Application of Textile Pressure Sensor Contacting Body Surface to Support Pressure Ulcer Preventive Care

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Abstract

Pressure ulcers, also called *bedsores*, are caused by continuous pressure on the skin during sleep. One critical risk factor for pressure ulcers is the decline in basic movement ability, which is an inability to reposition the body by oneself despite the prolonged application of high pressure to a part of its surface. Once the disease develops, treatment takes a long time; preventive care is important. For its preventive care, pressure dispersion care and postural change are important.

Recent research is assisting nursing care using sensing technologies. For example, data from pressure sensors incorporated into bed surfaces are applied to continuously monitor the risk of pressure ulcer occurrence and notify nursing staff when repositioning is necessary. Nevertheless, in actual nursing care, not only body-pressure-dispersion mattresses but also body-pressure-dispersion cushions are used together. Thus, a pressure sensor built into the bed surface cannot properly measure the pressure applied to the human body's surface. This inability causes such serious problems as inaccurate pressure calculations as well as the failure to identify sleeping postures, resulting in systems that cannot notify medical staff when appropriate repositioning is required. To monitor and estimate the risk of pressure ulcer occurrence more accurately, a method must be developed that more directly measures the pressure applied to the human body's surface. The development of such a measurement method will promote the understanding of pressure dispersion care and the accompanying acquisition of skills.

However, no technology was established to directly measure the pressure exerted by the human body on a specific part of the body. Although a pres-

sure sensor function can be incorporated into a garment or a body-pressure-dispersion cushion to measure such pressure, there has been no evaluation for pressure ulcer prevention care, perhaps because the measurement area is limited, or because it is difficult to ensure air permeability to prevent the wet skin, which causes pressure ulcers.

In contrast to them, devices that can measure the body surface contact pressure are developed using the textile pressure sensor proposed by Enokibori et al. [1]. This textile pressure sensor consists of a single piece of plain fabric that can be easily cut or sewn. Designing a sensor with a large area is quite simple, unlike post-attaching a sensor. Since the sensor breaths like plain fabric, the wetness on the skin is reduced. To the best of my knowledge, no research has developed sensorized garments or cushions or uses them in other applications.

Therefore, the main-purpose of this study is to construct and evaluate a body surface contact pressure measurement device incorporating the textile pressure sensor, which has not been investigated previously, to try to measure the body surface contact pressure during pressure dispersion care and assist pressure ulcer preventive care. To achieve this main-purpose, the proposed sensor is evaluated coping with two problems: 1) solving such problem as failing to identify the sleeping posture by the bed-sheet-type sensor during the use of a body-pressure-dispersion cushion, and 2) solving the problem that there is no visualization material for body pressure distribution including body pressure on a body-pressure-dispersion cushion.

First, coping with the first sub-problem, a garment-type pressure sensor was developed as a technology to measure the pressure exerted on the human body's surface under body-pressure-dispersion cushion usage. Since no garment-type sensor consists of a pressure sensor beforehand, a prototype was created and its sewing pattern was improved repeatedly. As mentioned above, nursing care often uses body-pressure-dispersion cushions, and the bed-sheet-type sensors sometimes fail to identify sleeping postures, resulting in failures to notify nursing staff when appropriate repositioning of patients is required. Therefore, the accuracy of sleeping posture identification based on body surface contact pressure was used to compare bed-sheet- and garment-type pressure sensors. Comparative evaluation of them was performed using the accuracy of sleeping posture identification and experimented with 20 subjects. The results showed that the garment-type tended to have higher identification accuracy than the other sensors, suggesting that the feasibility of the garment-type pressure sensor that applies to prevent pressure ulcers based on measuring body surface contact pressure.

Next, coping with the second sub-problem, an educational system was constructed to visualize the pressure distribution on a cushion and support nursing education and skill acquisition. The pressure distribution visualization system consists of bed-sheets and cushions with textile pressure sensors so that embedded sensors can easily follow the cushion shape changes. It also has a terminal for the real-time visualization of pressure distribution. To investigate the educational effects of the proposed system on the understanding of body-pressure-dispersion, a controlled experiment was conducted with 47 undergraduate nursing students. The system can be visualized in real-time and used for practical training. Pressure-visualization teaching materials using data recorded in advance were employed for uniform experimental conditions in multiple investigations. To evaluate the educational effect of the understanding of the body surface's contact pressure, students looked at the visualization materials and drew estimates of the high-pressure areas on human body diagrams. For quantitative evaluations, the concordance rate between the answers and the ground truth prepared by an experienced nurse was calculated. The evaluation results showed that the proposed system promoted the understanding of the body surface contact pressure for such localized areas as the head and the legs without visualized material, even in complex postural changes using a cushion for students who once learned using the proposed system. These results indicate the feasibility of a system that supports the efficient acquisition of skills using the visualization of body surface pressure even when body-pressure-dispersion cushions are used.

This study proposed an unprecedented body surface contact pressure measurement device, and, evaluations in this study provided the feasibility of a garment-type pressure sensor applied to prevent pressure ulcers based on body surface contact pressure and a system including a cushion-type sensor applied to supports the efficient acquisition of skills using the visualization of body surface pressure, even when body-pressure-dispersion cushions are used. In common with the two evaluations, the applicability of the proposed sensor to prevent pressure ulcers based on body surface contact pressure was demonstrated even in an environment where a pressure-dispersion cushion is used. Therefore, the main-purpose of this study was achieved, which is the construction of a body surface contact pressure measurement device incorporating the textile pressure sensor, and the evaluation of the device.

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Chapter 1

Introduction

1.1 Research Background

Pressure ulcers, also called *bedsores*, are caused by continuous pressure on the skin during sleep. In the early stages of the disease, epidermal inflammations occur. As the disease progresses, a wound reaches the subcutaneous tissue, potentially damaging muscles and bones (Figure 1.1.1). Once the disease develops, treatment takes a long time; preventive care is important. A 2018 survey [3] conducted by the Japanese Society of Pressure Ulcer (JSPU) reported the prevalence of pressure ulcers to be 0.80% to 2.81% in hospitals, 0.77% to 1.16% in long-term care insurance facilities, and 1.93% in home nursing stations. According to the same report, the risk factor for their development was insufficient basic movement ability, e.g. changing postures which exceeded 80% in all facilities.

One critical risk factor for pressure ulcers is the decline in basic move-

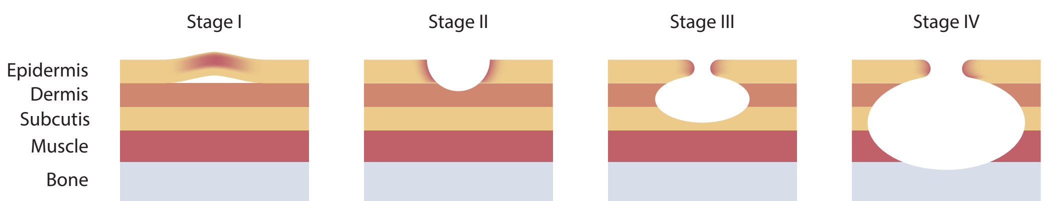


Figure 1.1.1: Progression of pressure ulcers (based on [2])

ment ability, which is the inability to reposition the body by oneself despite the prolonged application of high pressure to a part of its surface. Therefore, pressure dispersion care and postural change are important. Pressure dispersion prevents pressure from being applied to a single location due to a bone protrusion. The patient assumes a position in which the pressure caused by his or her own weight is dispersed over the entire contact surface or cushioning material is placed under the body. The postural change prevents continuous pressure on the same part of the body. The patient is repositioned once every two hours at least, day and night.

Body-pressure-dispersion mattresses are used in nursing care to provide pressure dispersion care. For example, a body-pressure-dispersion mattress generally reduces the magnitude of the pressure applied to a bone protrusion. Medical guidelines recommend assessing whether appropriate pressure management is achieved when installing a body-pressure-dispersion mattress. A common method to assess pressure management is using an insertion type of pressure sensor or placing a hand under the body.

Some recent studies have attempted to assist nursing care using sensing technologies. For example, data from pressure sensors incorporated into bed surfaces are applied to continuously monitor the risk of pressure ulcer occurrence based on integrated pressure values and notify nursing staff when repositioning is necessary. Nevertheless, in actual nursing care, not only body-pressure-dispersion mattresses but also body-pressure-dispersion cushions are used together. Thus, a pressure sensor built into the bed surface cannot properly measure the pressure applied to the human body's surface. This inability causes such serious problems as inaccurate pressure calculations as well as the failure to identify sleeping postures, resulting in systems that cannot notify medical staff when appropriate repositioning is required. To monitor and estimate the risk of pressure ulcer occurrence more accurately, a method must be developed that more directly measures the pressure applied to the human body's surface.

The development of such a measurement method will promote the understanding of pressure dispersion care and the accompanying acquisition of skills. A wound, ostomy, and continence (WOC) nurse has also identified the importance of addressing the force applied to body-pressure-dispersion cushions. Nevertheless, as mentioned above, no current system (including body-pressure-dispersion cushions) can adequately measure pressure dispersion. Furthermore, although some current medical education uses pressure visualization on bed surfaces, none explain when body-pressure-dispersion cushions are used. Evaluation of the educational effects of such systems also remains inadequate.

1.2 This Study's Problem Domain and Purposes

The lack of technology for directly measuring the pressure exerted by the human body on a specific part of the body causes two problems: 1) the inability to estimate the state of a sleeping subject using the pressure on a bed 2) the inability to effectively understand body-positioning care. To measure the pressure applied on the surface of the human body during postural change care, a pressure sensor function can be incorporated into a garment or a body-pressure-dispersion cushion.

Although recent research [4, 5, 6] has incorporated pressure-sensitive fabric into some tools and garments as described in detail later, applying them is difficult for pressure ulcer prevention since the widely used pressure-sensitive fabric consists of three layers, and obtaining a larger sensor area is difficult due to such fabrication requirements as sewing and cutting. Although film-type sensors as the force sensing array of Tekscan [7] are available, they cannot cope with wet skin, which is another leading cause of pressure ulcers.

In contrast to them, devices that can measure the body surface contact pressure are developed using the textile pressure sensor proposed by Enokibori et al. [1]. The textile pressure sensor consists of a single piece of plain fabric that can be easily cut or sewn. Designing a sensor with a large area is quite simple, unlike post-attaching a sensor. Since the sensor breaths like plain fabric, the wetness on the skin is reduced. To the best of my knowledge, no research has developed sensorized garments or cushions or uses them in other applications.

Therefore, the main-purpose of this study is to construct and evaluate a body surface contact pressure measurement device incorporating the textile pressure sensor, which has not been investigated previously, to try to measure the body surface contact pressure during pressure dispersion care and assist pressure ulcer preventive care. To achieve this main-purpose, the proposed sensor is evaluated coping with two problems: 1) solving such problem as failing to identify the sleeping posture by the bed-sheet-type sensor during the use of a body-pressure-dispersion cushion, and 2) solving the problem that there is no visualization material for body pressure distribution including body pressure on a body-pressure-dispersion cushion. The approaches to cope with two sub-problems are summarized as follows:

- Developing a garment-type pressure sensor using the textile pressure sensor and evaluating sleeping posture identification based on body surface contact pressure

- Developing a body pressure distribution visualization system, which includes a body-pressure-dispersion cushion using the textile pressure sensor and evaluating for nursing education

First, a garment-type pressure sensor was developed as a technology to measure the pressure exerted on the human body's surface under body-pressure-dispersion cushion usage (Figure 1.2.1). Note that textile pressure sensors can be fabricated into the garments themselves to increase the measurement area. They also solve the perspiration problem. Since no garment-type sensor consists of a pressure sensor beforehand, a prototype was created and its sewing pattern was improved repeatedly. As mentioned above, nursing care often uses body-pressure-dispersion cushions, and bed-sheet-type sensors sometimes fail such tasks as identification of sleeping postures, resulting in failures to notify nursing staff when appropriate repositioning of patients is required. Therefore, the accuracy of sleeping posture identification based on body surface contact pressure is used to compare bed-sheet- and

Figure 1.2.1: Garment-type pressure sensor using the textile pressure sensor

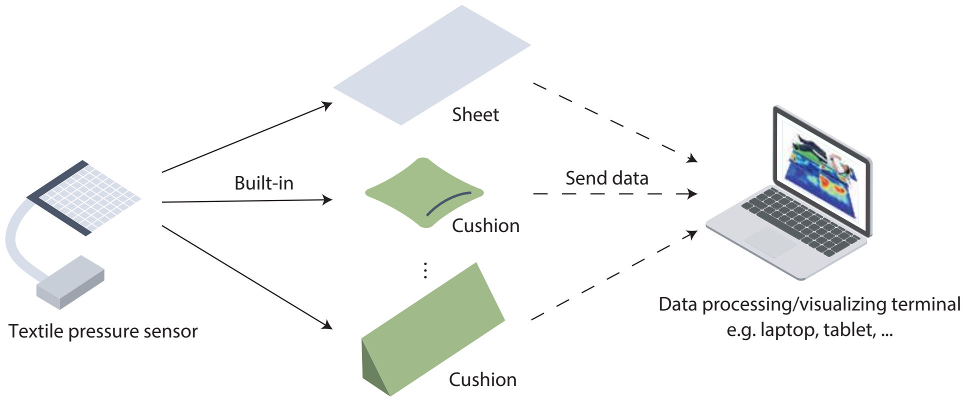


Figure 1.2.2: Overview of body pressure distribution visualization system for educational support

garment-type pressure sensors for evaluation. They are comparatively evaluated using the accuracy of sleeping posture identification and experimented with 20 subjects. The results showed that the garment-type tended to have higher identification accuracy than the other sensors, suggesting the feasibility of the garment-type pressure sensor that is applied to prevent pressure ulcers based on measuring body surface contact pressure.

Next, an educational system as illustrated in Figure 1.2.2 is constructed that visualizes the pressure distribution on a cushion to support nursing education and skill acquisition. The pressure distribution visualization system consists of bed-sheets and cushions with textile pressure sensors so that embedded sensors can easily follow the cushion shape changes. It also has a terminal for the real-time visualization of pressure distribution. To investigate the educational effects of the proposed system on the understanding of body pressure dispersion, a controlled experiment was conducted with 47 undergraduate nursing students. The proposed system can visualize the pressure distribution in real-time for practical training. Pressure-visualization was employed using data recorded in advance for uniform experimental conditions in multiple investigations. To evaluate the educational effect of the understanding of the body surface's contact pressure, students were asked to look at the visualization materials and drew estimates of the high-pressure areas on human body diagrams. For quantitative evaluations, The concordance rate between the answers and the ground truth prepared by an experienced nurse was calculated. The evaluation results showed that the proposed system promoted the understanding of the body surface contact pressure for such localized areas as the head and the legs without visualized material, even in complex postural changes using a cushion for students who once learned using the proposed system. These results indicate the feasibility of a system that supports the efficient acquisition of skills using the visualization of body surface pressure even when body-pressure-dispersion cushions are used.

In common with the above two evaluations, the applicability of the pressure sensor to prevent pressure ulcers based on body surface contact pressure was demonstrated even in environments where body-pressure-dispersion cushions are used. The results of the evaluation for the first sub-problem suggest an improved version of the garment-type pressure sensor for practical use and optimize the garment-type pressure sensor according to the patient's clothing size and contracture condition. Based on the results of the evaluation for the second sub-problem, it is expected that we will be able to measure body surface contact pressure using the garment-type pressure sensor in addition to the body-pressure-dispersion cushion and visualize the pressure dispersion status of the patient when seated by incorporating it into such equipment as a wheelchair. In the evaluations for each sub-problem, *implementation*, *data acquisition*, *analysis*, and the next implementation plan based on the analysis results could be considered, which can be considered that a real-world data circulation in the field of pressure-based pressure ulcer prevention care was established.

1.3 Structure of the Thesis

The following is the structure of this paper. Figure 1.3.1 summarizes the structure. Chapter 2 describes previous work on pressure ulcers and body surface contact pressure measurements. After that, this paper is divided into

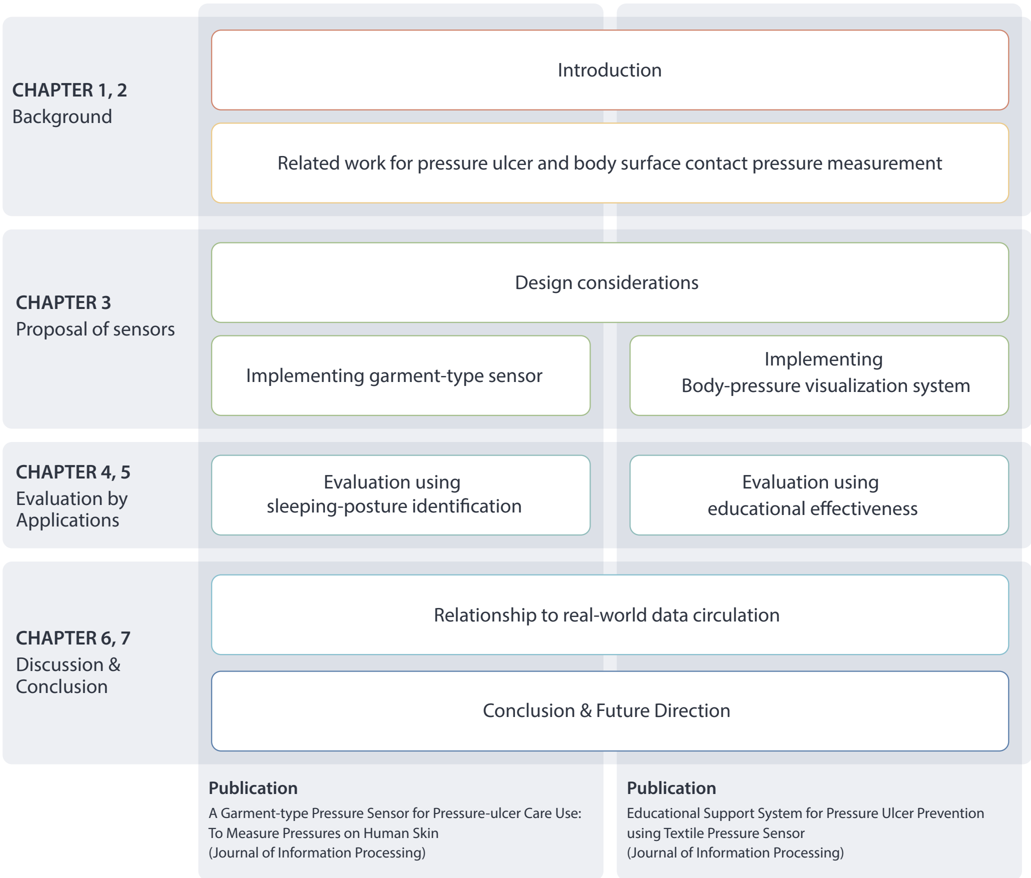


Figure 1.3.1: Structure of this thesis

the following sections: proposing method (Chapter 3) and evaluation by applications (Chapter 4, Chapter 5). Chapter 3 describes the development of a garment-type pressure sensor and a body pressure distribution visualization system. In this study, two sub-problems that have risen are focused on since no tools have been developed to measure body surface contact pressure. Chapter 4 describes the evaluation of a garment-type pressure sensor using the textile pressure sensor and sleeping posture identification. Chapter 5 describes the evaluation of the body pressure distribution visualization system for nursing education. These chapters respectively correspond to my publications. Chapter 4 is based on [72] [74] [75] [79] [80], Chapter 5 is based on [73] [76] [77]. Chapter 6 discusses this study from the perspective of real-world data circulation. Finally, Chapter 7 summarizes the conclusions and future direction of this paper.

Chapter 2

Related Work for Pressure Ulcer and Body Surface Contact Pressure Measurement

2.1 Introduction

The main-purpose of this study is to construct and evaluate a body surface contact pressure measurement device during pressure dispersion care for pressure ulcer prevention. To clarify the field of this study, this chapter mainly summarizes previous research on the aspects of preventing pressure ulcers and the technology that can be applied to body surface contact measurements. Section 2.2 summarizes the pathogenesis of pressure ulcers, their preventive care, and the issues associated with that care. Next, Section 2.3 summarizes research on sensors that can be used to measure the body surface contact pressure. Finally, Section 2.4 summarizes this chapter and clarifies the position of this study.

