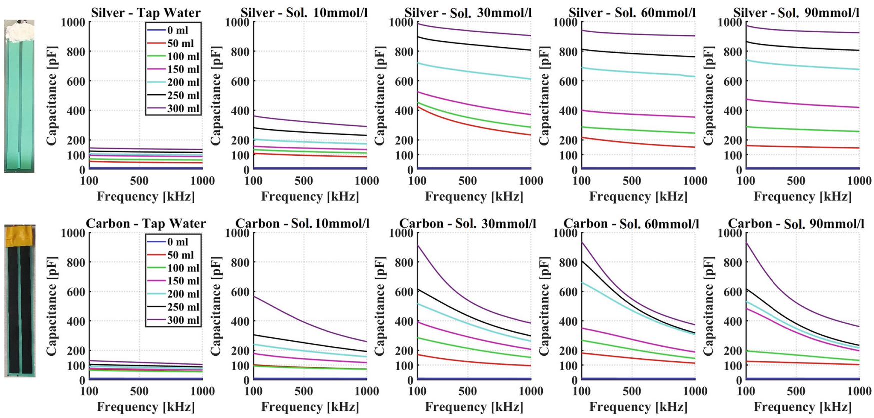

Fig. 5. The figure depicts the effect of electrolyte concentration on the capacitance measurement to quantify the voided volume with coplanar sensors printed with silver and carbon ink.

Figure 5 also shows the capacitive sensor behavior over the frequency spectrum of 100 kHz to 1 MHz. The higher sheet resistance of the carbon ink impairs capacitive measurement at high frequencies. However, at low frequencies, it measures the capacitance close to the silver ink sensor measurements, making it comparatively economical, sustainable, and a suitable candidate for printed capacitive sensors.

Capacitive sensor measurements in wet diapers are also prone to body movements when the sensor faces parts of the diaper squeezed owing to partial weight loading. Figure 6 shows the behavior of the capacitive sensor in a wet diaper when an incremental weight is applied on part of the diaper or on the entire diaper. It was found that the capacitance of the sensors increases when part of the diaper or the entire diaper is under a weight load, and it increases with the increase in weight either partially or on the whole diaper. It was observed that the capacitance increase was threefold with a just 1 kg point load on a wet diaper. This increase is significant enough to lead to false quantification of the voided volume.

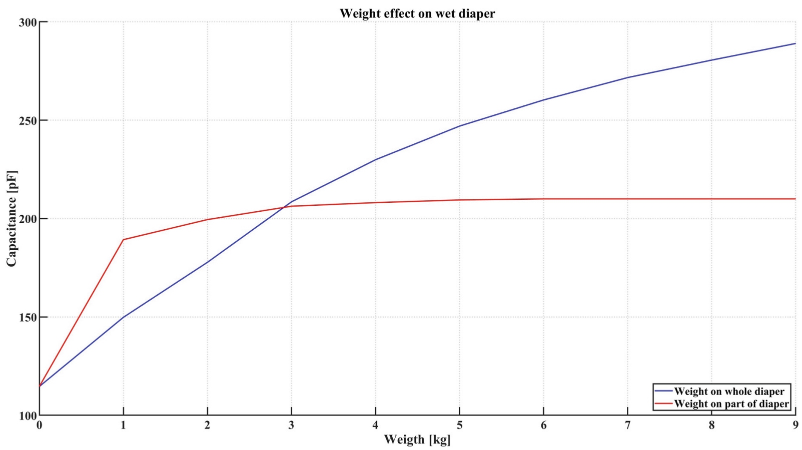

Fig. 6. Weight loading effect on wet diaper measurements with load implementation on partial and entire diapers.

Finally, the gravitational pull on wet diaper is also a factor that impairs accurate quantification measurements using a capacitive sensor alone. In this study, an amount of 100 ml liquid was introduced into diapers on the human torso in both standing and lying positions. Figure 7 depicts the gravitational pull effect on a wet diaper with 100 ml liquid over a time span of 10 min. The effect of the gravitational pull was measured after 1, 5, and 10 min. In the first 5 min, there was a significant drop in the measured capacitance, which stabilized after 10 min. Gravitational pull has a greater effect in the standing position than lying. After 10 min another 100 ml liquid was introduced to the diaper, and the change was significantly detected in both positions hence making coplanar capacitive sensor a suitable candidate for intermittent urination events detection.

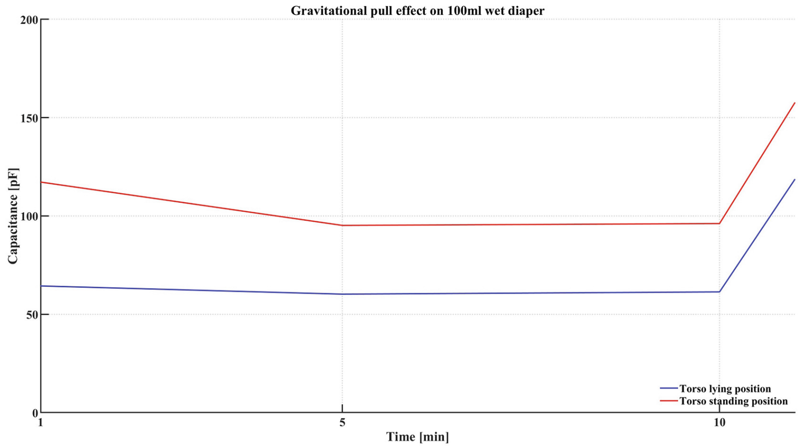

Fig. 7. The figure presents the gravitational pull of wet diaper on the measurements of capacitive sensors in both standing and lying positions.

4 Conclusion

The development of smart diapers with urination detection solutions can make the work of care providers easier; however, the precise quantification of human fluids in diapers still poses challenges. Capacitive sensors can indicate the wetness of a diaper and detect intermittent urination events. However, the results of this study show that the electrolyte concentration in urine significantly affects the readings of the coplanar capacitive sensors. In addition, the gravitation pull and body weight over capacitive sensors introduce artifacts into the measurements. Therefore, it is observed that the capacitance does not provide reliable information for the quantification of urine. In future work, more accurate quantification of fluids might be assisted by the incorporation of additional sensors to enable correction for variations in electrolyte concentration, changing gravitation pull, and applied pressure. A multi-sensor node using sustainable printed electronics technology combined with AI-based data processing algorithms is proposed for the future developments.

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Appendix – I

List of Abbreviations

AI: Artificial Intelligence
CAGR: Compound Annual Growth Rate
IOT: Internet of Things

LUTS: Lower Urinary Tract Symptoms
RFID: Radio Frequency Identification
USD: United States Dollar

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