A Novel Solution of Monitoring Incontinence Status by Conductive Yarn and Advanced Seamless Knitting Techniques

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ABSTRACT

This paper presents a novel solution for monitoring incontinence status through the design and development of the intelligent incontinence pants by the use of conductive yarns and incorporating advanced circular seamless knitting technology. The produced textile incorporates wire and electrodes by conductive yarn working with a siren system which can monitor, sense and alert the wearer and care provider on the incontinence status in real time so as to reduce the need for manual checking and minimize patient care workload. The engineered stitches, yarn materials, and unique seamless knitting techniques provide soft handling, special fabric mechanisms, and tactile comfort of the resulting product. The electrical resistance of knitted conductive yarn demonstrated a stable performance in wet processing. Fitting body trials were conducted to estimate product dimension and configuration. This study allows us to explore further the potential applications of conductive yarn and seamless knitting technology in bio-functional and intelligent healthcare products and solutions through integrating multidisciplinary knowledge and techniques.

Keywords: moisture sensor, e-textile, engineering design, seamless knitting, conductive yarn.

INTRODUCTION

The prevalence of urinary incontinence (UI) increases with age [1]. In the United States, 41%-57% of women over 40 suffer from this condition [2-4]. In the United Kingdom, approximately 6 million women are affected [5]. In Asia, 30%-50% of the women in Hong Kong and Taiwan have experienced UI as adults, and 18.5% of Hong Kong women investigated have suffered from persistent UI [6, 7]. Urinary incontinence can be short-term or long-lasting (chronic). For inpatients and bedridden elderly patients suffering from this condition, special and personalized care is required from assistants or physicians for frequent manual checking throughout the day to ensure patient comfort and health, and this result in high workload and cost. Therefore, an effective monitoring and assistant device such as incontinence pants would be a solution. Incontinence pants are available in the market. Most of the available pants are made of disposable nonwoven material with/without built-in pads in various styles depending upon the user's lifestyle and wearing needs. However, these products have no intelligent ability for real-time detection and monitoring of continence status. For patients who are disabled or unconscious, prolonged urinary soiling of unchanged underpants would induce infection and dermatologic problems. To overcome this problem, new approaches for incontinence management is needed to help the patients and alert care providers for timely intervention.

A wearable intelligent textile system has been introduced in the medical and healthcare domain for years. This new concept is aimed at enhancing the safety and quality of life in humans by providing them with a wearable continuous detection and monitoring system. Knitted sensing fabric made with conductive materials has been used as one approach that can be applied to a variety of functional textile products to monitor physical-mechanical and physiological parameters, such as strain and deformation, heart rate (electrocardiogram), respiration, body temperature, and kinetic motion, etc. In this report, we present a newly designed bio-functional textile product for incontinence management which utilizes electrical conductivity properties of metallic yarn in a moisture-sensitive environment.

Conductive fibers/yarns can be produced in filament or staple lengths and can be spun with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity for different end users [8]. Among the aforementioned monitoring of physical-mechanical and physiological parameters, the use of conductive yarns in detecting moisture is seldom reported. As the incontinence pant is in contact with the skin at the groin, perineum, and buttocks, its comfort tactile sensation, good absorbency and breathability properties are crucial for its acceptance in daily wearing. Conductive yarn is flexible so that it can easily conform to the body without additional irritation, and also preserve the fabric features of softness and drapability. Thus, incorporating thin and flexible conductive fiber yarn into knitted textile fabric provides the means to achieve wearing comfort and safety in a non-obtrusive way for incontinence management.