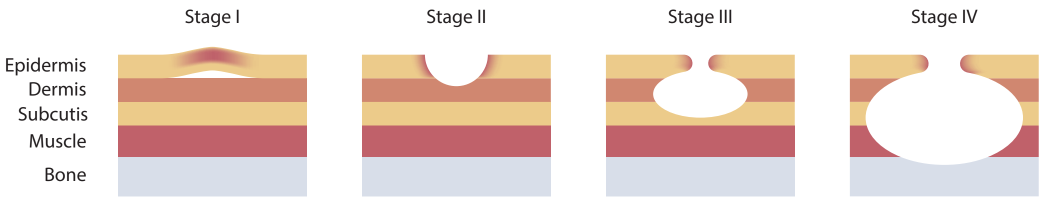


Figure 2.2.1: Progression of pressure ulcers (reprinted, based on [2])

2.2 Pathophysiology of Pressure Ulcers and Their Preventive Care

2.2.1 Pathogenesis and Prevalence of Pressure Ulcers

Pressure ulcers which are also known as *bedsores* are caused by continuous external forces on the skin during sleep or a displacement force on the same part of the body. Elderly people and patients with spinal cord injuries often develop them because they cannot sufficiently adjust their turning or sitting postures; healthy people unconsciously perform such movements. Figure 2.2.1 reprints the figure that illustrates the progression of pressure ulcers depicted in Chapter 1. In the early stages of pressure ulcers, epidermal inflammations occur. As the disease progresses, wounds may reach subcutaneous tissue and even damage muscles and bones. Once the disease develops, treatment takes a long time; preventive care is important.

Table 2.1: Prevalence of pressure ulcers (PU) by facility categories (created from Table 13 in [3])

Group	Number of patients	Number of patients with PU	Prevalence (%)
General hospitals	83,221	2,048	2.46
General hospitals w/medical long-term care sanatoriums	18,409	517	2.81
University hospitals	40,121	633	1.58
Psychiatric hospitals	1,872	15	0.80
Children's hospitals	2,604	39	1.50
Facilities covered by public aid providing long-term elderly care	6,260	48	0.77
Long-term care health facilities	8,821	102	1.16
Home medical care stations	15,988	309	1.93
Total	177,296	3,711	2.09

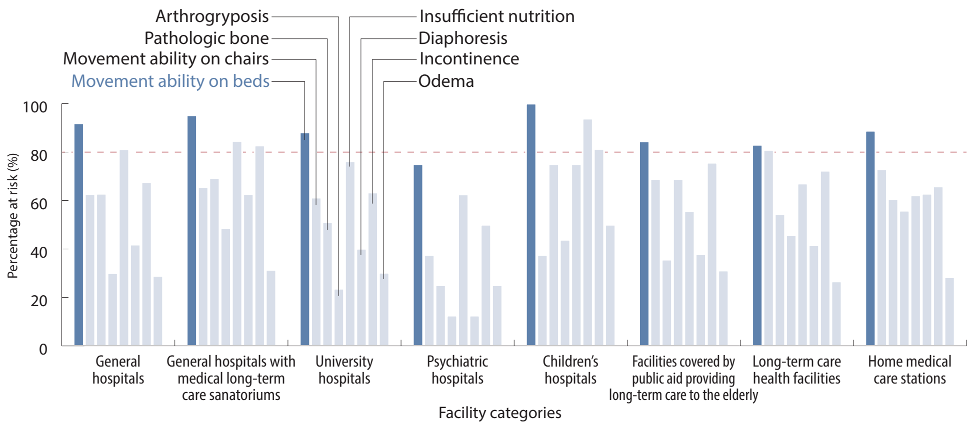


Figure 2.2.2: Risk factors for pressure ulcer countermeasures by facility categories (created from Table. 9 in [8])

Pressure ulcers are a common problem in elderly care. Their prevalence in nursing homes in Japan is approximately 2%. Table 2.1 shows their prevalence in 2018 by facility category reported by the Japanese Society of Pressure Ulcer (JSPU) [3]. According to the same report, the prevalence of pressure ulcers was 2.46% in general hospitals, 2.81% in general hospitals with medical long-term care sanatoriums, 1.58% in university hospitals, 0.80% in psychiatric hospitals, 1.50% in children's hospitals, 0.77% in facilities covered by public aid providing long-term care to the elderly, 1.16% in long-term care health facilities, and 1.93% in home medical care stations.

Figure 2.2.2 shows the percentage of items that corresponded to the risk factors for the prevention of pressure ulcers by facility category, as reported by the JSPU. The top three risk factors are generally the same in all facility categories: inability to move in bed, insufficient nutrition, and incontinence. The report claimed that basic movement ability in bed was the highest risk factor for the occurrence of pressure ulcers among all facility categories, exceeding 80%. In other words, patients' inability to change their postures due to a lack of movement ability while lying in bed is recognized as a high-risk factor for pressure ulcers.

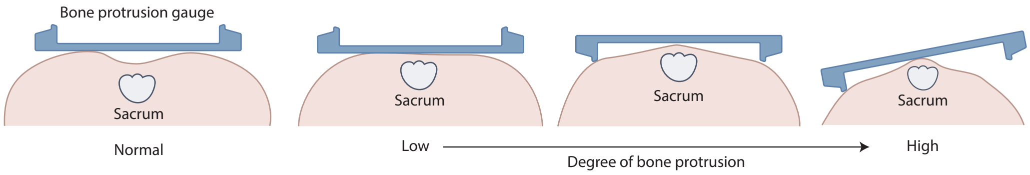


Figure 2.2.3: Measuring degree of the bone protrusion with a gauge

(a) Pressure and shear force sensor *PREDIA* [13]

(b) Body pressure distribution sensor *SR Soft Vision* [14]

Figure 2.2.4: Commercially available products for pressure ulcer preventive care

2.2.2 Method for Assessing the Risk of Pressure Ulcers

The basic principle of preventive care for pressure ulcers is assessing the risk faced by each individual. Caregivers can implement pressure ulcer preventive care based on individual risk levels. Although the direct cause of pressure ulcers is such external forces as pressure and displacement, a weakened body state or wet skin increases the risk of infections that might aggravate them [9]. Appropriate risk assessment based on these individual factors enables early preventive care.

Several risk assessment methods have been proposed. The selection of assessment is based on the characteristics of each method. A typical assessment method is the *Braden Scale* [10]. In Japan, the *Pressure Ulcer Risk Factor Evaluation Table* [11] and the *OH scale* [12] are often used, considering the characteristics of pressure ulcer occurrence among Japanese seniors.

Commercially available tools are used to assist in making appropriate assessments. For a simple measurement of bone protrusion, a bone protrusion gauge (Figure 2.2.3) is commonly used. Commercially available tools for measuring pressure include a pressure and shear force sensor (Figure 2.2.4(a)) and a body pressure distribution sensor (Figure 2.2.4(b)), which is placed on the bed to measure the pressure distribution.

2.2.3 Pressure Dispersion Care and Postural Change for Prevention of Pressure Ulcers

Caregivers provide the following care for patients who are at high risk of pressure ulcers to relieve the pressure on the body's surface that may cause them: appropriate skin management, nutritional management, pressure distribution care, and postural change. To compensate for the lack of basic movement ability on the bed, which is the top risk factor for the development of pressure ulcers, pressure dispersion care, and postural change are particularly important. Pressure distribution care is a treatment that dissipates the pressure caused by the body's own weight over the entire ground surface to prevent pressure from being applied to a single location from a bone protrusion. Postural change, which shifts the body's posture once every two hours at least, must be performed both day and night.

Pressure dispersion care includes the introduction of pressure-dispersion equipment to prevent pressure ulcers. In particular, the *OH scale* argues that patients who are unable to reposition themselves require a body-pressure-dispersion mattress. Selecting an appropriate type is critical for their medical situation based on individual assessment results. There are five types of body-pressure-dispersion mattresses: the *air-mat type* adjusts body pressure by shifting the internal pressure of the mattress; the *water type* adjusts the body pressure by changing the amount of water; the *urethane foam type* requires no power and has a low rebound and pressure dispersion effect; the *rubber type* requires no power and is easy to keep clean, and the *hybrid type* combines two or more methods. Based on the results of the assessment, it is important to select the appropriate type.

Although the introduction of a body-pressure-dispersion mattress is easy and effective, it is necessary to confirm whether appropriate pressure management is being achieved. As mentioned in Section 2.2.2, there is no effective

(a) Example of pressure dispersion care considering arm weight

(b) Example of pressure dispersion care with a cushion under legs

Figure 2.2.5: Example of pressure dispersion care demonstration by WOC nurse

way to measure the pressure across the entire contact surface of the human body when body-pressure-dispersion cushions are used together.

Each patient's condition and the pressure applied to the body's surface in each position must be understood to determine where to redistribute high pressure. Figure 2.2.5 shows an example of pressure distribution care by a certified wound, ostomy, and continence (WOC) nurse. The semi-lateral position is typical for preventing pressure ulcers in the sacral and greater trochanteric regions. Body-pressure-dispersion cushions increase the ground contact area and maintain a comfortable posture in the semi-lateral position. In addition to postural change, another method avoids continuous pressure by shifting the placement position of the body-pressure-dispersion cushion.

Generally, postural change care provides a schedule around which the supine and the left and right lateral positions are alternated to avoid continuous identical postures. The interval between postural changes recommended by the JSPU is generally two hours at least, although differences might depend on the patient's condition [11].

According to a report by Teramasu et al. [15], the percentage of patients whose postures are changed every two hours is 65.7% in the day and only 31.3% at night. One reason for the low rate is that postural changes must be done continuously every two hours at least even in the middle of the night. Such a workload is onerous due to the weight of human bodies. Besides, although the intervals between postural changes vary depending on the patient's condition, assessments tailored to individual conditions remain insufficiently conducted.

Teramasu et al. also cited a lack of awareness among nurses about the risk of pressure ulcers as another reason for the low rates. A part of these reasons can be considered as the lack of educational resources and many skills to learn. Muranaka et al. also pointed out that nursing students need to learn many skills, and claimed educational materials that can promote their comprehension to compensate [16]. Although Aoi et al. conducted a study to visualize the pressure applied to the bed surface for postural change and transfer techniques [17], no evaluation was conducted under the situation using a body-pressure-dispersion cushion.

2.3 Body Surface Contact Pressure Measurement Method and Its Application

This section summarizes the sensors that can be used to measure body surface contact pressure and their applications. First, Section 2.3.1 summarizes the methods of surface pressure measurement and commercially available sensors. Section 2.3.2 summarizes the research on the applications of pressure sensors that are incorporated into garments and equipment that can be used for nursing care.

2.3.1 Available Methods for Surface Pressure Measurement

The fundamental structure to measure the changes of the pressure distribution on a surface is arranging multiple pressure sensors. There are two methods for implementing this structure: putting on the pressure sensing elements and adding a pressure sensor function to the intersection points of orthogonal wiring.

The structure of Madokoro et al.'s method lined up pressure sensor elements on a bed [18]. They attempted to predict when the patient got out of bed by measuring her state. In contrast to previous studies using infrared distance sensors [19] and ultrasonic array sensors [20], this sensor does not compromise invisibility and prevents the caregiver from noticing it and removing it. Nevertheless, the number of pressure sensors is limited to six, probably due to the structure's complexity.

Some previous studies proposed methods to implement the pressure sensor function at the intersection point of orthogonal wiring. Commercially available sensors achieve pressure distribution measurement by calculating the changes in electrical resistance or capacitance using a combination of a transmitter and a receiver. Commercially available sensors include Nitta Corporation's *BIG-MAT* [21], XSENSOR Technology Corporation's *ForSite PT* [22], and Tekscan's *Matrix Pressure Sensor* [7]. These sensors have a layered electrode structure and are mounted on a thin film substrate.

The *Zebra Fabric*, which consists of two electrode layers and one piezoresistive layer, is commercially available from HITEK [23] and Eeonyx [24]. Examples of devices using *Zebra Fabric* include cushions [4, 25], car steering wheels [25], artificial limbs [5], musical instrument interfaces [26], sleeves [25, 27], and pants [6].

Recent studies have also explored the field of adding sensor functions to the cloth itself, and some of these have even been commercialized. Google ATAP's *Project Jacquard* [28] proposed a method of adding a touch sensor function by sewing the garment with the proposed conductive Jacquard thread. Statex's conductive fabric *Shieldex* [29] was also commercialized. *Shieldex* is widely used as a touch sensor in Donneaud et al's research [26]. In these methods, the touch sensor function is considered to be capable of detecting the body surface contact pressure. However, due to the high sensitivity of the self-capacitance method used in these methods, the capacitance can easily change depending on the object touched or humidity. Therefore, they are unsuitable for the application of this study.

Neither research nor commercial products have fabricated sensors themselves into garments or incorporated them into cushions that often deform. A film sensor is not resistant to bending. Since existing textile pressure sensors consist of three layers of fabric, it is difficult to sew or cut the fabric itself to make a garment. Furthermore, incorporating these sensors into garments or nursing-care equipment is complicated because it is difficult to secure air permeability to cope with wet skin that causes pressure ulcers.

The textile pressure sensor [1] proposed by Enokibori et al. utilizes conductive fibers as part of the warp and weft of the woven fabric, creating a textile that is pressure-sensitive due to a capacitive circuit between the conductive threads. Like in standard plain weave textiles, the sensor is breathable and can be easily processed for sewing, cutting, and stitching. In fact, a study incorporated this sensor into a wheelchair [30], [81], a vest [31], and bed-sheets [32]. The textile pressure sensor itself can be fabricated into garments and incorporated into cushions whose shape rarely deforms. Such features are difficult with other pressure sensors. To the best of my knowledge, no research has sewn a textile pressure sensor into a garment until my efforts which were achieved through this study.

2.3.2 Applied Research on Surface Pressure Measurement

Previous research has been conducted on the use and the application of pressure sensors in daily life to measure user states.

Recent research incorporated pressure sensors into a bed and measured the pressure distribution. Application examples include sleeping posture identification [33, 34, 35, 36, 37], limb detection [33, 38], activity recognition for rehabilitation [39], bed surface deformation by actuators based on pressure data [40], and predicting exit behaviors [41].

Some studies explored the measurement of pressure applied to the body surface. Leong et al. provided feedback to a prosthetic leg user with socks composed of *Zebra Fabric* [5], which is a pressure sensor that consists of three layers [23]. Skach et al. also incorporated *Zebra Fabric* into a pair of pants to identify sitting postures [6]. Xu et al. identified sitting postures by incorporating *Zebra Fabric* into a cushion and measuring the pressure distribution [4].

Many studies have proposed the method to measure the pressure applied to the body surface and estimated a user's state by incorporating pressure sensors into various tools. Nevertheless, since the measurement area of the surface that is making contact with the human body is limited, measuring the pressure distribution that is exerted on the buttocks and the flanks is insufficient, which are two areas at which pressure ulcers are likely to develop.

2.4 Conclusion

To clarify the field of this study, this chapter mainly summarized previous research on the aspects of preventing pressure ulcers and the technology that can be applied to body surface contact pressure measurements.

Section 2.2 summarized the pathogenesis of pressure ulcers, their preventive care, and the issues associated with that care. First, this section mentioned the importance of pressure ulcer preventive care. The need for pressure ulcer preventive care is widely recognized because pressure ulcers can occur in any category of nursing care facilities. In pressure dispersion care and postural change to prevent pressure ulcers, it is essential to understand pressure dispersion on the body's surface. In general nursing care, the high pressure applied to the body surface was estimated by evaluating the degree of bone protrusion based on the evaluation index of the risk of developing pressure ulcers, removing the high-pressure factor using dispersing the body pressure on a bed, and measuring the body pressure using an insertion-type pressure measuring instrument and a pressure distribution sensor on a bed surface. No research has attempted to measure the pressure applied to the body surface contacting surface under the situation when a pressure-dispersion cushion is used for pressure dispersion care. In this study, a body surface contact pressure measurement device was constructed incorporating a textile pressure sensor, measurement of the pressure distribution near the body was attempted.

Section 2.3 summarized sensors that can be used to measure body surface contact pressure. First, this section described the methods that can be used for surface pressure measurement. Next, previous studies on these techniques to apply to estimation of the state of subjects were discussed. There has been no evaluation for pressure ulcer preventive care, perhaps because the measurement area is limited, or because it is difficult to ensure air permeability to prevent the wet skin, which causes pressure ulcers. In this study, a body surface contact pressure measurement device was constructed incorporating a textile pressure sensor proposed by Enokibori et al. and evaluated solving sub-problems associated with their preventive care.

Chapter 3

Proposal Method for Body Surface Contact Pressure Measurement

3.1 Introduction

To achieve the main-subject of this paper, this chapter describes the proposal of a device that can measure contact surface pressure near the body's surface. Section 3.2 describes the currently available method, and Section 3.3 summarizes the requirements for measuring the contact surface pressure near the body of a care recipient. The section also describes the selection of a sensor that satisfies its requirements from several surface pressure sensors. Prior to implementation, Section 3.4 describes the woven fabric structure of the textile pressure sensor. Compared to such commercially available sensors shown in Figure 2.2.4(b), textile pressure sensors were implemented to meet their own requirements. Section 3.5 describes the implementation of a bed-sheet-type pressure sensor using a textile pressure sensor. Section 3.6 and Section 3.7 describe the development of garment-type pressure sensors and the body pressure distribution visualization system. Finally, Section 3.8 summarizes this chapter.

3.2 Study of Methods for Body Surface Contact Pressure Measurement

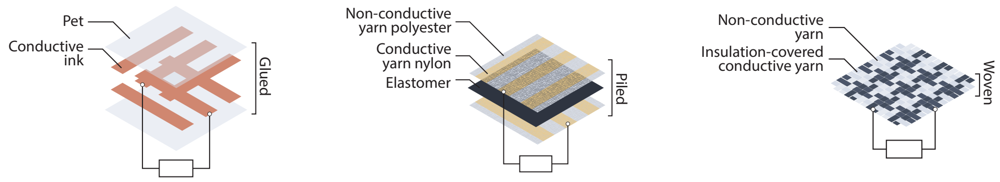
As a method to directly measure the body's surface contact pressure while a subject is sleeping, there is an insertion type of pressure measuring instrument (Section 2.2.3). Since it can measure the pressure at any single point, it can be used with a body-pressure-dispersion cushion, even though measuring the pressure over a wide area is difficult.

As a method to indirectly measure the body surface contact pressure in sleeping posture, a method to estimate the posture and simulate them is considered using Convolutional Pose Machine (CPM) [42], which can estimate the body limbs only from the camera image. Although it is an interesting approach based on camera images, it has some challenges such as the difficulty in estimating the contact area between the human body and the occlusion due to blankets and human bodies.

Although it is possible to directly incorporate a body surface contact pressure measurement function into a tool, many issues and controversial points must be solved. Such tools that can incorporate the pressure sensor function for pressure dispersion care are limited to garments worn by the patient and body-pressure-dispersion cushions. Although previous studies have incorporated pressure sensor functions into parts of garments and cushions, they have limitations. For example, no measurements have been conducted of the body surface contact pressure for pressure ulcer preventive care, and discussion on potential applications remains to be limited.

3.3 Study on Pressure Sensor That Can Be Incorporated into Nursing-Care Equipment

Many requirements must be investigated to incorporate body surface contact pressure measurements into tools before they can be used in pressure dispersion care. As mentioned above, when incorporating the pressure sensor function into garments or body-pressure-dispersion cushions, the sensor



(a) Film-type e.g., Nitta *BIG-MAT* [21]

(b) Three-layered fabric e.g., HITEK *Zebra Fabric* [23]

(c) Woven structure e.g., [1]

Figure 3.3.1: Structure of a sensor capable of measuring pressure distribution

should be deformable and allow cutting and sewing. Since wetness on the skin surface is a factor in the development of pressure ulcers, breathable material is preferable.

