2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

Water-sensitive urination detection system robust to body fluid and posture

Jun Obokata
School of Creative Science and Engineering
Waseda University
Tokyo, Japan
jun156521@asagi.waseda.jp

Yoshiyuki Isozaki
School of Creative Science and Engineering
Waseda University
Tokyo, Japan
yoshi.isozaki@fuji.waseda.jp

Yuuki Shida
School of Creative Science and Engineering
Waseda University
Tokyo, Japan
arares201@moegi.waseda.jp

Hiroyasu Iwata
School of Creative Science and Engineering
Waseda University
Tokyo, Japan
jubi@waseda.jp

***Abstract*—In this study, we propose a water-sensitive urination detection system that detects urination not by physical disconnection of an ultra-high-frequency tag, as in the conventional method, but by a decrease in communication strength due to the influence of water during urination. The tag is attached to the outside of the diaper and keeps communicating with the antenna under the mattress. False urination detection due to changes in posture was addressed using a three-dimensional tag arrangement and an algorithm that identifies when the user turns over. System evaluation tests were conducted. The effectiveness of the system was demonstrated by measuring the urination detection rate using a simulated urination test with a tube. The detection algorithm was used both before and after the user turned over. The results show that the system can detect turning over with high accuracy and that the possibility of false detection is low. These findings suggest that a water-sensitive urination detection system based on the moisture-induced attenuation of communication strength can be used for urination detection.**

I. Introduction

The global population is aging [1], and Japan, in particular, is currently facing the problem of a superaging society [2]. The Ministry of Economy, Trade and Industry estimates that the gap between supply and demand for caregivers is widening and that there will be a shortage of 690,000 caregivers by 2035. According to a survey by the Cabinet Office, 62.5% of caregivers feel that excretion care is a burden.

Although sensor systems and robots to assist caregivers have been investigated [3] [4] [5] [6] [7] [8], only a few sensor systems have been developed for urination detection [9] [10]. None of them have both remote notification and battery-less operation. Therefore, there is a risk of increasing the burden on caregivers. Thus, a battery-less urination detection device that can be easily used is required. Therefore, we developed a self-destructive urine detection film [11]. The tag is based on ultra-high-frequency (UHF) RFID and has a long communication distance and low cost. The system configuration and usage are illustrated in Fig. 1. The tag used in this system must be disposable so that it does not need to be collected and must be small and thin so that it does not cause discomfort when worn. To achieve these requirements, the antenna wiring was printed with conductive ink on poly(vinyl alcohol), which dissolves in urine, and the tag was operated as a UHF-band RFID tag. In the evaluation test, the tag successfully detected urination 100% of the time when n = 12 pseudo-urinations (using 150 ml of 37°C water) were performed. Conversely, the UHF RFID used in the urination detection tag has the characteristic that communication is degraded by moisture. Because this tag is used in close proximity to the human body and is significantly affected by the moisture contained in the human body, its operation becomes unstable and the detection rate degrades when it is attached to a diaper.

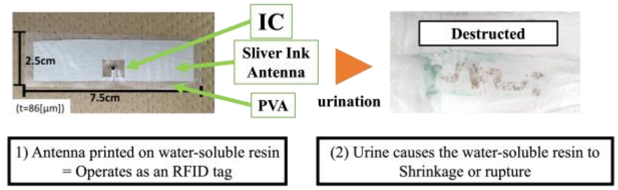

Figure 1. Structure of the self-destructive urine detection film

Previous research has shown that stable communication is possible when the distance between the tag and the human body is approximately 8 mm. However, it is difficult to maintain a stable distance of 8 mm between the tag and the human body when the tag is attached to the inner surface of a diaper so that it is directly exposed to urine. A structure that gives the tag a thickness of 8 mm can be considered; however, the tag should not be complicated or large because it is disposable and may cause discomfort to the wearer.

In addition, systems that use UHF RFID can be affected by posture. Depending on the sleeping posture, there is a risk of false detection due to the influence of moisture in the legs.

To solve these problems, the purpose of this study is to develop a urination detection system that can detect urination with high accuracy and stable communication even under the influence of the human body. In this study, we propose a detection system that can detect urination even when a tag is attached to the outer surface of a diaper instead of the inner surface. The tag attached to the outer surface of the diaper is not directly exposed to urine; therefore, it is necessary to develop a system that can detect urination without disconnection from the antenna circuit. In this study, we propose a method for detecting the presence or absence of urination on the basis of the change in communication strength due to urine absorbed by the diaper during urination, taking advantage of the fact that the communication strength of UHF RFID is affected by moisture.