The integration of advanced seamless knitting technology with conductive yarns can allow more novel design elements in stitch, pattern, and construction for specific functions. The conductive yarns knitted in seamless fabrics generate a complex behavior in terms of conductivity. The current is transferred from one yarn to the other. Contact resistance between yarns exerts an important role in the conductivity effect. The interaction between dampness/moisture and conductivity would allow the threshold setting of an alarm system. In this study, the intelligent pant made of conductive yarns was designed and developed by incorporating circular seamless knitting technology to sense, monitor, and alert wearers and care providers on urinary incontinence status. The performances of electrical resistance and washability of textile electrodes and conductive fabrics were evaluated objectively. Wear trials on manikin and real body were conducted to estimate its dimension and fitting. This study allows us to explore further the potential applications of conductive yarn and seamless knitting technology in bio-functional and intelligent healthcare products and solutions through integrating multidisciplinary knowledge and techniques.

MATERIAL

Development of Intelligent Incontinence Pant

The prototype of intelligent incontinence pant was developed on the Santoni 4-feed SM4-TR2 circular electronic seamless knitting machine with cylinder

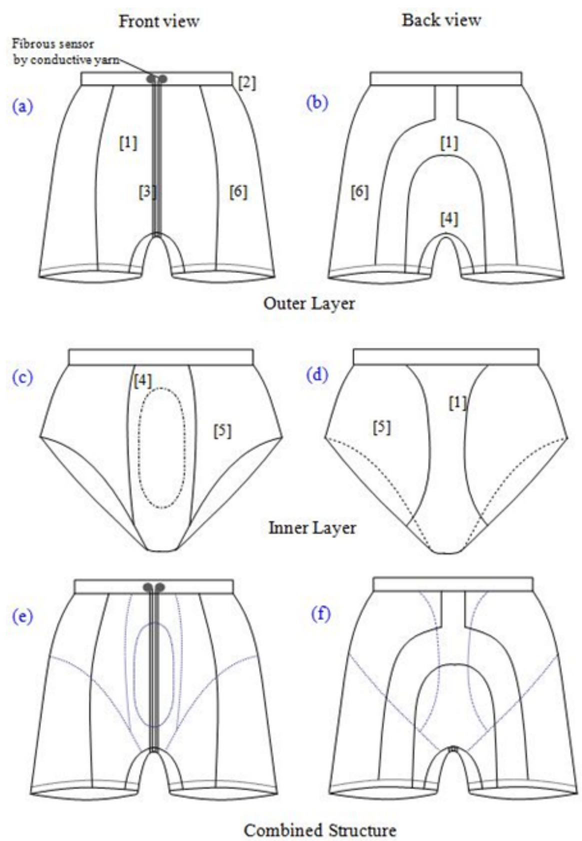


FIGURE 1. Style and structure design of incontinence monitoring pant.