Several sensors have been proposed to measure the pressure distribution on a surface. Each sensor has a matrix-shaped measurement line, and the pressure change value is obtained by measuring the capacitance or resistance value between two orthogonal measurement lines. A layered structure is often adopted to construct a matrix-shaped measurement line to simplify its handling as a thin surface sensor.

For example, Nitta's *BIG-MAT* [21] is made by laminating layers of measurement lines composed of pressure-sensitive conductive ink (Figure 3.3.1(a)). Although this sensor can be easily incorporated into a flat surface such as a bed, it is unsuitable for applications of this study because it is made of film and is not breathable.

HITEK's *Zebra Fabric* [23] is composed of a three-layer configuration with a layer of piezoresistive effect between the woven fabrics with partially conductive yarns (Figure 3.3.1(b)). It can be incorporated into a piece of garment and has been used in previous studies, including *ProCover* [5] and *SmartArse* [6]. Nevertheless, its three-layered structure complicates sewing or cutting the fabric itself to make a garment.

The textile pressure sensor [1] proposed by Enokibori et al. utilizes conductive fibers for some of the warp and weft threads of the woven fabric and

Figure 3.4.1: Composition example of a textile pressure sensor

constructs a capacitive circuit between the electrostatic threads to achieve the pressure sensor function (Figure 3.3.1(c)). Like ordinary plain fabric, it is breathable and can be stitched, cut, or sewn. Because of these characteristics, the sensor itself can be fabricated and tailored to a garment or incorporated into cushions that often deform.

Although previous studies incorporated textile pressure sensors into bedsheets and wheelchairs, no research has sewn sensors into garments or deformable cushions. In this study, garments and cushions are implemented incorporating a pressure sensor function using a textile pressure sensor with a woven structure.

3.4 Principle of Textile Pressure Sensor Using Woven Fabric Structure

This section describes a textile pressure sensor and its woven fabric structure.

Figure 3.4.1 shows a composition example of a textile pressure sensor, which has been proposed in [1, 43]. Conductive fibers are used as part of the warp and weft, constructing a capacitance circuit at each point where they intersect. When pressure is applied to the textile, the distance changes almost correspondingly between the warp and weft conductive yarns, and the capacitance is measured to obtain the pressure change at each point. This

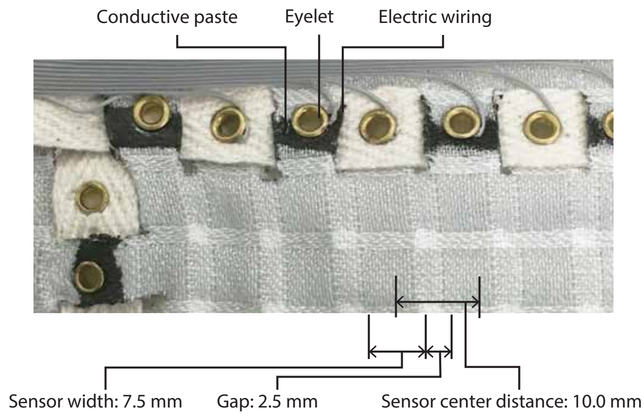


Figure 3.4.2: Design of textile pressure sensor

system is suitable for daily sensing of the body because it is breathable like ordinary plain fabric. It also resembles a normal fabric and can be sewn as a general garment.

The conductive fiber woven in this sensor is *Thunderlon*, which is twisted and insulated with polyester to cover its periphery. *Thunderlon*'s resistance does not change significantly when washed in water, and it increases by approximately 0.9 Ω after 40 washes with a neutral detergent, compared with 0.1 Ω per 1 cm of material. The resistance increases approximately 0.2 Ω at most in dry cleaning under the same conditions [1]. Since a textile pressure sensor woven with a conductive fiber has identical properties, it is expected to be considerably resistant to washing.

The capacitance values between the vertical and horizontal conductive yarns are measured by a capacitance measurement device (Figure 3.4.1 (b)) connected to the textile sensor by a conductive paste. Table 3.1 describes the specifications of the capacitance measurement device. After measurement starts, a no-pressure state is set as the minimum value, and the maximum value is set as the state where the hand is being pressed firmly. The relatively high and low capacitance values are shown as a heat map to visualize the

[1]See this link for a comparison of *Thunderlon*'s physical properties, specific resistance, and other properties with other fabrics `http://www.sanmo.co.jp/technology/Function/thunderon3.html` (last accessed: January 21, 2021).

Table 3.1: Specifications of the capacitive measurement circuit

Power	Lithium polymer battery or USB2.0
Memory	Flash ROM (2Gb)
Interface	Bluetooth 2.0 (Class 2), USB 2.0 microB, Flat cable connectors
Baud rate	Bluetooth 230400 bps
Specification	Base conductive 20 pF, Resolution 0.02 pF, Accuracy ±20%
Size	20 × 50 × 23

pressure distribution (Figure 3.4.1(c)). The measured values can be sent to a laptop or a smartphone by Bluetooth. As shown in Figure 3.4.2, the textile sensor used in this paper is a square with a 7.5-mm-square pressure-sensitive area, 2.5 mm between the pressure-sensitive areas, and 10.0 mm between center points.

3.5 Implementation of the Bed-Sheet-Type Pressure Sensor

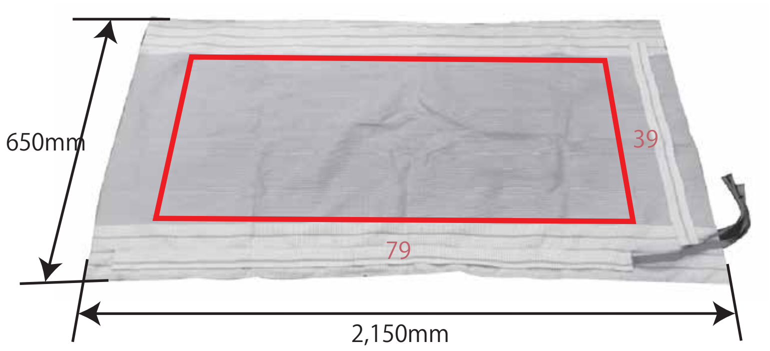


Figure 3.5.1: Bed-sheet-type pressure sensor

A sensor that can measure the pressure on a bed was also used for comparison with a body surface contact pressure measurement device. Although

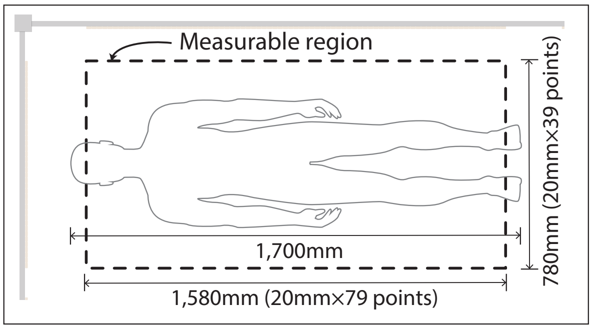


Figure 3.5.2: Design of bed-sheet-type pressure sensor

commercial sensors are available, such as the one shown in Figure 2.2.4(b), the same textile pressure sensor was implemented to match the experimental conditions. Figure 3.5.1 shows the bed-sheet-type pressure sensor used in this study. Its measurable range is 1,580 mm $\times$ 780 mm (Figure 3.5.2). This sensor has a matrix of 158×78 measurement points. Due to the limitations of capacitance measurement devices, the two adjacent points of the conductor connections are short-circuited, and the pressure-sensitive area is a square of 17.5 mm, the distance between pressure-sensitive areas is 2.5 mm, the distance between the center points is approximately 20.0 mm, and the number of measurement points is 79×39. The excess is tucked under the mattress as with normal bed-sheets.

3.6 Implementation of the Garment-Type Pressure Sensor

This section describes the implementation of a garment-type pressure sensor using a textile pressure sensor with a woven structure selected in Section 3.3.

(a) T-shirt-type sensor α (front) (b) T-shirt-type sensor α (back)

(c) T-shirt-type sensor β (front) (d) T-shirt-type sensor β (back)

(e) Pants-type sensor (front) (f) Pants-type sensor (back)

Figure 3.6.1: Prototype I: a prototype for body surface contact pressure measurement using commercial garment

Table 3.2: Outline discussion with staff members of nursing care facility

Date	2:00 -3:00 pm on July 13, 2016
Place	Merry Home Daigi Nursing Home
Participants	Eight facility members, Prof. Yuko Harasawa (School of Nursing, Nagoya City University), Prof. Enokibori (Graduate School of Informatics, Nagoya University), and author

3.6.1 Prototype I: Experimental Implementation of a Garment-Type Pressure Sensor

Before implementing this system, three prototypes of garment-type pressure sensors (Figure 3.6.1) were created to investigate the effectiveness of garments with pressure sensor functions for directly measuring body surface pressure on the skin. Commercially available long-sleeved T-shirts and pants from UNIQLO [2] were used as the base garment. Since my laboratory's past project [32] clarified that pressure ulcers tend to occur in the sacrum, the spine, and under the armpit, textile pressure sensors were sewn to the back, flanks, and buttocks of garments to measure the pressure applied to these areas. The sensor sewn to the garment has 20×40 measurement points.

3.6.2 Understanding Demand

Based on the prototype described in Section 3.6.1, We had a meeting with an expert in gerontological nursing, and some staff members of elderly-care facilities. The meeting's outline is shown in Table 3.2. They gave us practical feedback on the prototype. The feasibility of incorporating the pressure sensor function in other devices than garments was discussed. Since such details are beyond the scope of this paper, they are ignored here.

The discussion clarified that the pressure sensor should be a garment-type. The advantage of wearing pressure sensors all the time was also broached,

[2] See details in `https://www.uniqlo.com/` (Accessed January 21, 2021)

even though this study's initial starting point was to measure the body's surface contact pressure near the body during pressure dispersion care. Since a garment-type sensor can be worn all the time, it can continuously sense the patient's condition not only in bed but also in a wheelchair or while walking. This is consistent with the policy that recommends that people who need nursing care should be ambulatory instead of spending all their time in bed or a wheelchair. Although applying this pressure sensor to other garment-types than on beds is very interesting, it is beyond the subject of this paper.

The requirements for the garments needed by nursing care facilities were discussed before introducing a garment-type sensor. The discussion clarified the following requirements for garment sensorization: the capability of measuring the flank and sacral areas where pressure ulcers are likely to occur and simple putting on and taking off procedures. To satisfy both requirements as well as the feasibility of making garments by sewing textile pressure sensors, a prototype of a vest-type sensor was implemented, which can be opened in the front and easily put on and removed.

3.6.3 Prototype II: Vest-type Pressure Sensor

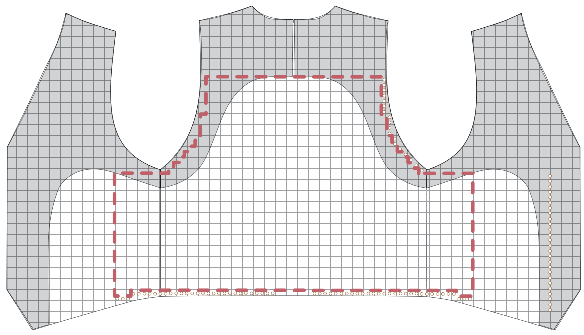
Based on the discussion in Section 3.6.2, a vest-type pressure sensor was developed. It is shown in Figure 3.6.2(a) and Figure 3.6.2(b), and its pattern is shown in Figure 3.6.2(c). Every part of this sensor (except its lining) is made with textile pressure sensors, and it can function as a pressure sensor anywhere with electrodes. To cover the flank and the back, the area shown in the figure was made for pressure measurement.

3.6.4 Discussion with an Expert in Gerontological Nursing

Opinions about the vest-type pressure sensor are collected from an expert in gerontological nursing. The expert pointed out that the thickness of the electrodes may cause excessive pressure on the body's surface during sleep,

(a) Vest-type sensor (front)

(b) Vest-type sensor (back)



(c) Vest-type sensor pattern

Figure 3.6.2: Prototype II: Vest-type pressure sensor

Table 3.3: Pajama sensor size details

Shirt		Pants	
Dress length	610 mm	Waist	410 mm
Shoulder width	415 mm	Inseam length	300 mm
Trunk width	525 mm	Leg length	700 mm
Sleeve length	580 mm	Sleeve periphery	290 mm
		Leg periphery	290 mm
		Hip periphery	490 mm

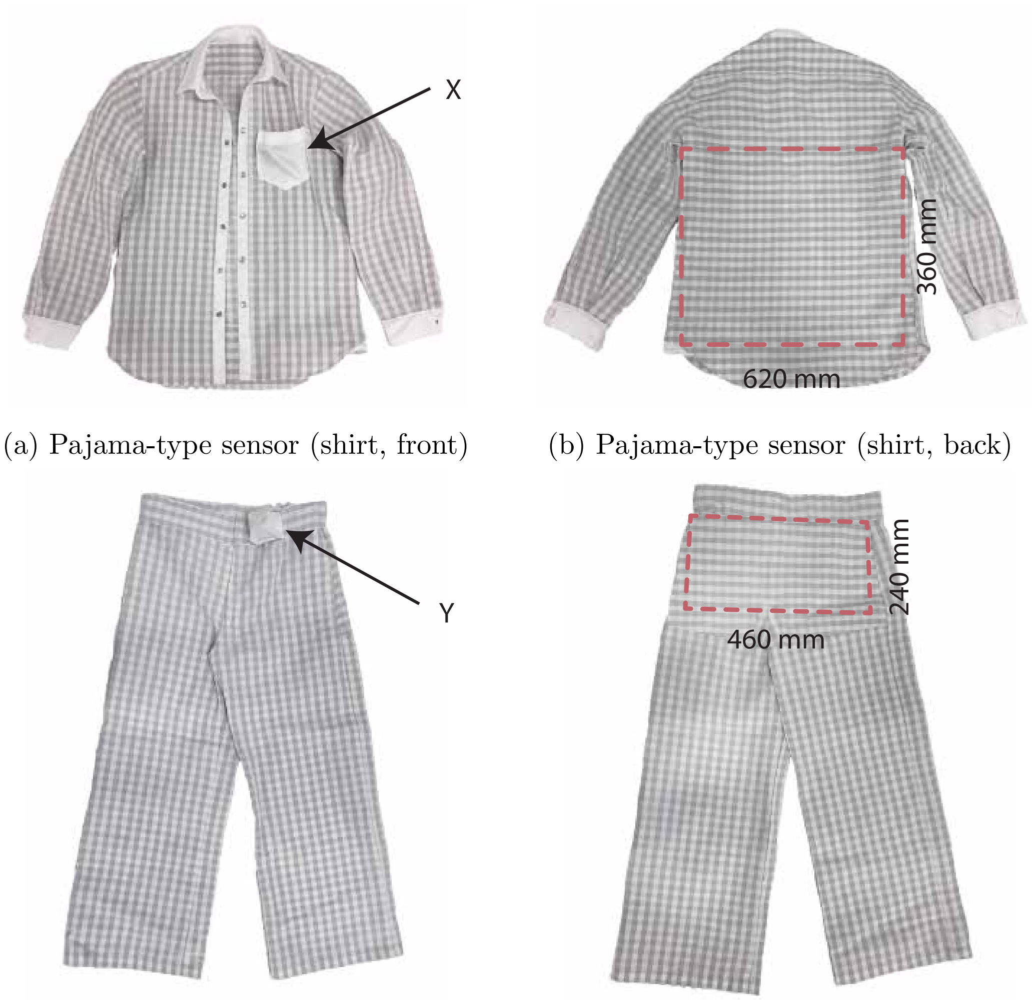
rendering them unsuitable for people with the risk of pressure ulcers. Thus, the following two requirements for sensor design are clarified: reducing the thickness of the electrodes and avoiding arranging the electrodes around the contact area between the human body and the ground.

For the vest-type pressure sensor, the thickness of the electrodes arranged around the neck of the vest may cause excessive pressure on the body's surface during sleep, rendering them unsuitable for people with the risk of pressure ulcers. Such thickness is caused by the large collar of the vest pattern, making it difficult to vertically place the electrodes. A pajama-type pressure sensor was assumed to narrow the cuffs. In addition to a shirt that measures the pressure of the back and the sides, pants were made to measure the high pressure at the sacral region.

3.6.5 Prototype III: Pajama-Type Pressure Sensor

Based on the results of the discussion in Section 3.6.4, a pajama-type pressure sensor was created. Figure 3.6.3 shows its appearance, and Table 3.3 describes the size of each part.

This sensor consists of two parts: a shirt and pants. textile pressure sensors are used to make these garments, except for the collar, the sleeves, the placket, and the pockets. The vest-type pressure sensor can measure at any site by installing electrodes. The electrodes were wired to cover the sacrum and flank, which are the most common sites for pressure ulcers. The areas



(a) Pajama-type sensor (shirt, front) (b) Pajama-type sensor (shirt, back)

(c) Pajama-type sensor (pants, front) (d) Pajama-type sensor (pants, back)

Figure 3.6.3: Pajama-type pressure sensor

indicated by the dashed lines shown in Figure 3.6.3(b) and Figure 3.6.3(d) were measured.

The shirt and pants of the garment-type pressure sensor have 18×26 and 12×23 matrix measurement points. The distance between the centers of the pressure-sensitive parts is 20 mm because the pressure textile has approximately 10 mm between them. The measurable ranges are 360×520 mm and 240×460 mm (Figure 3.6.3(d) and Figure 3.6.3(d)). The capacitance measurement devices are stored in the chest pocket (X in Figure 3.6.3(a)) and in a small waist bag (Y in Figure 3.6.3(c)).

The evaluation of the garment-type sensor described in Chapter 4 uses this implementation.

3.6.6 Garment Pattern Improvement with Experienced Uniform Designer

The shirt part of the pajama-type pressure sensor made in Section 3.6.5 was intended to measure the body's back and side. Nevertheless, the measurement area was limited to the body's back half because of the shirt pattern's seam. Therefore, uniform designs are discussed with a specialist in corporate uniforms and nursing garments. The following are requirements when designing a garment-type pressure sensor that differs from a normal garment pattern:

- No cutting the measurement area is allowed.
- No compromise on comfort is allowed.
- The part of the electrodes should be as thin as possible.
- The measurement area should be as wide as possible.

After the discussion, a technique commonly used in Japanese kimonos was incorporated, which is characterized by the use of a large, single piece of textile with minimum processing. A new pressure sensor was created resembling a type of Japanese casual wear called a *jinbei*. This sensor is described in Section 3.6.7.

3.6.7 Prototype IV: Jinbei-Type Pressure Sensor

Based on the results of Section 3.6.4, a jinbei-type pressure sensor was made. Figure 3.6.4 shows its appearance, and Figure 3.6.5 shows the garment's pattern that overlaps an example of pressure visualization when wearing it.

The jinbei-type pressure sensor consists of two parts, a jacket and pants. The distance between the measuring points is 20 mm, and the measuring area is 28×40 and 31×40 for the jacket and pants. The measurement ranges are approximately 2.49 times and 4.49 times larger than those of the pajama-type pressure sensor.

Since the jinbei-type pressure sensor is in the implementation stage, it was not used in the experiments in this paper. It will be introduced below in the further experiments described in Section 7.2.5.

3.7 Implementation of Body Pressure Distribution Visualization System

The pressure distribution visualization system consists of a cushion with a textile pressure sensor and a terminal that processes and visualizes the data. Figure 3.7.1 shows a schematic diagram of this system. The cushion is equipped with a textile pressure sensor, which wirelessly transmits the measured data to the terminal. The terminal removes noise from the received data with an intermediate value filter and visualizes the data as a pressure distribution map. The acquired data can be saved in the terminal and used for subsequent analysis.