In this study, urination was detected using communication attenuation when urine was absorbed by the diaper. However, when a user turns over during sleep, the position and angle of the tag relative to the antenna changes, resulting in attenuation of the communication strength. It is difficult to determine the cause of the attenuation by simply measuring the received signal strength indicator (RSSI) of a single tag. To prevent false urination detection, we constructed a urination detection algorithm that can discriminate between sleeping postures using three UHF tags.

II. METHOD

A. System Overview

An overview of the urination detection system is shown in Fig. 2. Data from continuous communication between a UHF tag and an antenna are collected using a reader/writer, and urination is detected using a personal computer. The system comprises (i) a water-sensitive urination detection system and (ii) a turnover detection algorithm.

In (i), the detection rate deteriorated because of moisture on the human body, which had been an issue in previous studies, and was improved by placing the tag outside the diaper.

In (ii), we solved the problem of false urination detection due to communication attenuation caused by changes in posture during sleep by arranging three UHF tags in a three-dimensional T-shape and using an algorithm to identify the posture of the user.

The next section describes the details of each system. The antenna is of a size that can cover the entire waist area, and the reader/writer is a specified low-power type that can be installed in multiple nursing care facilities without the need for an application. A UHF tag is used because it is superior in terms of communication stability and cost and has sufficient detection sensitivity.

B. Water-sensitive urination detection system

When urinating, urine is absorbed into the diaper from the inseam to the buttocks. In this study, we used the attenuation of the communication strength of the UHF tag due to the absorbed urine to detect urination. Previous studies have shown that when urine is absorbed by the diaper in the vicinity of the UHF tag, the communication strength decreases in proportion to the amount of urine (Fig. 3). This system attaches the tag to the outside of the diaper and communicates with the antenna under the mattress. When a person urinates, communication is interrupted because of moisture, and the system detects urination. This method is characterized by the fact that urination can be detected even when the tag is attached to the outside of the diaper, and the distance between the tag and the human body is maintained to reduce the influence of the human body and enable stable communication.

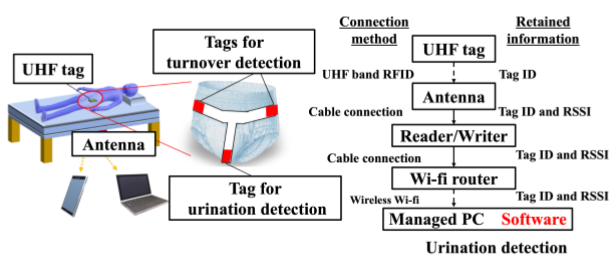

Figure 2. Urination Detection System Overview

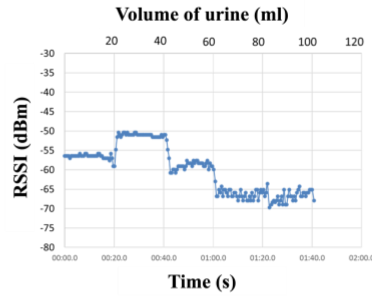

Figure 3. Decrease in RSSI due to urination

C. Turnover detection algorithm

The circularly polarized UHF-band RFID tag used in this study may not be able to communicate even within the communication range, depending on the angle between the antenna and the tag. First, when the antenna and tag are parallel, stable communication is possible and the RSSI is high. Next, when the antenna and tag are perpendicular to each other and the long side of the tag is parallel to the antenna, stable communication is possible to some extent even though the RSSI is slightly low. Finally, when the antenna and tag are perpendicular to each other and the short side of the tag is parallel to the antenna, communication is very unstable or not possible. UHF RFID is easily affected by moisture and metals, and communication becomes impossible when there is moisture or metal between the tag and the reader/writer and unstable when there is moisture or metal in the vicinity of the tag due to reflected waves. However, radio waves have the property of going around obstacles, and communication is possible even when obstacles exist between the tag and reader/writer if they are far apart.