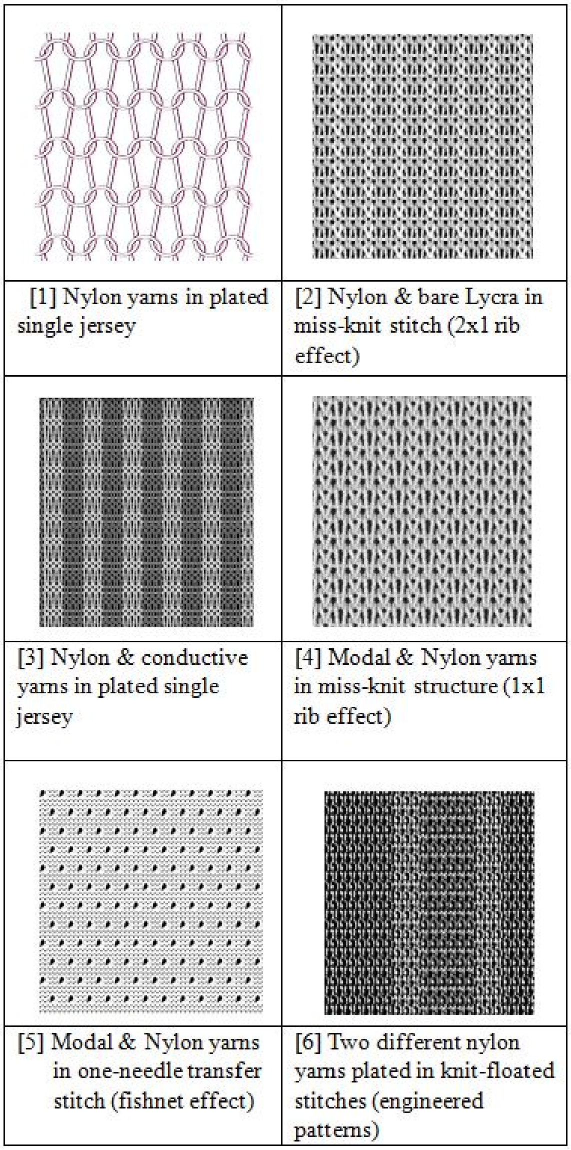


FIGURE 2. Knitting stitches design at specific areas of incontinence monitoring pant.

diameter of 17 inches, needle gauge of 24g, and needle number of 1296. Utilizing the unique seamless knitting technique, the developed pant consisted of two layers with different functionalities, both of which were knitted together at the tops by an elastic waistband made of textured nylon yarn 78D/68F and 280 denier Roica spandex. The outer layer was made of nylon with linear density of 78D/68F plated with nylon yarn 22/20 in low elastic tension. The textile electrodes sensing urinary status were produced by two plied conductive yarns comprising of nylon 66 core metalized with pure silver on the outside with yarn count of 70D/34F, which was plated knitted with nylon yarns of 78D/68F and 22/20 in the front side of the outer layer. In this case the textile fabrics act not only as a substrate but also serve as electronic wires and electrodes. The inner layer was made of Modal® with yarn count of 60s and nylon 22/20. *Figure 1 (a)-(f)* illustrates the design details of the incontinence pant.

Different stitches were designed in the specific areas and layers to enhance the properties of comfort, absorbency, ventilation, and engineered pattern of the pant. The waistband was formed by knit-miss stitches with 2x1 rib effect. The knit-floated stitches were applied in both body sides of the outer layer, which are the unique seamless stitches designed to provide special aesthetic effect with softer and comfortable handle. The conductive yarns were color yarns plated knitted into two narrow parallel strips along the front center to form two textile wires as shown in *Figure 1 (a)*. Two metallic snap fasteners were connected with the two ends of conductive parallel strips at the front waist band by conductive yarn to serve as the textile electrodes; while the snap fasteners were connected with the outside circuit of the siren signal system. The inner layer as displayed in *Figure 1 (c)-(d)* was knitted in small mesh stitches for most part, where the 1x1 "ribs" were formed by knit-miss stitches. Jersey stitches were used at front and back center parts and some room was left in the front part to allow it to conform to the body shape by applying the seamless over-lap technique. The perspective effect of the pant structures is shown in *Figure 1 (e)-(f)*. The illustration of various knitting stitches at specific areas is presented in *Figure 2 [1]-[6]*.

The developed prototype of functional pant through integrating the fore mentioned elements and technologies are displayed in *Figure 3*.

FIGURE 3. The developed prototype of incontinence monitoring pant in different views.

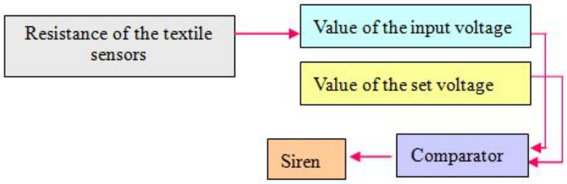


FIGURE 4. Schematic of siren signal.

Design of Siren Signal System

The system used to sense and alert the wearer to the continence status includes the textile sensor, the comparator, and the siren as depicted in *Figure 4*. The electrically conductive knitted stitches actually form a circuit network. The volume of leaked urine will change the resistance of the textile sensors, which will then result in variations of the input voltage. When the input voltage is larger than the set voltage, the siren is triggered.

The block diagram of siren signal system is shown in *Figure 5*. R_3 stands for the variable resistance of textile electrodes; U_1 is the input voltage, and U_2 is the set voltage. U_O is the voltage output of comparator. R_1, R_2 and R_4 are the elements' resistances on circuit board. VCC and GND are the positive and negative poles of power supply.