The cushion-type pressure sensors used in this study were all made from body-pressure-dispersion cushions that are used in nursing care facilities. Figure 3.7.2 shows them. Except for the triangular cushion, the *RHOMBO* series made by Lück GmbH & Co. KG was used. The manufacturer of the triangular cushion was unknown. The figure shows the measurement range of the sensors: the small-sized sensor, 30×22, the medium-sized sensor, 45×30, the large-sized sensor, 70×40. The triangular sensor's range is 60×20 on

(a) Jinbei-type sensor (jacket, front)

(b) Jinbei-type sensor (jacket, back)

(c) Jinbei-type sensor (pants, front)

(d) Jinbei-type sensor (pants, back)

Figure 3.6.4: Jinbei-type pressure sensor

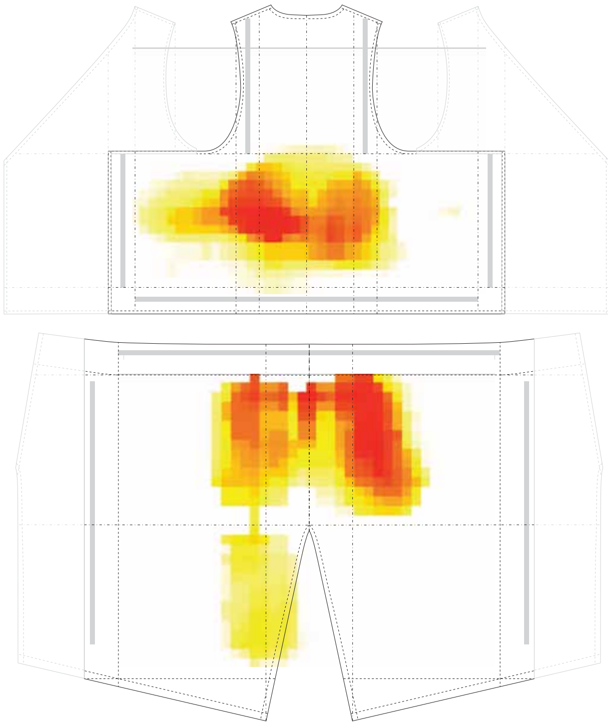


Figure 3.6.5: Pattern for jinbei-type pressure sensor with overlapping pressure visualization example

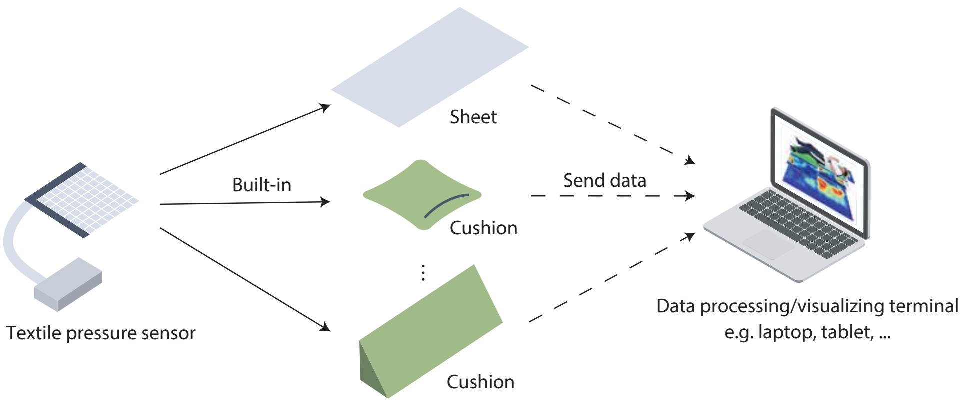


Figure 3.7.1: Configuration of body pressure distribution visualization system

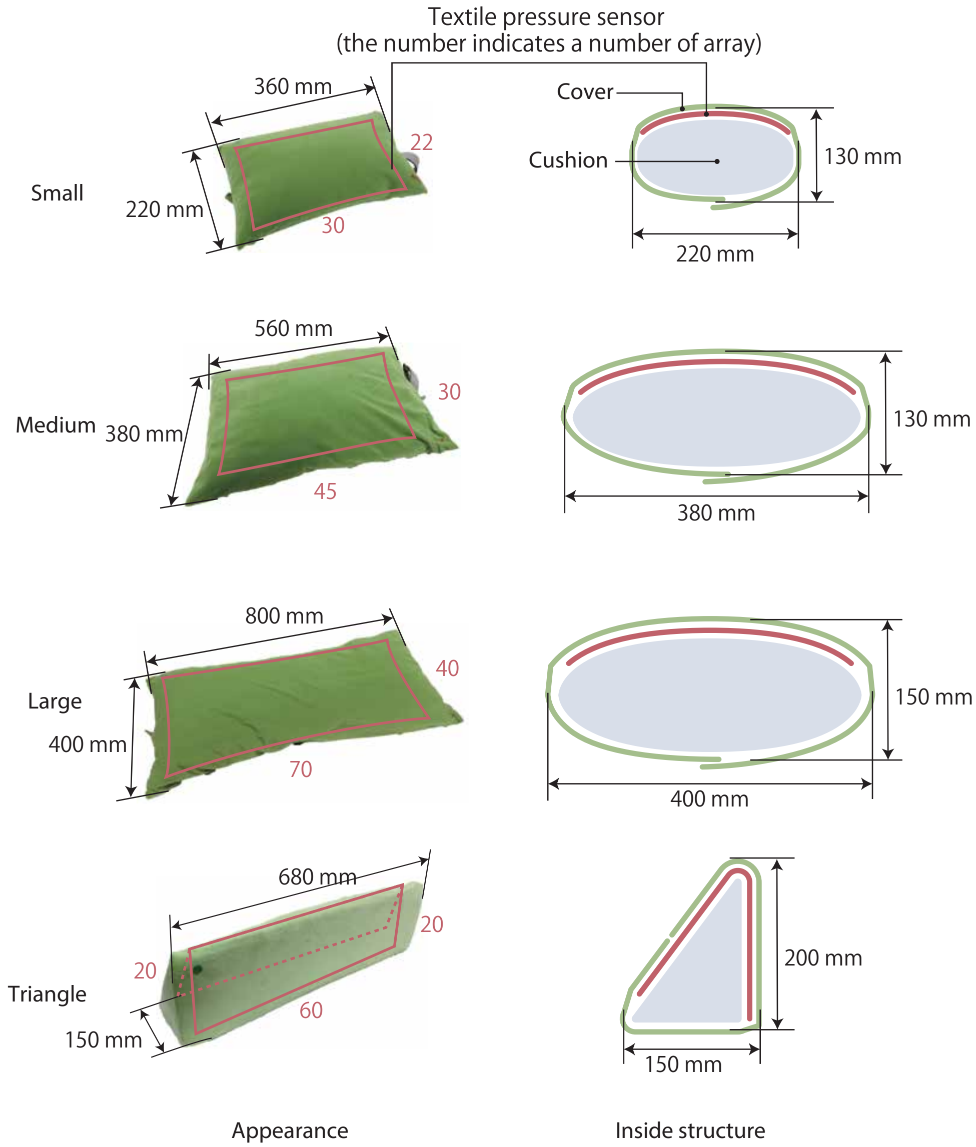


Figure 3.7.2: Cushion-type pressure sensor

the diagonal and the adjacent piece. Unlike bed-sheets, these sensors do not shorten the measurement sites, and the measurement points are lined up horizontally and vertically at 10 mm intervals. The textile pressure sensors were attached to one side of a cushion and covered.

3.8 Conclusion

To achieve the main-subject of this paper, this chapter described the implementation of a device that can measure contact surface pressure near the body's surface. First, Section 3.2 described that the currently available method is unsuitable for the application of this study, and Section 3.3 described the requirements for measuring the contact surface pressure near the body of care recipients. The discussion of this section clarified that a textile pressure sensor with a woven structure is suitable since it can be fabricated into a garment and it breaths like plain fabric coping with sweat that can cause pressure ulcers. Section 3.4 described the woven fabric structure of the textile pressure sensor. Section 3.5 described the implementation of a bed-sheet-type pressure sensor using a textile pressure sensor to meet its own requirements. Section 3.5 described the implementation of a garment-type pressure sensor. Since no garment-type sensor consists of a pressure sensor beforehand, a prototype was made and its sewing pattern was improved repeatedly. As a result, a garment-type pressure was proposed to measure the area covering the sacrum and flank, which are the most common sites for pressure ulcers. Section 3.7 described the implementation of a pressure distribution visualization system. Since the proposed cushion-type pressure sensors were all made from body-pressure-dispersion cushions that are used in nursing care facilities, resulting in similar usability to ordinary ones.

Chapter 4

Evaluation Using Sleeping-Posture Identification Based on Body Surface Contact Pressure

4.1 Introduction

This chapter describes an evaluation of the garment-type sensor proposed in Chapter 3 to assess its applicability of body surface contact pressure measurement, which is the main-purpose of this study. The sensors were evaluated using the accuracy of sleep posture identification based on a body surface contact pressure, which is one of the sub-problems.

First, Section 4.2 describes the research background of the sub-problem. Next, Section 4.3 discusses previous studies, and Section 4.4 summarizes the measurement obstruction (prior to the investigation) caused by the body-pressure-dispersion cushion when using a bed-sheet-type pressure sensor. As described in Section 1.1, nursing care settings use body-pressure-dispersion cushions, which cause such problems as failing to identify sleeping postures or failing to notify the nursing staff when appropriate repositioning is required. This problem is addressed with the accuracy of sleeping posture identification to evaluate the garment-type pressure sensor proposed in Section 3.6. The accuracy of the sleeping posture identification based on a body surface contact pressure was used to compare the bed-sheet and the garment-type pressure sensors. For a comparative evaluation, an experiment with 20 subjects was performed. Section 4.5 describes a method to collect the pressure data from 20 subjects. Section 4.6 describes a selection of the features to be evaluated and the test methods to be used for identification. Section 4.7 describes the results of the sleeping posture identification and the evaluation based on identification accuracy. Finally, Section 4.8 summarizes this chapter.

4.2 Research Background

For patients who are unable to reposition themselves due to a decline in basic movement ability, postural change is commonly introduced as one of pressure ulcer prevention care. Postural change is a care to reposition at least once every two hours, day and night, to prevent continuous high pressure. For patients at high risk of developing pressure ulcers, it is recommended that nursing care should include repositioning at intervals of two hours or less. This once-every-two-hour repositioning must be performed continuously even in the middle of the night. Such a workload is onerous due to the weight of human bodies.

Previous research has been conducted on the use of pressure sensors on a bed surface to support posture change. For example, data from pressure sensors incorporated into bed surfaces are applied to continuously monitor the risk of pressure ulcer occurrence based on integrated pressure values and notify nursing staff when repositioning is necessary. Nevertheless, in actual nursing care, not only body-pressure-dispersion mattresses but also body-pressure-dispersion cushions are used together. Thus, a pressure sensor built into the bed surface cannot properly measure the pressure applied to the human body's surface. This inability causes such serious problems as inaccurate pressure calculations as well as the failure to identify sleeping postures, resulting in systems that cannot notify medical staff when appropriate repositioning is required. To monitor and estimate the risk of pressure ulcer occurrence more accurately, a method must be developed that more directly measures the pressure applied to the human body's surface.

Therefore, in this chapter, an investigation was conducted to explore the applicability of pressure sensors to prevent pressure ulcers based on the body surface contact pressure using the garment-type pressure sensor proposed in Chapter 3. The accuracy of sleeping posture identification based on body surface contact pressure was used to compare bed-sheet- and garment-type pressure sensors. Comparative evaluation with 20 subjects was performed using the accuracy of sleeping posture identification. The results showed that the garment-type tended to have higher identification accuracy than the other sensors, suggesting the feasibility of a garment-type pressure sensor that applies to prevent pressure ulcers based on measuring body surface contact pressure.

4.3 Previous Research on Sleeping Posture Estimation and Garment Sensorization

Research on sensing postures and states during sleep is applicable to prevent pressure ulcers since they can be used to determine the duration of identical sleeping postures. Weimin et al. used a multimodal method to identify them using video images of a person lying on his or her side and pressure values at 60 points [44]. Since video-based sensing raises privacy issues, caregivers may feel an extra mental burden.

Some studies have estimated sleeping postures using only the pressure distribution on a bed. Yousefi et al. estimated five different sleeping postures using a pressure sensor with 32×64 measurement points [33]. Mineharu et al. estimated nine different sleeping postures using a pressure sensor with 34×52 measurement points [34]. Nishida et al. estimated sleeping postures from 221 pressure sensors [45]. On the other hand, Harada et al. visualized a 3D skeletal model to track the movement of a prone human body with a pressure distribution diagram [46]. Since these studies use pressure applied to a bed, they might fail to detect the correct pressure applied to the user's body they are using body-pressure-dispersion cushions.

Recent studies used sensors embedded in garments to sense the state of the human body. [47] and [48] used a stretchable fabric sensor that can be embedded in garments to create a band around the arm for sensing muscle activity. Paradiso et al. proposed a garment that can constantly measure body parts by placing a stretchable fabric device on a knit fabric [49]. For measuring the pressure applied to the body surface, Leong et al. provided feedback to prosthetic leg users with a sock [5] that incorporated the *Zebra Fabric* pressure sensor [23], which is a three-layered fabric sensor. Skach et al. incorporated the same *Zebra Fabric* into a pair of pants to identify sitting postures [6]. Foo et al. detected the location and time of leakages by wiring conductive threads into pants and measuring the resistance values [50]. Although some research embedded sensors into garments, no proposals have been described for a device that can measure the pressure applied to the entire body surface; nor have sufficient studies addressed the effects of using such a device to prevent pressure ulcers.

4.4 Measurement Obstruction by Body-Pressure-Dispersion Cushion in Bed-Sheet-Type Pressure Sensors

This section describes the problems when my laboratory's project conducted a demonstration experiment of a bed-sheet-type pressure sensor at a nursing home for the elderly. Before focusing on the problem, Section 4.4.1 describes the methods used to prevent pressure ulcers at elderly care facilities. Section 4.4.2 describes the cushions used in the experiment and gives an example of the problems caused by body-pressure-dispersion cushions.

4.4.1 Prevention of Pressure Ulcers in Elderly Care

In elderly care, caregivers place a body-pressure-dispersion cushion between the body and the bed to disperse the body pressure and prevent pressure ulcers. Here is a description of an example case.

Pressure ulcer care by supine position:

In the supine position, the pressure on the sacrum and the heels must be relieved, since this is the position at which the patient spends the most time while sleeping. To reduce the pressure on the sacrum, choose a pressure-dispersion bed and use a cushion to raise the sacrum.

Pressure ulcer care by semi-lateral position:

The semi-lateral position, which is an intermediate posture between the supine and lateral lying positions, prevents pressure on the greater trochanter and sacrum, making it ideal for the lateral position. To make this position, the patient is positioned at nearly 30 degrees to the bed using a cushion.

4.4.2 Interference with Bed-Sheet-Type Pressure Sensors Using Body-Pressure-Dispersion Cushion

Such care types are widely used in nursing homes. In my laboratory's past demonstration experiment at a nursing home, a body-pressure-dispersion cushion was placed between a patient and a bed-sheet-type pressure sensor. The project found that it was impossible to correctly measure the pressure that was directly applied to the patient's body surface because the way of touching the bed-sheet surface differed from person to person due to limb and spine contracture. Cushion selection and placement vary widely depending on the subject's body shape; the degree of limb contracture also differs from subject to subject. Satisfying all of these cases is quite difficult.

In the following, assuming pressure dispersion care of the sacrum by setting the cushion shown in Table 4.1, we can observe the pattern of the measurement obstruction.

Table 4.1: Cushions used in the experiment

	A	B	C
Appearance			
Shape	Rectangular	Square	Circular
Material	Sponge	Urethane	Beads
Height (approx.)	100 mm	150 mm	110 mm
Length (approx.)	540 × 220 mm	440 × 440 mm	Diameter 330 mm

Indistinct body-pressure change

Figure 4.4.1 (i) shows the pressure distribution on a bed in the supine position without a cushion. Figure 4.4.1(ii) shows the pressure distribution on a bed when rectangular cushion A is placed under the buttocks. Although the pressure around the cushion is estimated to decrease in association with the cushion placement, no change appeared on the bed-sheet-type pressure sensor. Thus, the state of the pressure ulcer is unknown.

Unmeasurable body-pressure change

Since the placement of hard cushion B under the buttocks may raise their position, the body surface pressure above the cushion is also thought to increase. Comparing the pressure distributions of (i) and (iii) in Figure 4.4.1, the pressure in the buttock position was originally expected to increase; it seems to have decreased from the pressure distribution.

Blurred body shape

Figure 4.4.1(iv) shows the pressure distribution for circular cushion C, which is larger and stiffer than the one used in Figure 4.4.1(ii). The shape of the body is blurred since its shape appears on the bed-sheets. Thus, this cushion makes it impossible to identify high pressure under

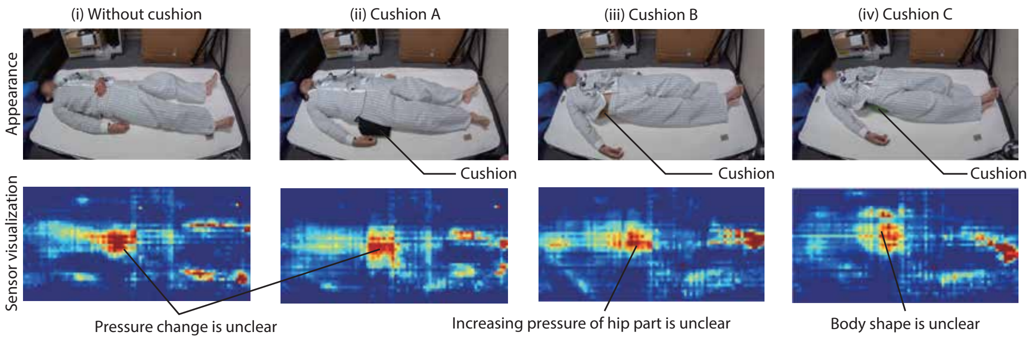


Figure 4.4.1: Examples of occlusions caused by body-pressure-dispersion cushions

the body.

The above problems were identified using cushions designed for pressure dispersion care.

4.5 Data Acquisition

Twenty subjects (four men and 16 women, age=34.7 $\pm$ 7.2), whose body shapes (height=163.0 $\pm$ 6.6 cm, BMI=20.1 $\pm$ 1.9) allowed them to comfortably wear the garment-type pressure sensor, participated in this study. They were middle-aged, unlike seniors who were the original targets of this study. Differences in pressure distributions between healthy seniors and middle-aged individuals have been reported using a bed-sheet-type pressure sensor [51]. The high-pressure areas tended to be smaller in the elderly than in other age groups. Although analyzing the effects of different age groups and different degrees of effectiveness is crucial in future work, in this study, the subject group was not limited to seniors, since its purpose was a comparative evaluation of bed-sheet- and garment-type pressure sensors.

4.5.1 Selection of Measurement Posture

Since the purpose of this study is to evaluate sleeping posture identification based on body surface contact pressure with a garment-type pressure sensor,

(a) Supine position

(b) Supine position with cushions

(c) Lateral position

(d) Lateral position with cushions

Figure 4.5.1: Cushion use for pressure ulcer preventive care in each sleeping posture

evaluating every possible sleep posture is unnecessary. In addition, since a garment-type pressure sensor was installed on the back of the sensor, data were collected only for the supine and semi-lateral positions from which pressure could be obtained. Because of the symmetry of the area of the onset of pressure ulcers, it can be considered that the left and right sides of the patients in the lateral recumbency were identical; only the right lateral recumbency was included. In the semi-lateral position, it takes time for each subject to create a posture by trial and error because the body is supported by multiple cushions. Therefore it was difficult to set the conditions for comparative evaluation and to isolate the problem. Such attempts were excluded from the experiment.

The prone position was also removed because it was impossible to obtain pressure values with the sensor in Figure 3.6.3 and because this position is rare in elderly care settings.

