Year 2023 Doctoral Thesis

Experimental study of contact stress measurement acting on frequent sites of pressure injury when backrest of nursing care bed is operated

(介護用ベッドの背もたれ操作時における褥瘡好発部位に作用する接触応力計測の実験的研究)

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CHAPTER 2. Film sensor for triaxial contact stress measurements on the human body

Abstract

Japan is aging at an unprecedented rate. Furthermore, the number of bedridden elderly people is also on the rise. One of the negative effects of lying in bed for a long period of time is that pressure injury may develop on the body that comes into contact with the mattress. Pressure injury is a common health problem among bedridden elderly people. The development process of pressure injury is as follows. When a person lies in bed, body weight concentrates on the bony prominences of the back of the human body. The blood flow of muscle, subcutaneous tissue, and skin owing to compression becomes worse. Severe cases lead to cell necrosis. Regarding the external force that causes pressure injury, it has been pointed out that in addition to contact pressure, the action of shear stress further exacerbates the symptoms. The measurement of contact stress on the human body has been reported using soft but thick sensors with a large measurement point area inserted into the contact interface. A thick pressure sensitive layer may disturb the contact interface. Furthermore, if the area of sensing point is large, the measurement may be affected by the unevenness of the contact surface. Therefore, the evaluation accuracy is likely to be insufficient. Flexible and very thin to measure the contact stress acting locally, including the projection of the bone of the human body, a sensor having small area of the sensing point was needed. The purpose of this study is to develop a small, thin, and

flexible 3-axis stress sensor to investigate pressure injury, and to measure the contact stress acting on subjects' areas where frequent sites of pressure injury when operating the backrest of a nursing care bed. Clarifying the actual contact stress that causes pressure injury will be useful for detailed examination of the mechanism of pressure injury development.

This paper summarizes these results and consists of six chapters. Chapter 1 presents the background and purpose. Chapter 2 presents the structure of the developed sensor and the measurement system for measuring contact stress that acts locally on bone protrusions of the human body. Recently, a tactile sensing system using a small, thin, and flexible sensor was developed by Sasagawa et al. In this study, a tactile-sensing system using the small, thin, flexible sensor developed by Sasagawa et al. was improved. This system can measure the contact pressure and biaxial shear stress. However, the adhesion between the upper and lower electrodes was insufficient, resulting in a lack of stability during low-stress measurements. To solve this problem, when overlapping the upper and lower electrodes, a 20 μm double-sided tape was used as an adhesive layer to strengthen adhesion, thereby ensuring stability during low-stress measurements. The shape of the electrodes was also improved. The measurement area of the previous sensor was 7.5 mm × 7.5 mm. The improved sensor had a measurement area of 3.2 mm × 3.2 mm, enabling further miniaturization. In addition, the surface of the sensor that came into contact with clothing was coated with an ultra-soft gel (5 mm × 5 mm in plane size, approximately 70 μm in thickness), which is a new procedure. This brings the sensor surface closer to the frictional state of human skin. The improved sensor was calibrated and it was found to show the appropriate relationships between output voltage and contact pressure as well as shear stress, even in the low-stress range of less than 1 kPa. The thickness of the measuring part of the improved sensor was 82 μm. Therefore, measurements using the sensor were almost unaffected by the thickness of the sensor.

Chapter 3 and subsequent chapters are about the experimental results using the improved sensor. In Chapter 3, contact stress was measured of at the frequent sites for pressure injury when operating the backrest of a nursing bed. In this study, our focus was on the scapula and sacrum areas. Thus, for measuring shear stress, an headward stress was exerted on the sacrum as the backrest was operated. The stress on scapula showed a tendency to act footward. The effect of shear stress was confirmed even after the patient returned to the lying position on the backrest. Therefore, residual shear stress may have occurred. It was also suggested that the knee lift-up, which is activated when the backrest of the bed is operated, may affect changes in contact stress. In Chapter 4, contact stress was measured with and without the knee lift-up. The effect of backrest manipulation on contact stress change in the sacral region was investigated. In Chapter 4, our focus was on the areas of the sacrum. As the result regarding the shear stress, there was a common tendency to act headward when the backrest was raised, regardless of the presence or absence of the knee lift-up. When the backrest was down, the shear stress of headward gradually decreased when the knee lift-up was activated. However, the shear stress did not decrease when the knee lift-up was not activated. Moreover, it did not vanish when the subjects returned to the supine position. These results suggest that there is a high possibility that shear stress remains after operating backrest when the without knee lift-up. Chapter 5 focused on the distribution of residual shear stress when the subject returned in a supine position after lowering the backrest. Four sensors were pasted on the skin of the subject's scapula and sacrum, respectively. The distribution of the residual shear stress was clarified with and without knee lift-up. The trends of residual shear stress acting on the scapula and sacrum were different. Footward shear stress was distributed in the measurement area of the scapula. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the scapula without knee lift-up tended to be greater than with knee lift-up. On the other hand, headward shear stress was distributed in the measurement area of the sacrum. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the sacrum without knee lift-up tended to be greater than with knee lift-up. These results suggest that the knee lift-up function may reduce residual shear stress.