The analytical equations of siren system are shown below. The comparison of the values of U1 and U2 determines the moment when the siren is sounded.

$$U_1 = \frac{R_4}{R_3 + R_4} \times VCC \qquad (1)$$

$$U_2 = \frac{R_2}{R_1 + R_2} \times VCC \qquad (2)$$

When $U_1 > U_2$, U_0 is at high level, which is close to the value of VCC; the speaker is driven, then an alarm is sounded; When $U_1 < U_2$, U_0 is at low level, which is close to the value of GND, the speaker is silent.

U_2 is the set voltage value. R_3 is the resistance of the sensor; when the pant is dry, the value of R_3 is very large up to ∞. From Eq. (1), we know that when the value of $\frac{R_4}{R_3 + R_4}$ is close to zero, then the value of U_1 is close to the value of GND. When the pant is wet, the value of R_3 decreases quickly, while the

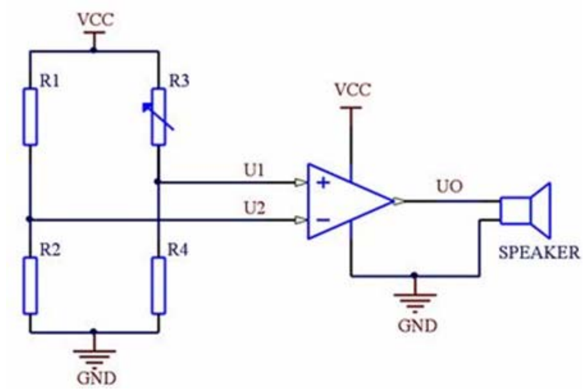


FIGURE 5. Block diagram of siren signal system.

value of $\frac{R_4}{R_3 + R_4}$ increases accordingly, then the value of U_1 is raised. When the input voltage is greater than the set voltage, i.e. $U_1 > U_2$, the siren is sounded.

Based on the above theoretical analysis, the prototype of the siren signal system was developed as presented in *Figure 6*.

Determine of Alarm Value of Siren

How to determine the set voltage is a key issue. The quantitative relationship between volumes of urine against variation of resistance was estimated in the following two experiments. Since the sodium concentrations in a solution influence resistance, in this study, physiological saline solution with 0.9 % sodium chloride was used to simulate the ingredients of urine to examine the variations of resistance with the changes of the "urine" volume. The distance between the two parallel textile electrodes influenced the R_3 and set voltage U_1 of siren system. Therefore, we adjusted the distances between the two electrode lines to 0.5 cm and 2 cm, respectively, to evaluate the resistance variations, which would be as a reference to assist users or physicians to set up their siren system based on the actual monitoring demands.

The general scheme of the textile moisture sensor and alarming system of the developed incontinence pant is shown in *Figure 7*.

The Influence of Wet Process on Conductivity

The incontinence pant should have high durability in washing (laundry) in actual use. A washability test was conducted to evaluate the effects of washing on the conduction effect of textile electrodes in the developed incontinence pants. Adopting the test condition of AATCC 61-1996, 20 washing cycles were carried out for each of the tested samples. To evaluate the influence of dyeing process in mass production on conductivity properties, the prototypes were dyed with acid dyes and leveling agent in light blue color under an actual industrial environment through the following main processes that included pretreatment, dyeing, finishing and drying. The dyeing temperature was raised up to 98°C for 15 minutes in the process.

FIGURE 6. The developed prototype of siren signal system.