4.5.2 Measurement Procedure

Each subject wore a garment-type pressure sensor for measuring the body surface contact pressure on a bed with a bed-sheet-type pressure sensor. In the supine position, a cushion was placed under the buttocks (Figure 4.5.1(b)). In the lateral position, a cushion was placed under the back (Figure 4.5.1(d)). The capacitance values of both the bed-sheet- and garment-type pressure sensors were measured at 6 Hz as follows:

1. Leave the bed and the garment in a no-pressure state for five seconds to obtain its capacitance value.
2. Stand upright on the bed to obtain the maximum pressure on the bed-sheets.
3. Sit upright on the bed to obtain the maximum pressure on the garment.
4. Without cushion
   (a) Lying supine (10 seconds)
   (b) Lying lateral (10 seconds)
   (c) Repeat (a) and (b) five times.
5. Using cushion A
   (a) Lying supine (10 seconds)
   (b) Lying lateral (10 seconds)
   (c) Repeat (a) and (b) five times
6. Perform the same procedure as in (5) using cushion B.
7. Perform the same procedure as in (5) using cushion C.

The measured values were smoothed over time using a moving average with a 1-second sliding window. Each posture was taken for ten seconds until the motion stabilized from the change in the posture. Because the middle frame was judged to be the most restful, the middle frame of each posture after smoothing was treated as the data for one posture.

4.6 Selection of Features and Test Methods for Evaluation

In this study, data on each sleeping posture was collected using bed-sheet- and garment-type pressure sensors to compare the effectiveness of the detection ability of the body surface contact pressure based on the accuracy of sleeping posture identification. Since the pressure sensor values were taken as two-dimensional images, the features using HOG [52] and SIFT [53], which have high accuracy in general human body detection and posture identification, are expected to be appropriate for sleeping posture identification. On the other hand, the pressure sensor's resolution was at most 79×39, even for a large-area, bed-sheet-type sensor, suggesting that the above features might be inadequate. Therefore, a suitable feature was examined prior to the detailed comparison. The case is detailed in Section 4.6.1.

It was also expected that the identification with the above features had a precision of approximately 0.9 or higher and that the resulting groups would not show normality or equal variability. Therefore, using a Welch's T-test [54] or a Mann-Whitney's U-test [55] was deemed to be inappropriate for determining the differences in the identification results. In the end, the Brunner-Munzel test [56] was chosen. See Section 4.6.2 for details about this process.

4.6.1 Selection of Features

To conduct a comparative evaluation using sleeping posture identification, a general method in the image category identification task was applied to the pressure distribution obtained from a bed-sheet-type pressure sensor without a cushion. The following are the candidate features: Feature F_{raw} is a vector of two-dimensional images flattened and used as input, HOG feature F_{HOG} is mainly used for human body detection, and SIFT feature F_{SIFT} is employed for keypoint detection in images with a dictionary using the Bag of Visual Words algorithm [57] to create a histogram. The support vector machine (SVM) with the radial basis function (RBF) kernels was used as an identi-

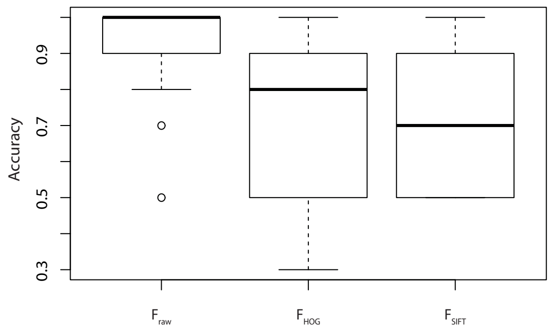


Figure 4.6.1: Result of accuracies of sleeping posture identification using candidate features

fication model with optimal parameters determined by Grid Search [1] from gamma $[1\times10^{-3}, 1\times10^{-4}$, Auto (the reciprocal of the feature's dimensionality is set)] and C-values $[1, 10, 100, 1000]$.

As shown in Figure 4.6.1, since F_{raw} had higher accuracy than F_{HOG} and F_{SIFT}, the same features were used for the sleeping posture identification in the following experiments.

4.6.2 Selection of Testing Methods

Figure 4.6.2 shows the accuracy distribution after 20 trials by single-person cross-validation. As shown in this histogram, the accuracy distribution is non-normative because the mode is skewed to one side. Equal variability was not expected, since no value greater than 1.0 exists and the mode is close to 1.0. Therefore the Brunner-Munzel test was used as a scheme that does not assume normality or equality of variance. The Brunner-Munzel test examines the null hypothesis that when values are taken from both groups one by one, the probability of either is equal. Only two-tailed tests were performed. In the case of normality and equivariance, the Brunner-Munzel test is as accurate as Welch's T-test and can be used as an alternative.

[1] `https://scikit-learn.org/stable/modules/grid_search.html` (Last accessed: January 21, 2021)

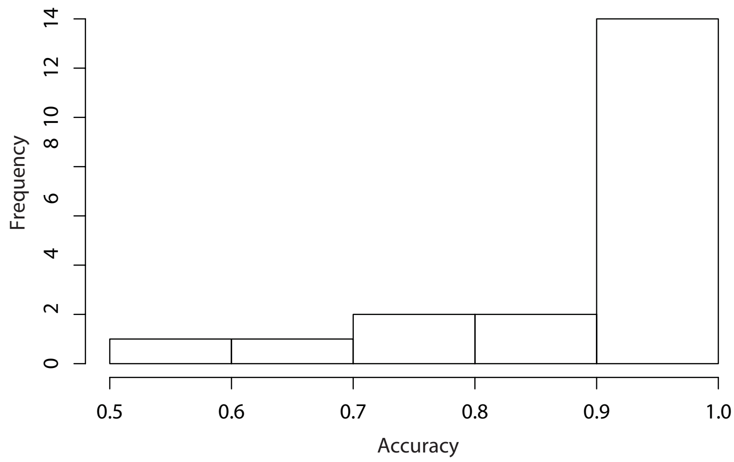


Figure 4.6.2: Distribution of 20 accuracies of sleeping posture identification using pressure data with leave-one-subject-out cross-validation

4.7 Evaluation of the Proposed Sensor Using Identification Accuracy of Sleeping Posture Based on Body Surface Contact Pressure

This section describes the results of comparative evaluation using sleeping posture identification based on body surface contact pressure using bedsheet- and garment-type pressure sensors. The data was examined, which were measured simultaneously by both sensors, for each sensor.

4.7.1 Comparative Evaluation of the Proposed Sensor With and Without Cushions

Experimental Procedure

The accuracy of the sleeping posture identifications was used as an evaluation index of the pressure sensor. A model to distinguish between the supine and lateral positions was trained using data without cushions to compare the

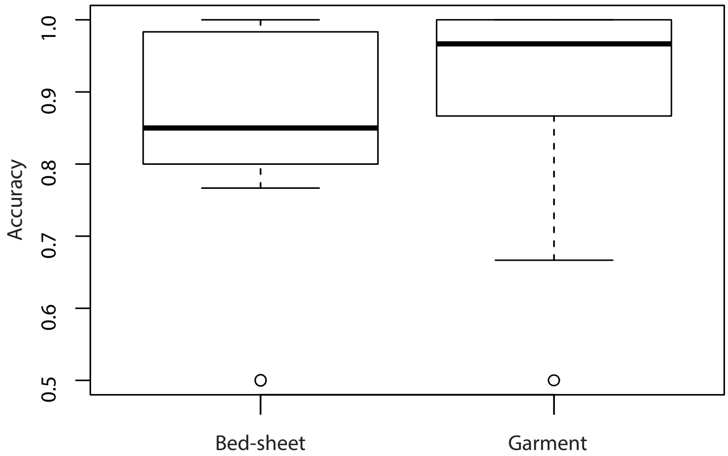


Figure 4.7.1: Result of accuracies of sleeping posture identification using bed-sheet- and garment-type sensors

identification accuracy of two types of sensors when three types of cushions (A, B, and C) were placed.

The SVM with the RBF kernel was used for identification, and its parameters were optimized on a trial-by-trial basis by Grid Search. In the experiment, considering the result in Section 4.6.1, the feature that transformed the two-dimensional pressure distribution by flattening it into a one-dimensional vector was used. The accuracy was derived from single-person cross-validation.

Result

The pressure distributions from the bed-sheet- and garment-type pressure sensors were classified into two categories: supine or lateral. Figure 4.7.1 shows the accuracy of the identifications. This result is a synthesis of the results of three cushions. The median, first, and third quartiles of the garment-type pressure sensor showed higher accuracy than the bed-sheet-type pressure sensor, while the Brunner-Munzel test reported a 15% probability for the type-I error. The median accuracy was higher for the garment-type pressure sensor.

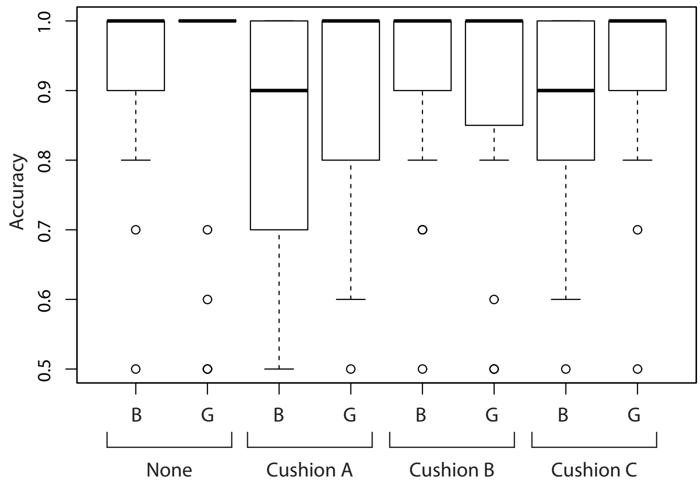


Figure 4.7.2: Result of accuracies of sleeping posture identification using both types of sensors with Cushions A, B, and C

This result suggests that the garment-type pressure sensor captured the body surface contact pressure values without influence from the cushion.

4.7.2 Comparative Evaluation of the Proposed Sensor for Each Cushion

Experiment Procedure

The proposed sensor was evaluated for each cushion. Similar to the method in Section 4.7.1, the SVM with the RBF kernel identified the sleeping posture, and its parameters were optimized on a trial-by-trial basis by Grid Search. In the experiment, considering the result in Section 4.6.1, the feature that transformed the two-dimensional pressure distribution by flattening it into a one-dimensional vector was used. The accuracy was derived from single-person cross-validation.

Result

The pressure distributions from the bed-sheet- and garment-type pressure sensors were classified into two categories: supine and lateral. Figure 4.7.2

shows the accuracy of the identification. When the cushions were not used, the accuracy of both sensors tended to be higher than in the other conditions. The cushion use decreased the accuracy of sleeping posture identifications. For Cushion A, the median accuracy was higher for the garment-type pressure sensor than the bed-sheet-type, although the Brunner-Munzel test reported a 40% probability of type-I error. Compared to the other placed cushions, the third quartile had the lowest value for both sensors, and the accuracy tended to be lower for both sensors. The difference in accuracy between the bed-sheet- and garment-type pressure sensors was not large when Cushion B was used. With Cushion C, the Brunner-Munzel test reported a 5% probability of type-I error, although the median accuracy of the garment-type pressure sensor was higher than that of the bed-sheet-type.

Discussion

When a soft and deformable cushion is used, it is expected to be depressurized at its periphery. Nevertheless, since there is no apparent change in the bed-sheet devices, the state of the pressure ulcer care is unknown. The garment-type pressure sensor tended to have higher accuracy when Cushion A was used, suggesting that it captured more body surface contact pressure values. The accuracy of both sensors tended to be lower than when using Cushions B or C, suggesting that a soft Cushion A may lower the detection accuracy of the body surface contact pressure.

A hard cushion under the buttocks may lift the hips off the bed, reducing the area of the bed and cushion that is the body. Since the same weight is applied and the weighted area decreased, it is expected that the pressure directly applied to the body surface above the cushion to increase. It is assumed that the same trend was observed when Cushion B was used. The difference in accuracy between the two sensors was not large when Cushion B was used, suggesting that the performance was similar between the two sensors when a harder cushion was used.

Depending on the shape of the cushions, the human body's shape may be blurred on bed-sheet-type devices, complicating identification of the parts of the body that are under pressure. The largest difference in accuracy between the two sensors was observed when Cushion C was used, an expected result in this situation. It suggests that Cushion C's circular shape was indeed strongly reflected in the pressure distribution on the bed-sheets and decreased the accuracy of the bed-sheet-type pressure sensor. On the other hand, the garment-type pressure sensor was unaffected by the circular-shaped cushion and tended to have higher accuracy.

4.8 Conclusion

In this chapter, the garment-type sensor proposed in Chapter 3 was evaluated to assess its applicability to body surface contact pressure measurement, which is the main-purpose of this study. This chapter described the evaluation using the accuracy of sleep posture identification based on a body surface contact pressure, which is one of the sub-problems. In actual nursing care, body-pressure-dispersion cushions are used together, causing such problems as failing to identify sleeping postures, which leads to a failure to notify nursing staff of the times for appropriate repositioning. The accuracy of the sleeping posture identifications was used to evaluate the garment-type pressure sensor to address this problem and compared the bed-sheet and garment-type sensors. For their evaluation, an experiment with 20 subjects was performed. The mean and median accuracy of the garment-type pressure sensor exceeded that of the garment-type pressure sensor, although the test reported that type-I error of 15%, suggesting that the garment-type pressure sensor more effectively detected the body surface contact pressure. The results showed that the garment-type tended to have higher identification accuracy than the other sensors, suggesting the feasibility of a garment-type pressure sensor that applies to prevent pressure ulcers based on measuring body surface contact pressure.

Chapter 5

Evaluation Using Educational Effectiveness of Visualization Based on Body Surface Contact Pressure

5.1 Introduction

This chapter describes the pressure distribution visualization system proposed in Chapter 3 to assess its applicability to body surface contact pressure measurement, which is the main-purpose of this study. This chapter describes The proposed system was evaluated using educational effectiveness based on a body surface contact pressure, which is one of the sub-problems. In the following sections, first, Section 5.2 describes the research background of the sub-problem. Next, the related research is discussed in Section 5.3, the method for assessing the comprehension of the body pressure distribution is described in Section 5.4, and the results of the assessment and its discussion are described in Section 5.5. Finally, this chapter is concluded in Section 5.6.

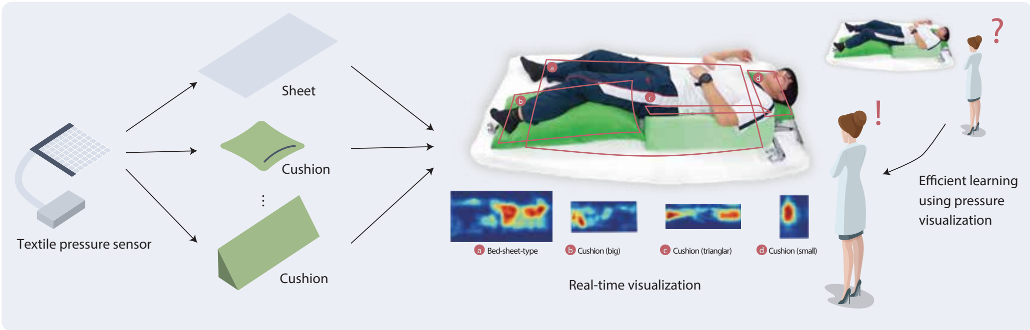


Figure 5.2.1: Overview of the proposed system and its evaluation methodology

5.2 Research Background

Understanding body mechanics and acquiring skills related to postural changes are critical to support the basic ability to move in bed. For nursing students and other health professionals who learn such skills, the pressure applied to each patient's condition must be understood as well as the body parts in each position to determine where to redistribute the high pressure. To redistribute it, caregivers have to understand how it is applied to a patient's body whose condition often changes. Nevertheless, the amount of time spent by nursing students on pressure ulcer care is often insufficient due to the difficulty of comprehending such skills [15]. A part of these reasons can be considered as the lack of educational resources and many skills to learn. Muranaka et al. also pointed out that nursing students need to learn many skills, and claimed educational material that can promote their comprehension to compensate [16].

Although a study [58] evaluated the educational effect of pressure visualization, it is limited to using the distribution of body pressure on bed-sheets. Thus, the educational effect of visualization remains unclear in actual care settings where body-pressure-dispersion cushions and other devices are often used. The evaluation of learning in this study was limited to a qualitative appraisal based on student feedback. Nevertheless, no studies have investigated pressure visualization materials under the same conditions as in actual nursing care, where pressure-dispersion cushions are frequently used, or measured the effect of promoting understanding.

Therefore, in this chapter, an educational system proposed in Chapter 3 is used to visualize the pressure distribution on the cushions as well as on bed-sheets and its effectiveness was evaluated. The outline of the proposed system and evaluation method is shown in Figure 5.2.1. The pressure visualization system consists of bed-sheets and cushions with built-in pressure sensors and a laptop to visualize the pressure distribution. The proposed system can display the pressure distribution in real-time and be used for practical training. It will help students learn efficiently because it provides them the opportunity to observe their instructor's practices while checking the pressure changes.

An investigation was performed to clarify the effectiveness of the proposed system's comprehended body pressure dispersion in a controlled experiment with 47 nursing students. Although this system is capable of real-time visualization and can be used for practical training, Visualization material that was recorded and photographed was used to make the experimental conditions uniform over several investigations. In the experiment, the following postures that are commonly used in postural changes were simulated: supine, lateral, semi-lateral, and Fowler's, which is a 45-degree elevated position with the upper body lying on the back. The comprehension of the body pressure distribution was evaluated by asking the students to estimate the high-pressure areas on body charts. The evaluation results showed that the proposed system promoted the understanding of the body surface contact pressure for such localized areas as the head and the legs without visualized material, even in complex postural changes using a cushion for students who once learned using the proposed system. The result shows the feasibility of a system that supports the efficient acquisition of skills using the visualization of body surface pressure.

5.3 Previous Research for Nursing Education Using CAI Materials

Muranaka et al. argued that nursing education curriculums require too many subjects and identified a shortage of nursing educators. They listed the requirements for computer-assisted instruction (CAI) materials to promote the comprehension of nursing students [16]. Examples of requirements include clarifying the purpose of materials and using images and video to hold attention. Examples of CAI teaching materials include multimedia materials using images and video, and others that visualize various conditions during nursing treatment by incorporating sensors into the bed or attaching them to the practitioner.

Many studies have explored the feasibility of a system that supports nursing education using multimedia materials. Aoi et al. developed CAI material for postural change and transfer technique [17]. The result of their questionnaire survey of 21 students shows that 76% believe that the material will increase self-learning. 100% answered that the materials were useful for review purposes and concluded that they were a useful self-learning tool. Doi et al. reported that the visualization of body mechanics during bed-sheet placement using stick figures improved nursing care movements [59]. Iwamoto et al. promoted the comprehension of aseptic manipulation exercises with video materials for finding mistakes. More than 90% of their students reported that the materials promoted their knowledge acquisition [60]. Matsui et al. used a bed-sheet-type pressure sensor to visualize the distribution of body pressure to promote the comprehension of a postural change technique [58]. They asked their students to complete a post-questionnaire as a qualitative evaluation and found that video and image materials effectively attracted the interest of students, promoted their comprehension, and helped them acquire skills.