In this study, in addition to detecting urination, it was necessary to detect turning over in bed. Therefore, in addition to one tag for urination detection attached between the legs on the outside of the diaper, one tag for turnover detection was placed on each side of the left and right buttocks, making a total of three tags used as a single device. Assuming actual use in nursing care facilities, it would be time-consuming for caregivers to attach and retrieve the three tags separately from the diaper. Therefore, we designed the tags to be placed on a T-shaped belt and attached to diapers with hook-and-loop fasteners on the back of the belt. This reduces the time required for attaching and retrieving the tag and misalignment of the tag. Many brands of diapers are available in three to four sizes, and three different sizes are available to accommodate individual differences in body shape.

The communication availability of the three tags attached to the diapers is summarized in the supine and side lying positions. First, we consider the supine position. The tag for urination detection in the groin can communicate with the antenna because it is parallel to the tag. The tag for detecting turning over on the side of the buttocks cannot communicate with the antenna because the antenna and tag face are perpendicular and the short side of the tag is parallel to the antenna.

Next, we consider the case in which a user turns left (left-side lying position). The tag for urination detection in the groin is perpendicular to the antenna; however, the long side of the tag is parallel to the antenna; thus, communication is possible. The left side of the tag can also communicate because the antenna and tag are parallel when the user turns over. The tag on the right side is parallel to the antenna; however, the human body is between the antenna and the tag; thus, communication is not possible due to the effect of moisture.

When the tag is turned to the right, the communication availability of the left and right tags is switched from when the tag is turned to the left. These results are summarized in Table 1.

TABLE I. Communication availability of each tag when supine or turned over

	Left	Inseam	Right
Supine	×(short sides parallel)	○(parallel sides)	×(short sides parallel)
Turn to the left	○(parallel sides)	○(parallel long sides)	×(human body caught)
Turn to the right	×(human body caught)	○(parallel long sides)	○(parallel sides)

The combinations of communication availability of the three tags in the three different sleeping postures are all different. Therefore, it is possible to determine the sleeping posture by constantly measuring the RSSI values of the three tags.

D. Integration Algorithm

The combinations of communication availability of the three tags in the three different sleeping postures are all different. Therefore, it is possible to determine the sleeping posture by constantly measuring the RSSI values of the three tags.

TABLE II. Communication availability of each tag before and after urination

		Left	Inseam	Right
Supine	Before urination	×	○	×
	After urination	×	×	×
Turn to the left	Before urination	○	○	×
	After urination	○	×	×
Turn to the right	Before urination	×	○	○
	After urination	×	×	○

III. Evaluation

A. Experimental Method

Evaluation tests were conducted to investigate the effectiveness of the developed urination detection system. Two tests were conducted: one to evaluate the detection rate and sensitivity during urination, and the other to evaluate the accuracy of turnover discrimination and the false detection rate of urination during non-urination. Finally, a confusion matrix for urination detection and false detection was derived from the results of the two tests to evaluate the overall accuracy of the system.

1) Experimental Setup

In this study, a mannequin (AWT-F, ProShare Navis (Azwan), Japan), which reproduced the torso to the thigh area of the human body, was tested with a diaper on it. In this study, a size M diaper (for waist 60–85 cm) was used, and a T-belt was designed for size M with a width of 50 cm and a length of 23 cm.

However, because UHF tags are affected by moisture in the human body, it is necessary to reproduce the moisture in the human body. Therefore, we placed a sponge in a Ziploc bag and made several moisture blocks that absorbed 60% of the sponge's water volume. These blocks were placed inside the mannequin to reproduce the effects of the human body. The blocks were placed in six locations: two on the inner leg, two on the buttocks, and two on the sides of the buttocks to which turnover detection tags were attached.

To evaluate the accuracy of the urination detection tag, we conducted an evaluation test using simulated urination with water. In this study, it is necessary to perform simulated urination under the influence of water in the human body to detect urination using communication attenuation due to water. Therefore, we attached a tube for urination to the human model and conducted a pseudo-urination test.

Although the urinary drainage tube enables the user to fix the position of urination, the range of urine absorbed by the diaper changes depending on the time it takes to urinate. The inner diameters of the tubes were adjusted to match the actual time required for urination. The results showed that the time required to urinate with an inner diameter of 2.0 mm was close to the average time required for both men and women. Therefore, a tube with an inner diameter of 2.0 mm was used in this study.