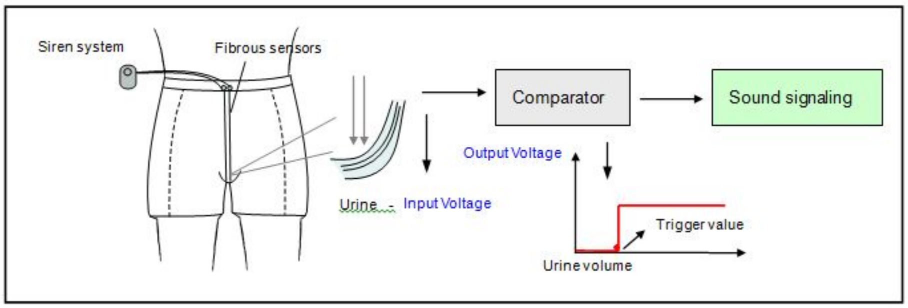


FIGURE 7. Scheme of the textile moisture sensor and alarming system of incontinence monitoring pant.

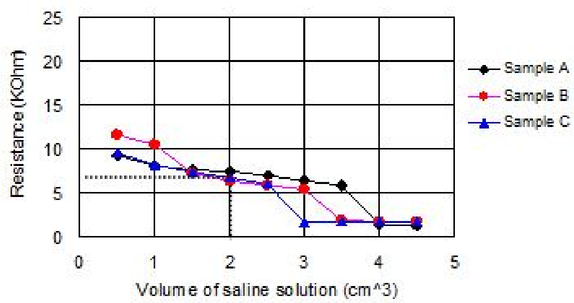
RESULTS AND DISCUSSION

When moisture is absorbed into a fabric, the electrical resistance of the fabric will change, which would enable us to detect the changing moisture in the studied fabric. The variation in the degree of electrical resistance is affected by the amount and ingredients of moisture. The newly designed incontinence monitoring pant in this study was based on this principle.

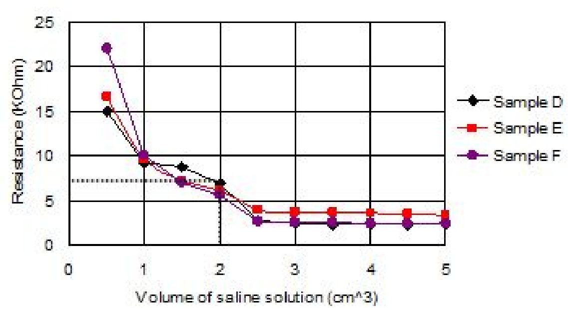
Six identical pant samples were studied in the experiments. *Figure 8 (a-b)* shows the resistance variations plotted against applied volume of saline solution (VSS) when the distances between two electrodes were set at 0.5 cm and 2 cm, respectively. From the two figures, we can see that the resistance values were decreased with increased VSS. When the volume of saline solution was up to 2.5 cm^3, the resistances values stabilized. It was noted that the resistance values of A-F samples were relatively clustered when the VSS were up to 2 cm^3, and at this moment the corresponding resistance value of the system was about 7 KOhm. Therefore, in the present resin system, we assumed that once the set resistance value was up to 7 KOhm, the resin system would automatically identify the presence of urine and alert the user and care provider about the presence of urinary incontinence.

Good resistance to wet processing allows the pant with silver yarns to maintain conductivity properties and functional performance in practical wear. The same samples B and E were selected and tested in the followed dyeing and washing processes. *Figure 9 (a-b)* show resistance variations for the two textile electrodes distanced at 0.5 cm and 2 cm after dyeing treatment and 5, 10 and 20 times of washing. It was found that the values of resistance were lower than those without wet processing. Similar changes appeared in the two situations when the electrodes were set at two different distances, e.g. when the VSS was up to 2 cm^3, the corresponding resistance values were about 1-1.5 KOhm after 20 times of washing. We postulate that the rolling (stiring) and friction produced in wet processing may alter the spacing and micro-structures between fibers and yarns, thus influencing the moisture absorbency, wicking, and diffusion capability of the knitted materials. This could in turn result in the discrepancies in the resistance values of the tested samples before and after dyeing and washing processes. The reduced resistance values, to some extent, indicate that wet processing may enhance sensitivity of the designed moisture sensors. In addition, the volume of leaked urine trapped in the pant could also affect the resistance values in practical use. Therefore, the set voltage of the siren system needs to be further determined in vivo after taking into account and integrating all of the aforementioned factors.