Although various studies have been conducted on this subject, none have focused on the care of patients who change postures with cushions, which are often used in actual nursing care settings. In addition, the study is

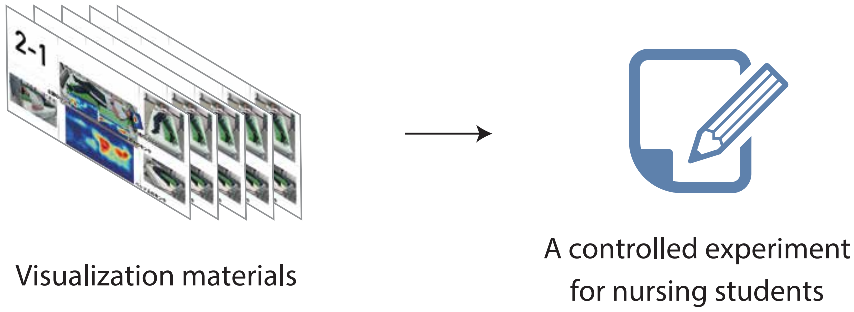
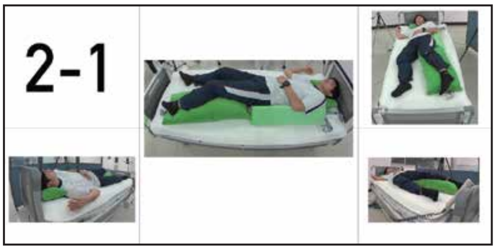


Figure 5.4.1: Evaluation setup

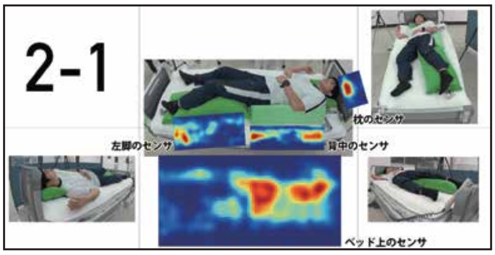
limited on the effect of visualizing the body surface pressure for promoting comprehension because it is only a qualitative evaluation based on student comments. In this study, the pressure that the sheet-type pressure sensor cannot measure was visualized with a cushion-type pressure sensor and investigated whether visualization promotes comprehension by quantitatively assessing the comprehension of body pressure distribution.

5.4 Evaluation Method for Promoting Comprehension of Body Pressure Dispersion Using Visualization of Body Pressure Distribution

An investigation was performed to clarify the effectiveness of the proposed system on the comprehension of body-pressure-dispersion in a controlled experiment with nursing students. This system can be used for real-time visualization as well as for practical training. As a controlled experiment described above, visualization material with recorded data was used to make the experimental conditions uniform in multiple investigations (Figure 5.4.1). Section 5.4.1 describes the method that created the teaching materials used for the evaluation. Section 5.4.2 describes the method that evaluated the level of learning comprehension. Finally, Section 5.4.3 describes a method



(a) Question slide $Q_{set2,q1}$



(b) Question slide $Q^{visualized}_{set2,q1}$

Figure 5.4.2: Example of a questionnaire slide

for evaluating the system's usefulness using the proposed evaluation method with nursing students.

5.4.1 Visualization Materials

The visualization material consists of a set of questions $\mathbf{Q}_{set}$, which contains $Q_{set,q1}$, ..., $Q_{set,q6}$. Figure 5.4.2(a) shows an example of a question slide. A wound, ostomy, and continence (WOC) nurse changes the patient's body position. A single slide contains snapshots of the video simultaneously taken by four cameras.

The bed-sheet- and cushion-type sensors proposed in Section 3.7 and Section 3.5 were used in the demonstration. Figure 5.4.2(b) shows an example of question slide $\mathbf{Q}^{visualized}_{set}$ with pressure distribution. Visualized sensor values at the same time as the camera was placed as a heat map in this question slide and the heat map was placed accompanying each sensor included in the figure.

Two sets of questions $\mathbf{Q}_{set1}$ and $\mathbf{Q}_{set2}$ were created. The composition of the question slides in each question set is shown in Table 5.1.

Table 5.1: Composition of the question set

No.	Posture	Note
$Q_{set1,q1}$	Supine	An ideal supine position. The body pressure is equally balanced.
$Q_{set1,q2}$	Supine	Although it resembles an ideal supine, the pelvis is tilted and strong pressure is applied to the right lumbar region.
$Q_{set1,q3}$	Lateral	Since the center of gravity is resting heavily on the torso's right side, there is strong pressure on the right lumbar region.
$Q_{set1,q4}$	Lateral	An ideal semi-lateral position. The body pressure is distributed to the left leg as well.
$Q_{set1,q5}$	Fowler's	Although it resembles an ideal Fowler's position, the pelvis is tilted and the body is twisted, and there is strong pressure on the right lumbar region.
$Q_{set1,q6}$	Fowler's	An ideal Fowler's position.
$Q_{set2,q1}$	Supine	An ideal supine position, supported by cushions, with body pressure distributed throughout the body.
$Q_{set2,q2}$	Supine	Although it resembles an ideal supine posture supported by a cushion, the strong pressure on the torso's right side is darker near the correct region.
$Q_{set2,q3}$	Lateral	An ideal semi-lateral position. The body pressure is distributed to the left leg as well.
$Q_{set2,q4}$	Lateral	Since the center of gravity is resting heavily on the torso's right side, there is strong pressure on the right lumbar region.
$Q_{set2,q5}$	Fowler's	Although it resembles an ideal Fowler's position, the pelvis is tilted and the body is twisted, and there is strong pressure on the right lumbar region.
$Q_{set2,q6}$	Fowler's	An ideal Fowler's position, supported by cushions, with equal pressure distribution on both sides.

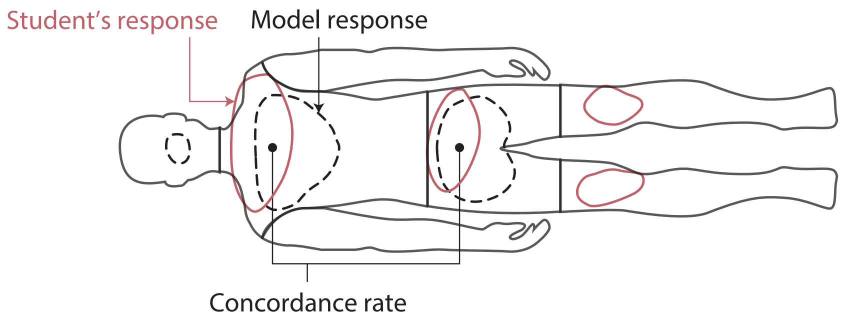


Figure 5.4.3: Assessment of consistency rate between student and model responses

5.4.2 Method for Evaluating Comprehension of Body Pressure Distribution

To evaluate the subjects' comprehension of the distribution of body pressure, The consistency rate between their estimated high-pressure areas on the human anatomy chart and responses made by experienced nurses was used. This is discussed in detail below.

Evaluation Method

The subject looks at the question slide and estimates the part of the body that is experiencing pressure. An answer sheet on which there was a printed drawing of the human body was prepared and each question featured a task that pertained to an enclosed estimated area. A diagram presenting the response and an example is shown in Figure 5.4.3. The solid line indicates the student's response area. The dashed line area is the model response area. An experienced nurse prepared model responses in advance based on the pressure distribution shown on the question slides and the areas to be focused on from a nursing perspective.

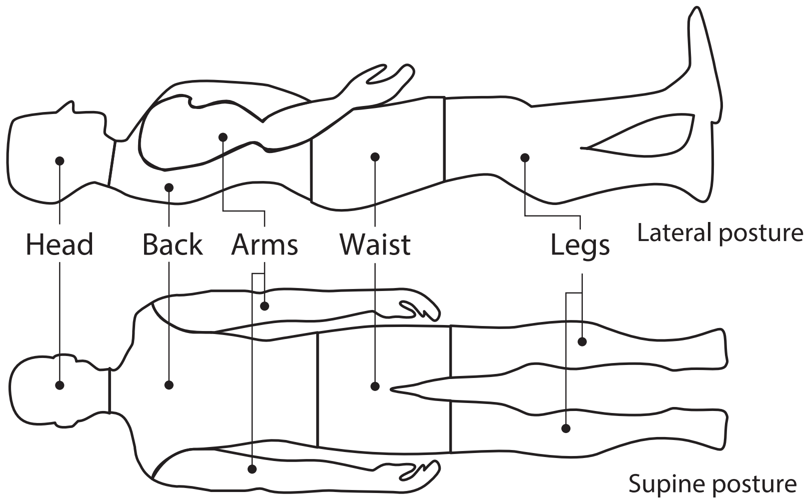


Figure 5.4.4: Division of evaluated area

Comprehension Assessment Methodology

The measurement of the correctness of the subject responses (hereafter *response scores*) was defined as the consistency rate between their responses and the enclosed area of the model response. The Jaccard coefficient [61] [1] was used to calculate the consistency rate. To evaluate the differences in the comprehension of the body pressure distribution by body area, masks were made for each site shown in Figure 5.4.4 and the consistency rate was calculated for each area.

5.4.3 Experimental Procedure

The flow of the experimental procedure is shown in Figure 5.4.5. First, 47 nursing students enrolled in *Nursing Assistance Theory IA* at the school of nursing, Nagoya City University, were collected as subjects. They previously learned to change a patient's posture in a classroom setting and practical training. To evaluate the effect of the controlled experiment on their comprehension of body-pressure-dispersion, they were divided into two groups:

[1] $J(A,B) = \frac{|A \cap B|}{|A \cup B|}$

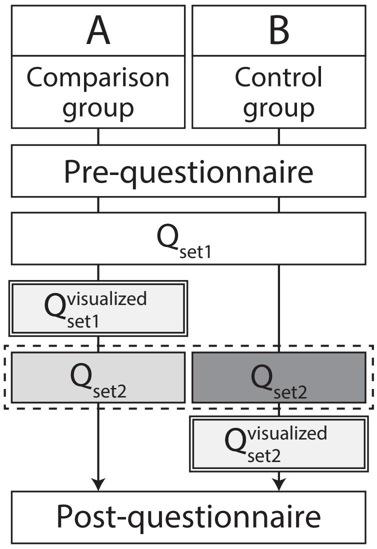


Figure 5.4.5: Procedure for controlled experiments in simulated exercises

Comparison group A and Control group B, with 23 and 24 subjects.

To investigate the characteristics of both groups, $\mathbf{Q}_{set1}$ asked the students in advance what they have already learned in class as well as a common question without any relevance to pressure distribution. Next, Comparison group A looks at and responds to $\mathbf{Q}_{set1}^{visualized}$ with the pressure distribution diagram and then looks at and responds to $\mathbf{Q}_{set2}$ without it. Control group B looks at $\mathbf{Q}_{set1}$ and then at $\mathbf{Q}_{set2}$ without the pressure distribution map. For educational reasons, Control group B obtains supplementary learning in $\mathbf{Q}_{set2}^{visualized}$ with a pressure distribution map to eliminate the learning differences from Comparison group A. Finally, both groups responded to a post-questionnaire that includes a question about what they referred to.

5.5 Comparison and Discussion of Response Scores for Each Set of Questions

An experiment with 47 people was conducted and collected 846 responses (6 responses *times* 3 question sets *times* 47 people). No deficiencies were found in their responses.

Table 5.2: Statistics (mean and variance) and q-values of response scores for groups A and B (*: $q < 0.10$)

	head			**back**			**arms**			**waist**			**legs**		
	score	score	q	score	score	q	score	score	q	score	score	q	score	score	q
	A:Q_{set1}	B:Q_{set1}		A:Q_{set1}	B:Q_{set1}		A:Q_{set1}	B:Q_{set1}		A:Q_{set1}	B:Q_{set1}		A:Q_{set1}	B:Q_{set1}	
q1	0.08±0.04	0.08±0.03	0.60	0.24±0.06	0.16±0.04	0.44	0.01±0.00	0.00±0.00	0.28	0.40±0.03	0.33±0.03	0.28	0.00±0.00	0.00±0.00	1.00
q2	0.02±0.01	0.06±0.03	0.26	0.20±0.03	0.12±0.02	0.25	0.06±0.01	0.05±0.01	0.26	0.24±0.05	0.17±0.02	0.47	0.12±0.01	0.08±0.01	0.33
q3	0.01±0.00	0.04±0.02	0.60	0.15±0.01	0.12±0.01	0.38	0.33±0.04	0.25±0.04	0.27	0.39±0.04	0.31±0.02	0.20	0.12±0.02	0.13±0.01	0.84
q4	0.02±0.00	0.04±0.01	0.96	0.13±0.01	0.15±0.03	0.96	0.19±0.02	0.18±0.03	0.71	0.29±0.03	0.20±0.02	0.23	0.14±0.02	0.09±0.02	0.34
q5	0.00±0.00	0.00±0.00	1.00	0.13±0.01	0.10±0.02	0.26	0.00±0.00	0.00±0.00	1.00	0.33±0.02	0.23±0.02	0.13	0.00±0.00	0.00±0.00	1.00
q6	0.00±0.00	0.00±0.00	1.00	0.10±0.01	0.21±0.06	0.38	0.00±0.00	0.00±0.00	1.00	0.43±0.02	0.39±0.03	0.66	0.00±0.00	0.00±0.00	1.00
	A:Q_{set2}	B:Q_{set2}		A:Q_{set2}	B:Q_{set2}		A:Q_{set2}	B:Q_{set2}		A:Q_{set2}	B:Q_{set2}		A:Q_{set2}	B:Q_{set2}	
q1	0.00±0.00	0.00±0.00	1.00	0.16±0.04	0.10±0.03	0.23	0.04±0.00	0.02±0.00	0.22	0.27±0.07	0.29±0.03	0.66	0.13±0.01	0.06±0.01	**0.05***
q2	0.00±0.00	0.00±0.00	1.00	0.20±0.04	0.14±0.04	0.26	0.08±0.02	0.03±0.00	0.28	0.33±0.06	0.21±0.04	0.25	0.12±0.02	0.08±0.01	0.66
q3	0.14±0.03	0.00±0.00	**0.00***	0.17±0.01	0.16±0.03	0.28	0.36±0.03	0.26±0.06	0.20	0.39±0.03	0.36±0.03	0.43	0.04±0.01	0.03±0.00	0.66
q4	0.23±0.04	0.02±0.01	**0.00***	0.18±0.02	0.08±0.01	0.13	0.32±0.03	0.23±0.03	0.25	0.31±0.01	0.25±0.02	0.25	0.07±0.01	0.03±0.00	0.20
q5	0.00±0.00	0.00±0.00	1.00	0.12±0.01	0.09±0.01	0.25	0.03±0.01	0.04±0.02	0.85	0.42±0.03	0.33±0.04	0.13	0.21±0.05	0.11±0.02	0.20
q6	0.10±0.02	0.01±0.00	**0.00***	0.27±0.04	0.15±0.03	0.20	0.00±0.00	0.00±0.00	1.00	0.32±0.02	0.27±0.01	0.34	0.16±0.03	0.07±0.02	0.23

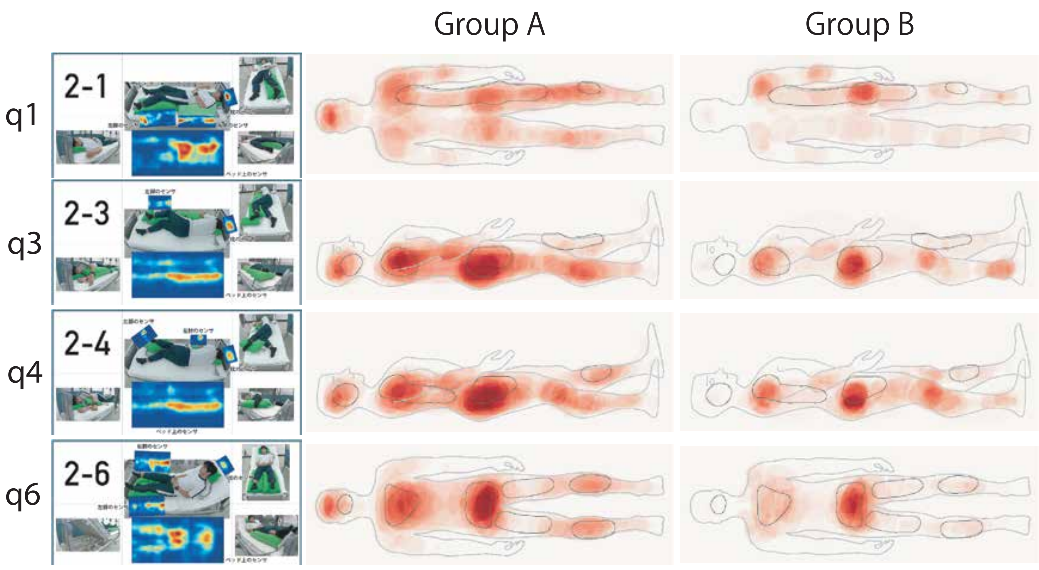


Figure 5.5.1: Heat map with response areas (showing a pressure distribution map that is hidden in the actual investigation)

Table 5.2 shows the statistics (mean and variance) of the response scores of Groups A and B. For each question, the q-values of the test results were noted for the differences in scores between the groups.

The Bunner-Munzel test [56] was used, which does not require normality or equal variance. To solve the multiple-testability problem with p-values which are calculated using Brunner-Munzel tests, the q-values were calculated by controlling for the False Discovery Rate (FDR) using the Benjamini-Hochberg method [62]. Figure 5.5.1 shows a part of the student response areas that are overlaid as a heatmap for the responses that included areas with q-values of 0.10 or less.

These results indicate that subjects concentrated more attention on the pressure on the heads and legs, which are more likely to be placed on cushions. Detailed results are discussed in the following sections.

5.5.1 Potential Comprehension Comparison of Groups A and B

In $\mathbf{Q}_{set1}$, although groups A and B never saw the visualized pressure distribution, they answered the same question, and therefore the responses to $\mathbf{Q}_{set1}$ indicate the potential comprehension of groups A and B.

In the $\mathbf{Q}_{set1}$ row of Table 5.2 and in the column of q-values from $q1$ to $q6$, no q-values were below 0.10.

These results confirm that there was no comprehension difference between the groups without the proposed system. Based on the above, Section 5.5.2 describes a discussion on the differences in the response scores between Comparison group A, which experienced the proposed system, and Control group B, which did not go through it.

5.5.2 Evaluation of the Effectiveness of the Proposed System in Promoting Comprehension by Controlled Experiments

In $\mathbf{Q}_{set2}$, an evaluation was performed to clarify the effectiveness of the proposed system promoted comprehension of body-pressure-dispersion by comparing group A, which underwent the pressure distribution visualization system, i.e., it received supportive learning, and Control group B that did not.

Results

Looking at the q-value column of Table 5.2, significant differences were found in three parts of the question that included the head part ($q3, q4, q6$) and one question that included the leg part ($q1$). Comparison group A had a higher response score than Control group B in each case. There were no significant differences in the other parts.

Discussion

When $q6$ is focused on in Figure 5.5.1, the head's pressure distribution is not visible on the paper because it is hidden by the cushion, although the pressure applied to the head is visualized by the textile pressure sensor embedded in the cushion. Therefore, when Comparison group A saw the visualized question slides, they focused on the pressure on the cushions, and their response scores were higher than those of Control group B. When $q1$ is focused on inFigure 5.5.1, the right half of the body is lowered by the cushion, and its right half, including the right leg, is under high pressure. In this supine position, the pressure on the sides of the body is easily missed when the body is tilted with a cushion. The significant difference in the legs at $q1$ draws attention to these easily overlooked pressures.

The response scores for Comparison group A were higher than those for Control group B because the subjects did not focus on the pressure on the cushions. They mistakenly believed that they were dissipating the body pressure when they placed the cushion on the bed, and they overlooked the high-pressure areas to which they should have paid attention, even on the cushion. It was confirmed that the students gained knowledge because the textile pressure sensor can easily follow the shape of the cushion and be embedded in flexible objects. No previous study visualized the pressure on a cushion and measured the effect of education. The above considerations will improve future instruction that concentrates on the pressure on the cushions when creating body positions.

In this investigation, the subjects were nursing students who had already learned about body-pressure-dispersion. It is expected that the proposed system will increase the comprehension of those who are working in the field and promote further comprehension.

On the other hand, there were no significant differences among the dorsal, arm, and lumbar areas. Since the scapula and sacral regions are leading areas for pressure ulcers, instruction countermeasures should be emphasized. Therefore, the students in this study learned to some extent, even though the effect of visualizing the pressure distribution was difficult to achieve.