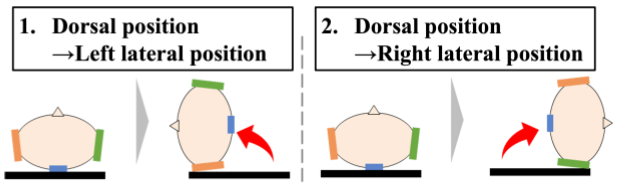

Figure 4. Two types of turnover patterns and the position of each tag

2) Evaluation test of detection sensitivity during urination

In this study, the detection sensitivity during urination was investigated, and the detection rate during single and double urination was calculated. d is the distance from the lowest point of the inseam to the end point of the tag. d=40mm, 60mm, and 80mm, the RSSI distribution and urination detection rate results indicated that d=60mm was the optimal location with the most stable distribution and high urination detection rate. The tag was placed at Pcenter and Pm. Tags were placed 10 times at each of the two measurement points, Pcenter and Pmax, and simulated urination was performed 20 times. The measurement point with the highest RSSI in the RSSI distribution in the antenna was Pmax, and the measurement point at the center of the measurement range was Pcenter.

3) Evaluation test of discrimination accuracy of turning movements and false urination detection rate

In this study, we evaluated whether the algorithm can discriminate the correct posture when a person turns over in bed and whether false urination detection occurs when the person changes his or her sleeping posture.

The human model was placed in a diaper and turned over, and the four states of supine, left-side lying, right-side lying, and urination detection were determined using the algorithm before and after the motion, and the accuracy of the determination was recorded. 30 tests were conducted, 15 times each for two types of turning patterns: (1) supine to left lateral recumbency and (2) supine to right lateral recumbency (Fig. 4).

B. Results

1) Evaluation of detection sensitivity during urination

Figs. 5 and 6 show the results of RSSI changes recorded one by one when urination was detected at Pmax and Pcenter, respectively. The results show that communication was lost. Consequently, urination was detected 20 times, the average detected urine volume was 130.5 ml, and the maximum detected urine volume was 210 ml, suggesting that 100% of the urination was detected when the user urinated twice. The detection rate was 80% when the user urinated once at 150 ml, suggesting that the system can reduce the burden on caregivers.

In this study, urination was detected when communication was lost for 30 s in a row. In this test, the RSSI decreased to 65 dBm at 150-ml urination in 3 of 4 attempts without detection. This suggests that the above method for improving the detection rate is effective. Conversely, this method may cause false urination detection when the RSSI changes because of turning over; thus, it should be considered when implementing it in an algorithm.

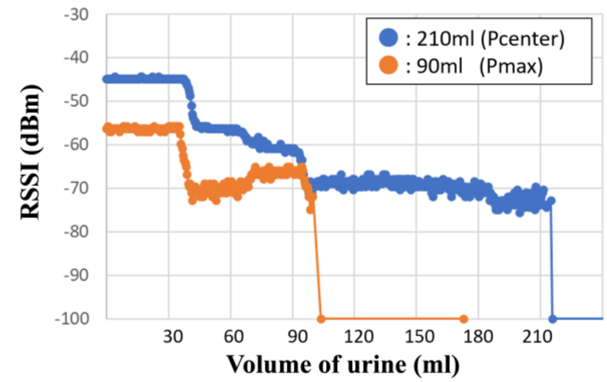

Figure 5. Examples of RSSI changes due to urination at each measurement point

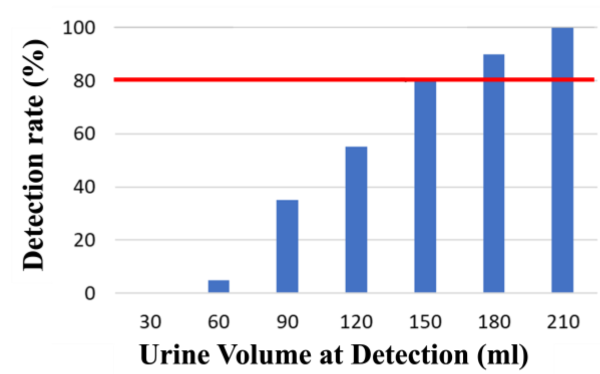

Figure 6. Detected urine volume and detection rate when affixed to d = 60 mm

2) Evaluation of discrimination accuracy of turning movements and false urination detection rate

TABLE III. Normal discrimination and false detection rates during turnover operation

Turnover Pattern	①	②	Total
Normal Discrimination	14/15	13/15	90 %
Sleep postural misclassification	0/15	1/15	3.3 %
Urination false detection	1/15	1/15	6.7 %

The results are presented in Table 3. First, the system succeeded in discriminating the sleeping posture in 27 of 30 trials, and it was confirmed that it could detect turning over with 90% accuracy. In addition, false discrimination of the sleeping posture, i.e., the robot failed to detect turning despite the user turning, occurred only once in 3.3% of the cases. Finally, there were two cases in which the user did not urinate but was falsely detected to have urinated after turning, indicating a false detection rate of 6.7%. If a false detection occurred, the caregiver would change the patient's diaper after receiving a urination notification, resulting in an empty diaper change. However, the false-positive rate of this system is low at 6.7%, suggesting that the false-positive rate is unlikely to increase the caregiver's workload.