The usage efficiency of conductive (metallic) yarns should be considered in healthcare product design and development. Although highly conductive, metallic fibers are expensive and heavier than most textile fibers, conductive materials have more strict requirements for their production conditions and environment, for instance, keeping them away from chemicals containing sulfur, and avoiding using chlorine-containing cleansing products to clean cutting table, sewing machine, iron or steam table, proper control of the amount of its use can save manufacturing costs and reduce production complexity.

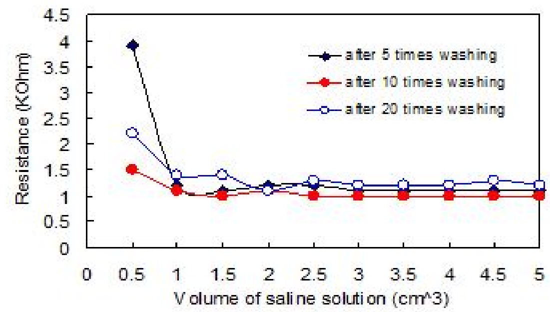


(a) Textiles electrodes distanced with 0.5 cm

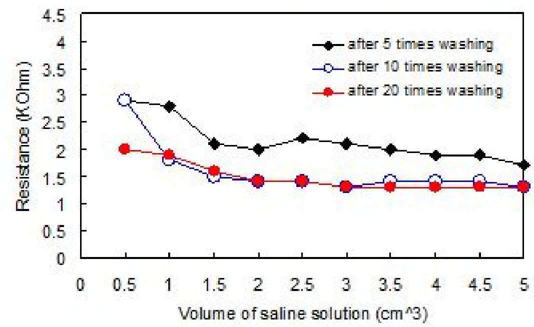


(b) Textiles electrodes distanced with 2 cm

FIGURE 8. Resistance variations versus applied volume of saline solution when the two electrodes were at two different distances.



(a) Textiles electrodes distanced with 0.5 cm



(b) Textiles electrodes distanced with 2 cm

FIGURE 9 Resistance variations after 20 times of washing when the two textile electrodes distanced at 0.5 cm and 2 cm.

In this study, the incontinence pant was designed to conform to the body shape with controlled usage of conductive yarn, which ensured the wearable capability of real-time sensing of continence status as well as allowing an alarm to be set off without obstructive intervention.

It is known that different types of moisture-sensitive sensors have been designed and some of them are available in the market for incontinence monitoring. Some moisture sensors are inserted in the disposable pads through cut slit such as the “flat sensor” [9]. Some moisture sensors are designed to be used in the liners placed beneath the bed sheet or between the bedding and mattress to detect incontinence, e.g. “enuresis sensor” [10]. The major difference of the newly developed moisture sensor described in study is that two strips of conductive yarns with very small dimensions were used as the sensor wires and knitted on the pants by using seamless knitting technology, which resulted in more comfort and convenience in actual use, and reduced production cost.

The developed siren signal system and design principle applied in this study can also be extended to different product categories used in hospitals in order to enhance monitoring of patients and provide an alarm system, such as an enuresis-monitoring bed cover, a sweating monitor, or vomitus detector. The introduction of more practical bio-functional and intelligent textiles products for clinical application would facilitate both health care givers and patients in daily nursing care and therapies for different diseases.

CONCLUSIONS

The technical textiles field has been rapidly growing. Wearable bio-functional and intelligent textile products and devices are a hybrid area requiring a multidisciplinary collaboration in the form of aesthetic design, biomedical engineering, science, and technology. This study presents a novel solution to monitor incontinence status through the design and development of intelligent incontinence pants by the use of conductive yarns advanced circular seamless knitting technology. More related works are under way to explore the possibilities through the design and development of various advanced intelligent textiles that integrate creative concepts, performance materials, knitted constructions, and attractive styles and configurations to suit the age of wearers and wearing occasions in order to provide the optimal healthcare product for specific purposes.

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