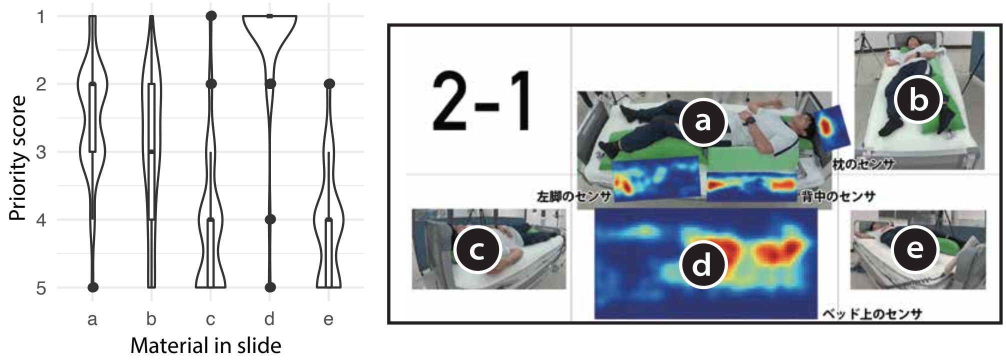


Figure 5.5.2: Findings of elements useful for the comprehension of pressure distribution

Pressure ulcers frequently occur on the arm, but no focused instruction was provided on it. An area in the arm part is small and could not be measured by this evaluation index. However, the actual reason is unknown and needs to be investigated further.

5.5.3 Evaluation of the Proposed System Based on a Post-Questionnaire

An evaluation was performed with post-questionnaires on the usefulness of the visualization of pressure distribution by subjects. In this questionnaire, each element of the material slides was assigned a number, as shown on the right in Figure 5.5.2. Responses were ranked in the order of usefulness. The left part of Figure 5.5.2 also summarized the responses obtained in the layered violin plot to show the distribution and a box plot to see the basic statistics. The distribution of responses shows that d, a, b, e, and c were the most frequently used as references in that order. 84.4% of the subjects (38/45, excluding two who did not respond) reported that they most frequently used d (pressure distribution on the bed-sheets) as a reference. The usefulness of the pressure distribution map on the bed-sheets and cushions was tabulated on a 10-point scale, with a mean and standard deviation of 9.17 + 0.90 points.

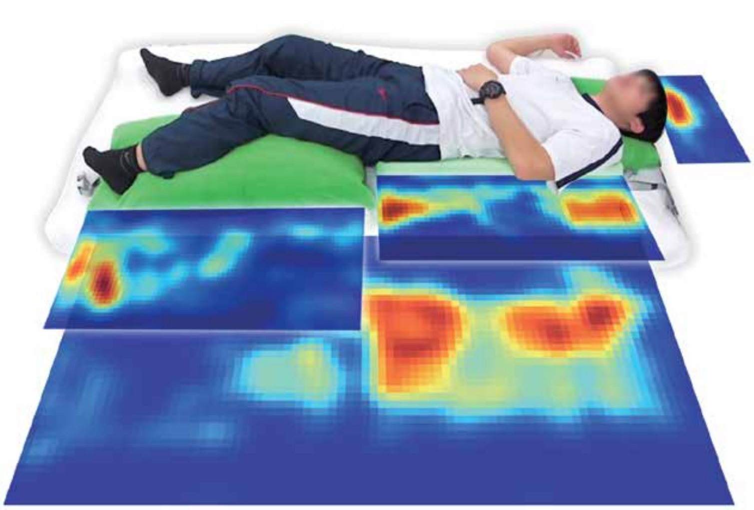


Figure 5.5.3: Overlapping pressure distribution using augmented reality

To a question asking about paying attention to the pressure on the pillows and cushions before looking at the pressure distribution chart (4: agree - 1: not at all), the median response was 2. To a question asking about paying more attention to the pressure on the pillows and cushions after looking at the visualized pressure distribution (4: agree - 1: not at all) the median response was 4. The following comments are received: “At first, I couldn’t pay attention to the pressure on the pillows and cushions, but after seeing the pressure distribution diagram, I felt the need to consider the position of the body, including the pressure on the pillows and cushions;” “I simply thought that I could relieve the pressure with cushions, but after looking at the pressure distribution diagram, depending on how I used the cushions, they were sometimes useful. I learned that it is an adverse effect.” These results suggest that the visualized pressure distribution helped comprehend the body pressure in complex positions using cushions based on actual care and increased correct comprehension of body pressure.

On the other hand, some participants expressed the difficulty of understanding the positional relationship between the visualized pressure distribution on the cushion and the pressure areas on the body surface. Layered pressure distributions using augmented reality (AR) might solve this problem. Figure 5.5.3 shows an overlapping image of pressure distribution using AR. The cushions must be properly aligned, and their localization in AR space is challenging.

5.6 Conclusion

In this chapter, the pressure distribution visualization system proposed in Chapter 3 was evaluated to assess its applicability to body surface contact pressure measurement, which is the main-purpose of this study. This chapter described the evaluation using educational effectiveness based on a body surface contact pressure, which is one of the sub-problems. The effects of the proposed system on the comprehension of body-pressure-dispersion were investigated in a controlled experiment with 47 nursing students. The proposed system for nursing students effectively promoted comprehension of body pressure distribution in such localized areas as the head and the legs during complex postural changes using cushions. These results suggest that introducing the proposed system will allow nurses to focus on dangerous high-pressure areas during complex postural changes using cushions without visualized material to improve the effectiveness of pressure ulcer care for students who once used the proposed system. It is indicating the feasibility of the proposed system that supports the efficient acquisition of skills based on a body surface contact pressure.

Chapter 6

Relationship to Real-World Data Circulation

6.1 Introduction

This chapter describes the relationship between this study and real-world data circulation. Section 6.2 discusses real-world data circulation and its relation to the healthcare field. To achieve the main-purpose of proposing and evaluating a device for measuring body surface contact pressure, two sub-problems are addressed. Section 6.3 describes the relationship between the two applications and the real-world data circulation. In addition, Section 6.4 describes the future vision of the real-world data circulation in this study. Finally, Section 6.5 summarizes this chapter.

6.2 Relationship Between Real-World Data Circulation and Healthcare

Real-world data circulation (RWDC) is a field of study that has attracted much attention in recent years because so much data are being collected in the real-world. According to *Graduate Program for Real-World Data Circulation Leaders*, real-world data circulation is defined as *acquiring* data through the

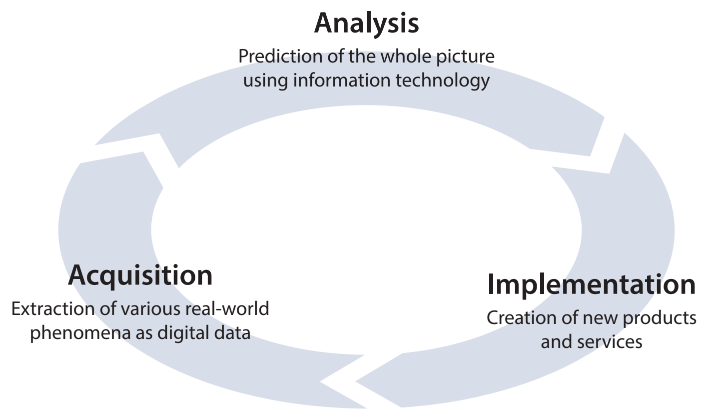


Figure 6.2.1: Conceptual diagram of real-world data circulation

observation of various phenomena in the real-world, *analyzing* the data using information technology, and *implementing* analysis results as new products and services with which society can create a cycle of processes that create social values [63]. The relationship among data *acquisition*, *analysis*, and *implementation* is summarized in Figure 6.2.1. *Industry 4.0* [64] pointed out that information technology will fuel the transformation of various industries. In this way, information technology is being introduced to collect data in a wide range of fields. Therefore, the value of functions that utilize data and works in society will continue to increase.

Real-world data circulation is a concept that can be applied to various fields that handle data. For example, in the field of personalized automobiles, driving characteristics can be analyzed from driving data and utilized for vehicle control. In the field of tailor-made medicine, omics analysis can be used for drug discoveries based on genetic and medical history information.

The concept of real-world data circulation can also be applied to the healthcare sector, where a trend encourages the collection of large amounts of data. For example, Apple Inc. provides *ResearchKit* [65], a framework that supports the research of medical professionals. Previously it was extremely difficult to collect data from people around the world who own standardized devices, but now it is possible to handle huge amounts of standardized data from iOS devices such as *iPhone* and *Apple Watch*, which have the largest market share. Such real-world data circulation will allow medical researchers to analyze real-world data collected from individual subjects and obtain meaningful results and advance the understanding of disease states.

In particular, elderly care support is a field in which data utilization is essential due to the increasing demand for more efficient care in aging societies. *The 2018 White Paper on Information and Communications* [66], published by the Japanese Ministry of Internal Affairs and Communications, also mentions the need to provide appropriate medical and nursing care services to patients and others by using data to achieve optimal health management, medical treatment, and nursing care for each individual through data integration.

6.3 Real-World Data Circulation in This Study

In this study, a device that can measure the body surface contact pressure was *implemented*, data were *acquired*, and the problems that occur in actual nursing care through *analysis* using the acquired data were attempted to be solved. Therefore, it can be considered as a form of real-world data circulation. The solutions for the two issues were set as sub-problems. The relationship between each sub-problem and the real-world data circulation is explained below.

First, as a sub-problem, the problem that the bed-sheet-type pressure sensor fails to classify the sleeping posture for the use of a body-pressure-dispersion cushion was solved by incorporating the pressure sensor function into the garment. The relationship between this study and real-world data circulation is shown in Figure 6.3.1. Since there has never been a sensor that consists of a pressure sensor for an entire garment, the sensor was *implemented* by improving the sewing pattern. Assuming the use of a body-pressure-dispersion cushion, body surface contact pressure data from 20 subjects were *acquired* by using the bed-sheet-type pressure sensor and the garment-type pressure sensor. In order to compare and evaluate the results with those of the bed-sheet-type pressure sensor, the *analysis* was performed

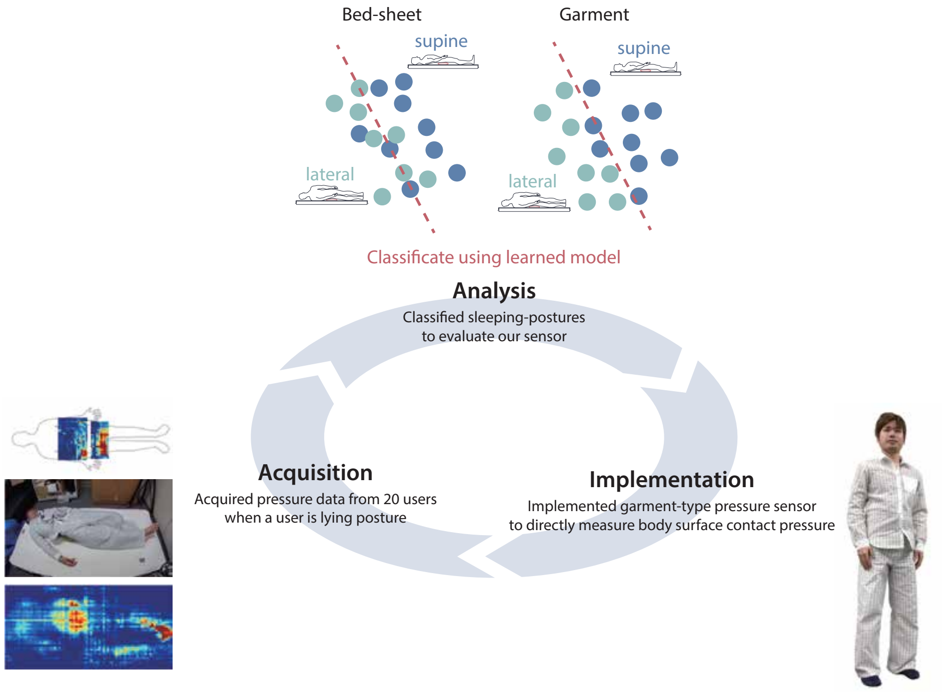


Figure 6.3.1: Relationship between evaluation by sleeping posture classification real-world data circulation

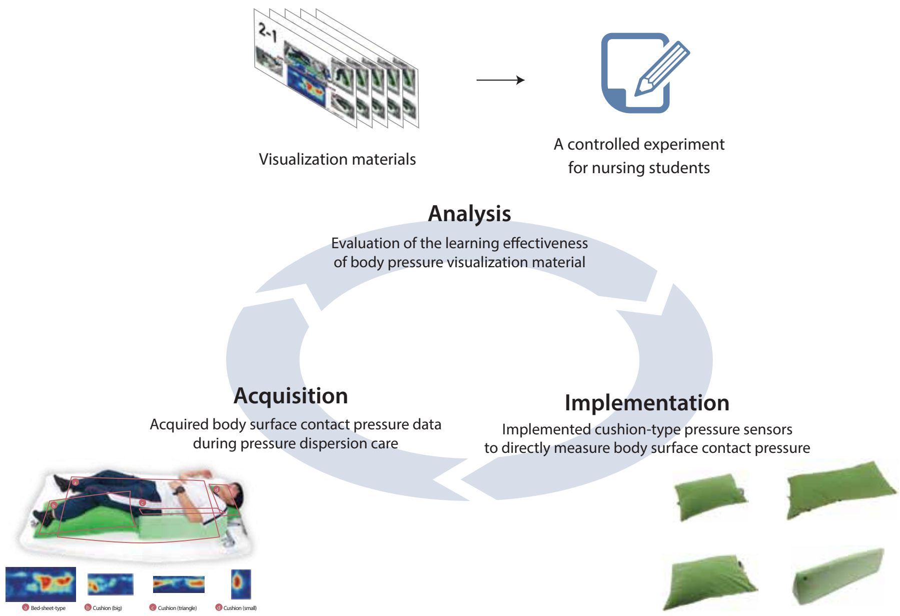


Figure 6.3.2: Relationship between the evaluation of educational effectiveness of pressure visualization and real-world data circulation

using the sleeping posture classification accuracy as an evaluation index. The results of the study indicated the possibility of applying the garment-type pressure sensor to pressure ulcer prevention care based on body surface contact pressure even in an environment where pressure-dispersion cushions are used. The results of this study suggest that we can implement an improved version of the garment-type pressure sensor for practical use and optimize the garment-type pressure sensor according to the patient's garment size and contracture condition.

Next, as the second sub-problem, the problem of the lack of visualization materials for body pressure distribution including body pressure on a pressure-dispersion cushion was solved by developing a body pressure distribution visualization system including body-pressure-dispersion cushions incorporating a textile pressure sensor. The relationship between this study and real-world data circulation is shown in Figure 6.3.2. Since there has been no educational material that visualizes the body pressure dispersion when using a pressure-dispersion cushion to promote the understanding of body pressure dispersion, a system to visualize the body pressure distribution was *implemented*, including a device that incorporates a fabric pressure sensor into a pressure-dispersion cushion used in the field. Using the proposed system, pressure data on the body surface were *acquired* during pressure dispersion care, and visualization materials were created. Forty-seven undergraduate nursing students were surveyed in a controlled experiment to statistically *analyze* the effectiveness of the proposed system in promoting the understanding of body pressure dispersion. The results of the survey indicated the effectiveness of the system in assisting students to learn the technique efficiently using visualization of body surface pressure, even in an environment where body-pressure-dispersion cushions are used. The results of this study suggest that it is possible to conduct measurements using garment-type pressure sensors in addition to pressure-dispersion cushions and to visualize body pressure dispersion during seating by incorporating them into the seat surface of a wheelchair.

In the evaluations for each of the sub-problems, *implementation*, *data acquisition*, *analysis*, and the next implementation plan would be considered based on the analysis results, which can be considered that a real-world data circulation was established in the field of applications for pressure ulcer preventive care based on body surface contact pressure.

6.4 The Positioning of This Study and Future Deployment Ideas from the Viewpoint of Real-World Data Circulation

This section describes the future of real-world data circulation in the field of pressure ulcer prevention care applications based on body surface contact pressure, which was established through two research projects. Figure 6.4.1 shows the position of real-world data circulation in this study and an image of future deployment. Since we can explain that pressure sensors will reduce the

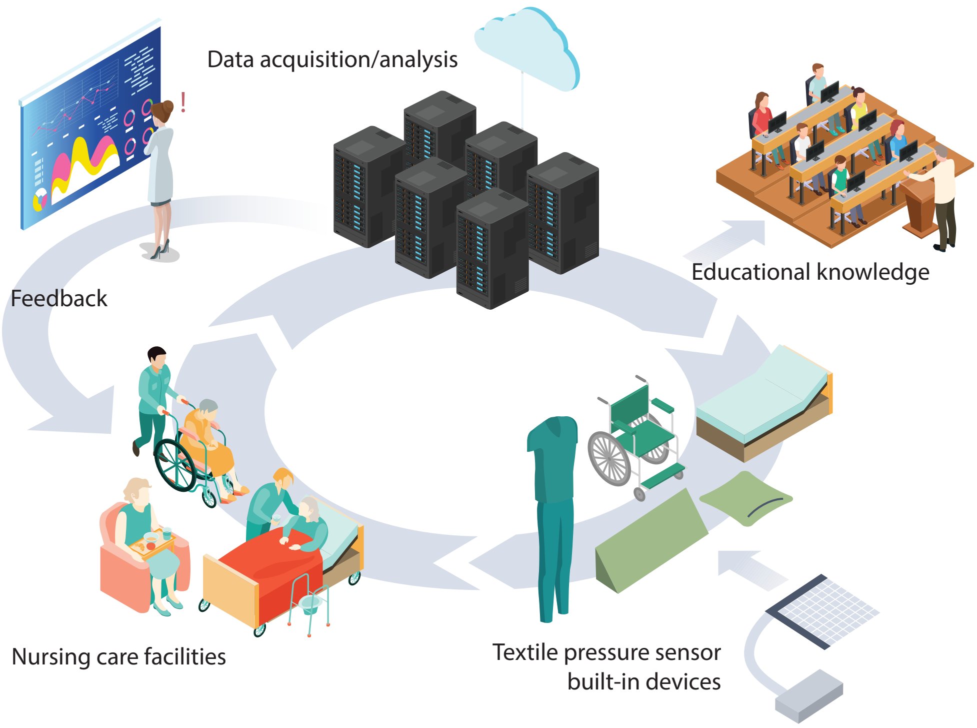


Figure 6.4.1: Real-world data circulation in this study and future deployment ideas

workload on nursing care, we can promote the introduction of the proposed sensor in nursing care facilities to provide direct benefits. If the proposed system is introduced into such facilities, data can be *acquired* from them, and big data can be constructed. With big data, data from facilities can be *analyzed* with a lower incidence of pressure ulcers to improve nursing care methods. Such analysis of nursing care methods included in the big data can be shared with educational systems and instructions for on-site assistance. In addition, various cases can be extracted and circulated to education systems. In this way, I believe that the social values of this study can be further enhanced.

The research topics addressed in this study are at the beginning of this process. The textile pressure sensor is expected to play a very important role in this real-world data circulation because it can be embedded in various tools to acquire real-world data. Although the number of devices to be incorporated was limited in this study, the pressure sensor function was incorporated into vests, pajamas, and *jinbei* for garments, and into several sizes of cushions. These devices can be custom-made to meet the needs of each individual, and the purpose is consistent with the aforementioned need to realize optimal health management, medical treatment, and nursing care for each individual. The sleeping posture classification method based on the surface pressure of the body surface, which was evaluated in Chapter 4, can be applied to continuous posture classification not only on the bed but also when seated and is expected to be useful in supporting nursing care. In addition, the educational support method for pressure dispersion care, which was evaluated in Chapter 5, can be regarded as an example that is a returning of the nursing technique analysis to the educational material in that the educational effect was shown from the analysis of body surface contact pressure data.

6.5 Conclusion

This chapter described the relationship between this study and real-world data circulation. Section 6.2 discussed real-world data circulation and its relation to the healthcare field. To achieve the main-purpose of proposing and evaluating a device for measuring body surface contact pressure, two sub-problems were addressed. Section 6.3 described the relationship between the two applications and the real-world data circulation. In the evaluations for each of the sub-problems, *implementation*, *data acquisition*, *analysis*, and the next implementation plan were considered based on the analysis results, which can be considered that a real-world data circulation was established in the field of applications of pressure ulcer preventive care based on body surface contact pressure. In addition, Section 6.4 described the future idea of the real-world data circulation in this study. In this way, the social values of this study can be further enhanced, therefore the research topics addressed in this study are at the beginning of this process.