3) Evaluation of system accuracy using a confusion matrix

According to evaluation test 1, the detection rate of urination was 80% when 150-ml urine was discharged. According to evaluation test 2, the probability of false detection was 6.7% when urination was not performed. The confusion matrix for urination detection and false urination detection is shown below.

TABLE IV. Confusion matrix for urination detection and false urination detection

	Detection	Non-detection
Urinating	16 (True Positive)	4 (False Negative)
Non-urination	2 (False Positive)	28 (True Negative)

On the basis of Table 4, we calculate the F value representing the accuracy of the binary classification. The goodness of fit and recall were 0.889 and 0.800, respectively, and the F value of the confusion matrix for urination detection was 0.842, suggesting that the system can adequately detect urination and that the possibility of false detection is low.

C. Discussions

1) Relationship between resting RSSI and detected urine volume

In this study, urination detection was performed using communication attenuation due to urination. The higher the RSSI before urination, the greater the attenuation of the communication required for the communication to be disconnected. We hypothesized that the higher the RSSI at rest, the greater the amount of urination required for detection. To test this hypothesis, we plotted the resting RSSI on the horizontal axis and the amount of urine detected in the corresponding trial on the vertical axis based on the data from the urination detection rate test described in 6.1.

The results are presented in Fig. 8. The yellow boxes indicate the 10 trials at the measurement point Pcenter, and the blue boxes indicate the 10 trials at Pmax. The mean RSSI value at rest at each measurement point was −54.9 dBm at Pcenter and −44.9 dBm at Pmax. The mean detected urine volume at each measurement point was 117 and 144 ml at Pcenter and Pmax, respectively. A linear approximation of these plots yielded the following equations:

$$y = 3.3336x + 296.78$$
$$R^2 = 0.1639$$
$$R = 0.4048$$

A modest positive correlation was found between resting RSSI and the amount of urine detected. The detection rate at Pcenter was 90% and that at Pmax was 70% for 150 ml of urination at the two measurement points, suggesting that the low detection rate at Pmax was due to the high initial RSSI, which did not fully attenuate the communication after 150 ml of urination. Therefore, a high RSSI at rest is not better than a low RSSI; however, a low RSSI is better than a high RSSI within the range where stable communication can be obtained.

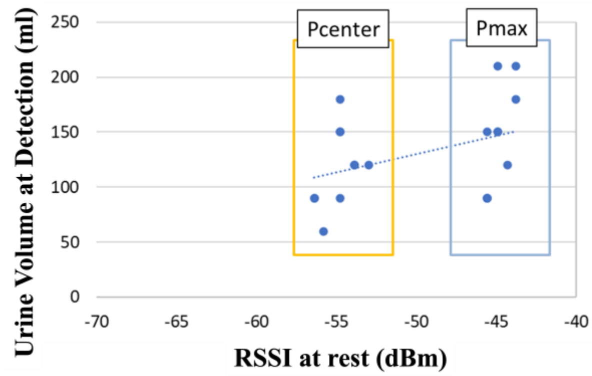

Figure 8. Relationship between resting RSSI and the detected urine volume

D. Limitations

Because a human body model was used for validation in this study, a greater effect of water in the body is expected when using the developed system on a real human body. In addition, because a general mattress was used, a decrease in the overall RSSI intensity is expected when a thick mattress is used in a nursing care facility. Care should be taken during urination detection. Furthermore, the tag is not designed to be worn with anything other than diapers. When urine pads are used, the positional relationship between the tag, the human body, and the antenna may change, which may require countermeasures. The system also identifies the sleeping posture to prevent false urination detection by assuming that urination is not detected when the user is lying on his or her side. However, the system cannot detect urination when the user is lying on his or her side for a long time. In the future, it will be necessary to develop an algorithm that can detect urination even in the lateral decubitus position.

IV. Conclusion

In this study, we proposed a water-sensitive urination detection system that detects urination not by physical disconnection of a UHF tag, as in the conventional method, but by a decrease in communication strength due to the influence of water during urination. The system consists of a tag attached to the outside of a diaper that continuously communicates with an antenna under the mattress. When the user urinates, the communication is interrupted because of moisture, and the system detects urination. The distance between the tag and the human body is maintained to reduce the influence of the human body, and stable communication is possible. The problem of false urination detection due to changes in posture is addressed by the tag arrangement and algorithm. For tag placement, we developed a three-dimensional tag arrangement that can discriminate between urination and turning over by combining three tags and determining whether communication is possible.

Verification and system evaluation tests were conducted. The detection algorithm was used before and after turning over. The results show that the system can detect turning over with high accuracy and that the possibility of false detection is low. According to the system evaluation test, the false detection rates for sleep posture and urination were 3.3% and 6.7%, respectively, suggesting that the possibility of increased burden on caregivers due to false detection is low.

These findings suggest that a water-sensitive urination detection system using moisture-induced attenuation of communication strength can be used to detect urination. We will conduct further evaluation tests of the system on a real human body in the future.

ACKNOWLEDGMENT

The authors would like to thank Mr. Hiroyasu Iwata for his support of our research. The authors would also like to thank the participants for their help with the experiment.

REFERENCES

[1] A. E. Born, B. Gomes, N. S. Etkind, J. Verne, F. E. M. Murtagh, C. J. Evans and I. J. Higginson, "What is the impact of population ageing on the future provision of end-of-life care? Population-based projections of place of death," Palliat Med Volume 2, p329-336, Feb, 2018.

[2] T. Obi, D. Ishmatova and N. Iwasaki, "Promoting ICT innovations for the ageing population in Japan," International Journal of Medical Informatics Volume 82, Issue 4, April 2013, Pages e47-e62, 2013.

[3] D. Fischinger, P. Einramhof, K. Papoutsakis, W. Wohlkinger, P. Mayer, P. Panek, S. Hofmann, T. Koertner, A. Weiss, A. Argyros and M. Vincze, "Hobbit, a care robot supporting independent living at home: First prototype and lessons learned," Robotics and Autonomous Systems Volume 75, Pages 60-78, January 2016.

[4] B. C. Stahl, N. McBride, K. Wakunuma and C. Flick, "The empathic care robot: A prototype of responsible research and innovation," Technological Forecasting and Social Change Volume 84, Pages 74-85, May 2014.

[5] D. Portugal, P. Alvito, E. Christodoulou, G. Samaras and J. Dias, "A study on the deployment of a service robot in an elderly care center," International Journal of Social Robotics Volume 11, Pages 317–341, Nov, 2018.

[6] J.-W. Kim, Y.-L. Choi, S.-H. Jeong and J. Han, "A care robot with ethical sensing system for older adults at home," Sensors Volume 22 Issue 19 10.3390/s22197515, August, 2022.

[7] M. Nokata, K. Ikuta and H. Ishii, "Safety-optimizing method of human-care robot design and control," Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292), May 2002.

[8] L. V. Aerschot and J. Parviainen, "Robots responding to care needs? A multitasking care robot pursued for 25 years, available products offer simple entertainment and instrumental assistance," Ethics and Information Technology Volume 22, pages 247–256, May, 2020.

[9] J. H. Cho, J.-Y. Choi, N.-H. Kim, Y. Lim, J. H. Ohn, E. S. Kim, R. Jiwon, J. Kim, Y. Kim, S.-W. Kim and K.-I. Kim, "A Smart diaper system using bluetooth and smartphones to automatically detect urination and volume of voiding: Prospective observational pilot study in an acute care hospital," Journal of Medical Internet ResearchVolume 30 Issue 7, Pagese29979, July 2021.

[10] S.-J. Eun, T.-K. Whangbo and D. K., Park and a. K.-H. Kim " Development of Personalized Urination Recognition Technology Using Smart Bands, "International Neurourology Journal Volume S76-83 (Suppl 1), April 2017 .

[11] A. H. Y.Isozaki, "Development of Self-Destructive Urine Detection Film Using Water-soluble Resin," Proc. of 44th Annual International Conference of IEEE Engineering in Medicine and Biology (EMBC2022), paper no.1049, 2022.