Chapter 7

Conclusion

7.1 Summary

In this study, a textile pressure sensor device for the preventive care of pressure ulcers was developed and evaluated based on the body surface contact pressure. Chapter 1 summarized the issues in the preventive care of pressure ulcers. A need to establish a technology to measure the pressure applied to the surface of the human body was identified. Although previous studies measured the pressure applied to a part of the body, applying this technology to prevent pressure ulcers is difficult. Since a three-layered sensor is widely used, obtaining a larger sensor area is difficult because of such complications as sewing and cutting as well as coping with permeability is difficult. To solve these problems, a garment with which can measure the pressure on the body's surface was constructed using a textile pressure sensor [1] that is placed near a cushion's surface. Therefore, the main-purpose of this study was defined, which is to construct and evaluate a body surface contact pressure measurement device incorporating the textile pressure sensor. No previous study has not been investigated to measure the body surface contact pressure during pressure dispersion care. To achieve this main-purpose, the proposed sensor was evaluated coping with two problems: 1) solving such problem as failing to identify the sleeping posture by the bed-sheet-type sensor during the use of a pressure-dispersion cushion, and 2) solving the problem that there is no visualization material for body pressure distribution including body pressure on a pressure-dispersion cushion. The two sub-problems are summarized as follows:

- Developing a garment-type pressure sensor using a textile pressure sensor and evaluating sleeping posture identification based on body surface contact pressure
- Developing a body pressure distribution visualization system, which includes a body-pressure-dispersion cushion incorporating a textile pressure sensor and evaluating for nursing education.

To clarify the position of this study, Chapter 2 summarized related work from the aspects of the pathogenesis of pressure ulcers, their preventive care, and technologies that can be applied to the body's surface contact measurement. Section 2.2 summarized the pathogenesis of pressure ulcers and explained the importance of their preventive care. Section 2.3 summarized sensors that can be used to measure body surface contact pressure and their applications. Although many sensors have been proposed to measure the pressure distribution and commercially available sensors can also be used, obtaining a wider measurement area is difficult as well as coping with sweat that can cause pressure ulcers. Although sensors that can measure a part of the body surface have been proposed, no research has explored preventive care for them.

Chapter 3 described the requirements for a body surface contact pressure measurement device that can be used close to the body's surface and its implementation details. The requirements for measuring such surface pressure are easy processing, such as cutting and sewing, and breathable material. Comparing with the existing pressure sensors, it was stated that the textile pressure sensor [1] is suitable for the application. Section 3.6 and Section 3.7 described the implementation of a body pressure visualization system that includes garment- and cushion-type pressure sensors using a textile pressure sensor.

Chapter 4 described the evaluation of a garment-type pressure sensor made by sewing a textile pressure sensor. Because body-pressure-dispersion cushions are used in nursing care, such problems occurred as failures to correctly identify sleeping postures and the inability to notify the nursing staff when appropriate repositioning is required. To evaluate the proposed garment-type pressure sensor that was developed to cope with this problem, the accuracy of sleeping posture identification based on body surface contact pressure was used. An experiment with 20 subjects was performed to evaluate the accuracy of the sleeping posture identification. The garment-type pressure sensor tended to give higher accuracy than the bed-sheet-type. The results showed that the garment-type tended to have higher identification accuracy than the other sensors, suggesting the feasibility of a garment-type pressure sensor applied to prevent pressure ulcers based on body surface contact pressure.

Chapter 5 described an evaluation of an educational system that can visualize pressure distributions on cushions for improving nursing education. A pressure distribution visualization system consists of bed-sheets and cushions with textile pressure sensors so that embedded sensors can easily follow the cushion's shape. The educational effect of the proposed system on the understanding of body-pressure-dispersion was investigated in a controlled experiment with 47 undergraduate nursing students. The system can be visualized in real-time and for practical training. Pressure-visualization teaching material with data that were recorded in advance was used for uniform experimental conditions in multiple experiments. To evaluate the educational effect of understanding the body's surface contact pressure, the students drew their estimates of high-pressure areas on human body diagrams by looking at the visualization materials. To evaluate quantitatively, the concordance rate between the student answers and the model answer from experienced nurses was calculated. The evaluation results showed that the proposed system promoted the understanding of the body surface contact pressure for such localized areas as the head and the legs without visualized material, even in complex postural changes using a cushion for students who once learned using the proposed system. These results indicate the feasibility of a system that supports the efficient acquisition of skills using the visualization of body surface pressure even when body-pressure-dispersion cushions are used.

In Chapter 3, an unprecedented body surface contact pressure measurement device was proposed, and furthermore, evaluations in Chapter 4 and Chapter 5 provided the feasibility of a garment-type pressure sensor applied to prevent pressure ulcers based on body surface contact pressure and a system including a cushion-type sensor applied to supports the efficient acquisition of skills using the visualization of body surface pressure, even when body-pressure-dispersion cushions are used. In common with the two sub-problems, the applicability of the proposed sensor to prevent pressure ulcers based on body surface contact pressure was demonstrated even in an environment where a pressure-dispersion cushion is used. Therefore, the main-purpose of this study was achieved, which is the construction of a body surface contact pressure measurement device incorporating a textile pressure sensor, and the evaluation of the device.

Chapter 6 described a discussion in this study from the perspective of real-world data circulation. First, the chapter outlined its concept and explained why its importance continues growing in the healthcare field, including nursing care. In the evaluations for each of the sub-problems, *implementation*, *data acquisition*, *analysis*, and the next implementation plan based on the analysis results were considered and a real-world data circulation for pressure-based pressure ulcer prevention care was established. Furthermore, it can also be used to support nursing care acquiring big data purposes. Since the analysis of the collected big data can be utilized for further nursing care support and education, this study will play a part in it in the future.

7.2 Future Direction

Garments and cushions with pressure sensor functions were implemented and evaluated to measure the body surface contact pressure near its surface. The applicability of garment-type pressure sensors was evaluated by comparing them with bed-sheet-type pressure sensors using an evaluation scale based on posture identification accuracy. In addition, the applicability of cushion-type pressure sensors was evaluated from the aspect of quick learning to prevent pressure ulcers by visualizing the body surface contact pressure.

Although the possibility of applying the measurements of the body's surface contact pressure was explored to support the preventive care of pressure ulcers, issues remain that emerged through the experiments. This chapter summarized the limitations and the future directions of body surface contact pressure measurement devices.

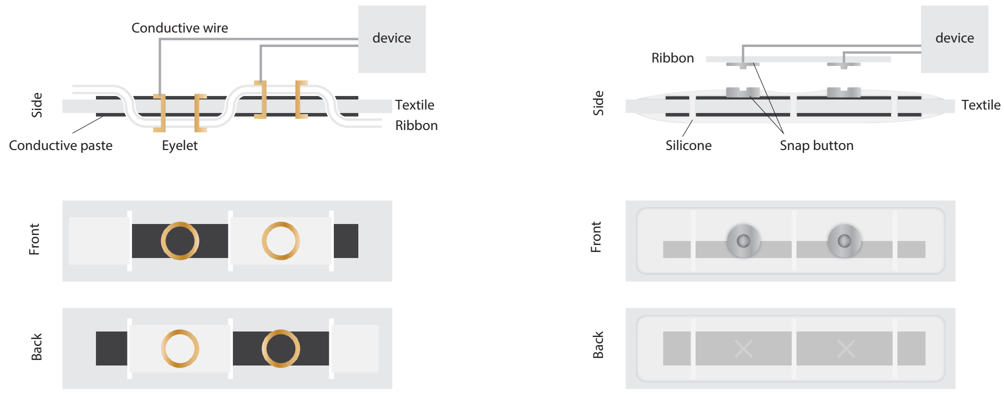
7.2.1 Washability of Body Surface Contact Pressure Measurement Devices

The conductive fiber used in this sensor is *Thunderlon*, which is twisted and insulated with polyester to cover its periphery and then woven. Its resistance, which does not change significantly when washed in water, increases by approximately 0.9 Ω after 40 washes with a neutral detergent, compared with 0.1 Ω per 1 cm of material, and by approximately 0.2 Ω in dry cleaning under the same conditions [1]. The textile pressure sensor woven with a conductive fiber having identical properties is expected to have considerable washability.

Although the textile itself can be washed, it is difficult to do with the terminals connected to the electrical circuit that measures the pressure. To cope with this problem, the terminal can be detachable, or the entire terminal can be covered with a waterproof sealing material, such as silicon.

A prototype of a detachable terminal is examined. Although the sensors used in this study conduct electricity to the textile with pigeonholes by conductive paste (Figure 7.2.1(a)), the removable sensor uses metal snap buttons for the terminals, which are connected to the conductive fibers by conductive paste. Silicon material is used for sealing to insulate the terminals and improve the waterproofing and durability of the terminal area. The circuit is

[1] Comparison of *Thunderlon*'s physical properties, specific resistance, and other properties with other fabrics `http://www.sanmo.co.jp/technology/Function/thunderon3.html` (Last accessed: January 21, 2021)



(a) Using pigeonhole (b) Using snap buttons

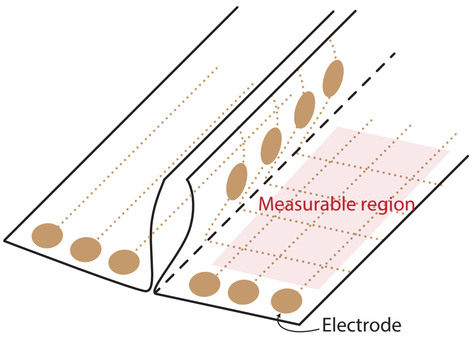
Figure 7.2.1: Terminal connection method to the textile pressure sensor

connected by soldering the corresponding snap buttons to the conductors. A schematic diagram of the detachable terminals is shown in Figure 7.2.1(b).

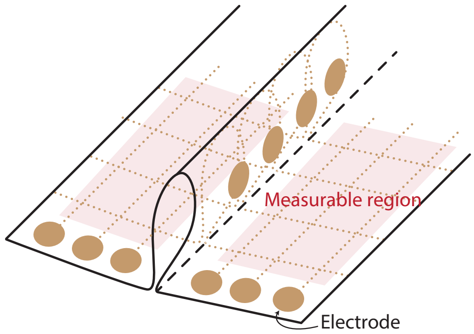
Although the removable terminals were mounted, many extant problems must be solved before they are available for practical use, such as the poor contact with the terminals caused by violent movements by the wearer. One reason why solving this problem is technically difficult is that using commercially available ultra-small snap buttons made hand-soldering extremely onerous. When mass production becomes possible, perhaps this problem can be solved by custom ordering the relevant parts. It is believed that the silicon covering is resistant to washing, although this possibility has not been experimentally evaluated yet. These issues will be addressed in the future.

7.2.2 Expansion of Measurement Range of Garment-Type Pressure Sensors

In the garment-type pressure sensor used in this study, making the electrical connection of the pattern's jointed part was complicated because the garment's pattern required textile cutting and sewing, and the measurement range was limited in this study. Therefore a technique from Japanese kimonos is borrowed and a large piece of textile with minimum processing was incorporated into the patterns described in Section 3.6.5 and Section 3.6.6.



(a) Measurable area when the textile is joined by general sewing



(b) Measurable area when the textile is pinched out and sewn into a bag form

Figure 7.2.2: Sewing method of the textile pressure sensor

Nevertheless, to produce a three-dimensional structure in a garment, the pattern must be sometimes divided. As an idea to expand the measurement area without cutting the textile, a design was devised which continuously kept the textile pinched out and sewing it into a bag form (Figure 7.2.2(a)), where it is cut in a normal sewing process. As a result, a garment-type pressure sensor was created with a wider measurement area.

Although an idea was proposed which is widened the measurement area, some problems remain. First, the new textile was unsuitable for pressure ulcer preventive care (the main-purpose) because the overlapping portion of the textile was thick and caused pressure ulcers. Perhaps this method can be applied for other uses. Another possible problem is the noise due to the capacitance change caused by overlapping the textile. Since the study is insufficient, it will be a future issue.

7.2.3 Discussion on Introducing the Proposed System to Nursing Care Facilities

Experienced nursing care specialists and nursing home staff gave feedback on the body surface contact pressure measurement device for its use in nursing homes. Applicability was explored which is incorporated the pressure sensor function into garments and cushions using textile pressure sensors, although issues remain that must be solved before the garments and cushions can be used for daily monitoring.

Technical issues include the problems of washing resistance and thickness, as described above. Although the textile pressure sensor is sewn, its thickness is lower than that of the garment-type sensor proposed in previous studies, and the thickness of the terminals and other parts remain problematic for pressure ulcer preventive care.

In addition, the issue that seniors at care facilities tend to avoid wearing pressure measurement devices was found. The difficulty of long-term measurement experiments using garments that can measure body surface contact pressure was reconfirmed. The same concern had been raised by a policy that promotes allowing seniors to choose the garments of their preference at the end-of-life care period.

The above issues suggest the difficulty of wearing such devices on a daily basis. As mentioned in Chapter 5, they can also be used as teaching materials or as a temporary examination garment.

On the other hand, introducing them to bed-sheets and wheelchairs is easy. In recent years, a technology that can be inferred from a small amount of information using a huge amount of data has greatly expanded compared to when the method was conceived that directly measured body surface contact pressure. Therefore, it would be possible to estimate the risk of developing pressure ulcers only from sensors incorporated into bed-sheets and wheelchairs. In fact, my laboratory is conducting a research project on skeletal estimation with the convolutional pose machine [42] just using the pressure distribution obtained from bed-sheets, not from camera images.

7.2.4 Application of Garment-Type Pressure Sensor to Bruise-Detection

From discussions with nursing care specialists, we identified a way to utilize body surface contact pressure measurement devices, such as garment-type pressure sensors, for purposes other than preventing pressure ulcers in elderly

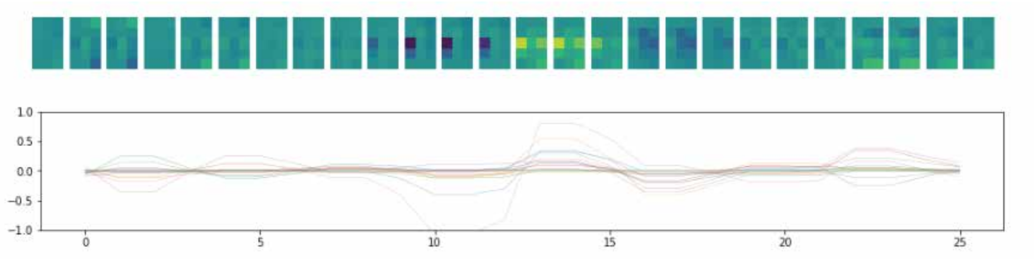


Figure 7.2.3: Visualization of pressure distribution and pressure change in 15 regions when a pair of pants is bruised

care.

For example, bruises from unknown injuries are a problem in the care of seniors with dementia. According to a report by Mitadera et al. [67], many accidents involving falls in nursing care facilities have been observed in situations where no assistance or supervision was available. To detect the affected/injured area, the pressure on the body's surface must be measured. Perhaps garment-type pressure sensors can be applied as bruise-detection wear.

To investigate whether garment-pressure sensors can detect such impact, the pressure value of garment pressure sensors was experimentally measured imitating the wearer had a bruise. A mannequin was used to bruise the wearer for obvious ethical and safety concerns. Figure 7.2.3 shows the sensor values for each of the 15 regions of pressure distribution on pants when measured at 2 Hz. The maximum and minimum pressure values in the area where the impact was felt vacillate greatly, indicating that the impact's position and time can be estimated.

In the pilot study, the wrinkles caused by the garment or any changes in pressure values due to body movement were not measured because the experiments were conducted under controlled conditions. To detect the impact during the actual wearing of garments, impact values must be distinguished from pressure change values that occur in daily life. To solve this problem, it is deemed that anomaly detection technology can be applied using neural networks, which has been studied in recent years, thus its pilot study has

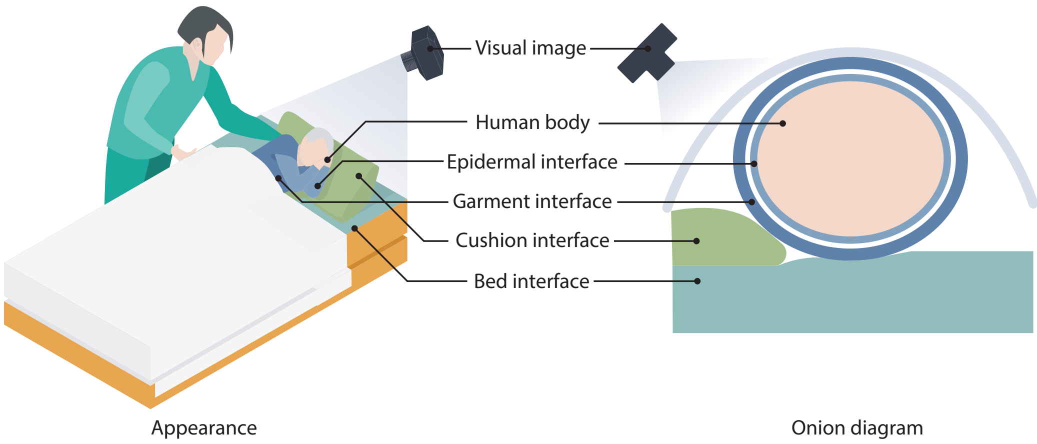


Figure 7.2.4: Sensors available during pressure dispersion care and their correspondence

already been conducted [82]. I would like to tackle the above problem of anomaly detection as a future research topic.

7.2.5 Exploration of Epidermal Devices

The contact surface pressure was measured nearer the body's surface by incorporating a pressure sensor function into garments and cushions. The devices that can estimate contact surface pressure during pressure dispersion care form an onion-like structure around the human body: RGB and infrared cameras, bed-type sensors, cushion-type sensors, and garment-type sensors. Figure 7.2.4 shows a schematic diagram of sensors that can be used for pressure dispersion care and their correspondence. The outermost RGB and infrared cameras estimate the skeletal structure and simulate the surface pressure of the body surface, although they cannot be used with blankets. On the other hand, a sensor incorporated into a bed surface or a cushion can measure the pressure on the body's surface. Although it can measure by a blanket the pressure on the part of the body that is hidden, automatic localization is difficult where the pressure is applied on the body. A garment can certainly solve this problem, even though it is difficult to identify the sensor's position due to textile misplacement. In fact, some studies argue that moving the joints misaligns the measurement points due to garment misalignment, which requires calibration [68].

To measure the body surface contact pressure, a method is required that directly attaches a sensor to the skin, which is even closer to the skin than a garment. Although electronic components have been miniaturized, electronic circuits can be embedded on the skin, and research on epidermal devices is growing. For example, Weigel et al. proposed *iSkin* [69], which is laminated with conductive PDMS (Polydimethylsiloxane) and can be attached to interact with the skin, and *SkinMarks* [70], which incorporates a pressure-sensitive element and an EL display and demonstrates I/O functions on the skin. Kao et al. proposed *SkinWire* [71], which demonstrated wiring from the back of the hand to a fingertip accelerometer using a tattoo sticker and conductive thread.

The recent challenges in the field of smart skin include thinner devices, complex wiring, and comfort. In *Weaving a Second Skin* [78], a smart textile that can be attached to the skin using functional yarn as part of the woven fabric was explored. This study evaluated the comfort of wearing the textile and the customizability of its appearance, which are critical factors for wearable devices. Since I was involved in this project as a visiting researcher, it was discussed in this dissertation.

Still, there are such issues as that the sensor's range is limited, it is as breathable as a general woven fabric, therefore it offers potential for the practical prevention of pressure ulcers in the future. In experiments with subjects, good evaluations of wearing comfort were obtained. Research on epidermal devices for body surface contact pressure is a future subject.

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