CHAPTER 1. Introduction

1.1 Background

Japan is aging at an unprecedented rate, with the proportion of people aged 65 and over reaching nearly 30% of the total population. The average life expectancy for both men and women is over 80 years [1,2]. This has resulted in various issues surrounding medical care for the elderly, which are increasingly garnering attention. As the number of chronic diseases increases with age, older people are more likely to suffer from multiple chronic diseases and complex diseases can worsen health conditions [3]. Additionally, a survey by Imai et al. [4] found that there are more bedridden elderly people in Japan than in the United States. In Japan, it has been pointed out that public resources for the care of bedridden elderly people are insufficient. More specifically, among developed countries, the number of health and welfare personnel, such as doctors, nurses, certified care workers, physical therapists, and occupational therapists, per 1,000 people aged 65 and over is the lowest in Japan. Pressure injury is a common health problem among bedridden elderly people. And is a frequent health problem worldwide [5-7]. In a study by VanGilder et al. [8], the prevalence of pressure injury in healthcare facilities in the United States decreased from 13.5% in 2006 to 9.3% in 2015. Meanwhile, the prevalence of pressure injury in medical facilities across Japan was estimated to range from 0.96%–8.32% in 2006 [9]. In 2016, it was 0.77%–2.81% [10]. The prevalence of pressure injury is decreasing. However, the occurrence of pressure injury in elderly patients aged 65 and older remains a challenge [10]. As pressure injury worsens, patients experience significant pain and discomfort [11]. It also has a negative impact on the quality of life [12]. Moreover, treatment is expensive. Higher severity of pressure injury increases costs for patients and healthcare providers [13,14]. This is because severe cases take longer to heal, and the incidence of complications is higher. The cost of treating pressure injury is likely to increase in the future as the population ages. A pressure injury occurs when the blood flow in an area under pressure from body weight stagnates and worsens, causing destruction and damage to the skin and underlying tissue [5,15-17]. Patients who spend a considerable amount of time in bed owing to illness or disability are at high risk of developing pressure injury.

The development process of pressure injury is as follows. When a person lies in bed, body weight concentrates on the bony prominences of the back of the human body. The blood flow of muscle, subcutaneous tissue, and skin owing to compression becomes worse. Severe cases lead to cell necrosis [5]. Pressure injury is classified into Stages I–IV based on their severity. Stage I indicates the early stage of pressure injury formation. Stage IV indicates full-thickness skin and tissue loss [18]. Pressure injuries tend to form when strong pressure is applied to areas of the human body where bones protrude. The areas where pressure injury is most likely to develop vary depending on the posture of a person lying in bed. When a person lies supine in bed, pressure injury tend to develop on the occipital tuberosity, scapula, sacrum, and heels [19]. Regarding the external force that causes pressure injury, it has been pointed out that in addition to contact pressure, the action of shear stress further exacerbates the symptoms [20]. Particularly, elderly people tend to have fragile skin owing to physical changes associated with aging, such as thinning of the dermis and subcutaneous tissue, and a decrease in elasticity [21-23]. However, the actual contact stresses, including shear stresses, acting on the back of a bedridden elderly person are not clear. Therefore, the details of the mechanism behind the development of pressure injury have not been elucidated in detail.

The measurement of contact stress on the human body has been reported using soft but thick sensors with a large measurement point area inserted into the contact interface [24], pressure-sensitive films [25], hard sensors [26, 27], or by embedding them in the contact object [28-30]. However, most of these are limited to measuring body pressure distribution. As for the developed sensor, which measured the shear stress on contact surface, there were hard and soft thing. However, there is only thick sensor. A thick pressure sensitive layer may disturb the contact interface. Furthermore, if the area of sensing point is large, the measurement may be affected by the unevenness of the contact surface. Therefore, the evaluation accuracy is likely to be insufficient. Flexible and very thin to measure the contact stress acting locally, including the projection of the bone of the human body, a sensor having small area of the sensing point was needed. Recently, a tactile sensing system using a small, thin, and flexible sensor was developed by Sasagawa et al. [31-33]. This system can measure the contact pressure and biaxial shear stress. However, when measuring contact stress on bone protrusions, the measurement area of the sensor was large. Additionally, measurements in low stress regions were unstable. The purpose of this study is to develop a small, thin, and flexible 3-axis stress sensor to investigate pressure injury, and to measure the contact stress acting on subjects' areas where pressure injury is most likely to occur when operating the backrest of a nursing care bed. Clarifying the actual contact stress that causes pressure injury will be useful for detailed examination of the mechanism of pressure injury development. The results of the study can be used to improve and develop welfare equipment and equipment to prevent the occurrence and deterioration of pressure injury. This will serve as a reference for considering effective nursing care methods to decrease contact pressure and shear stress, which are factors that cause pressure injury in bedridden individuals.

1.2 Organization of the thesis

This paper consists of six chapters of this study. Chapter 1 presents the background and purpose. Chapter 2 presents the structure of the developed sensor and the measurement system for measuring contact stress that acts locally on bone protrusions of the human body. Chapter 3 presents the measurement results of contact stress on the human body using the improved sensor. Chapter 4 presents effect of the knee lift-up function on changes in sacrum contact stress when the backrest of a nursing bed is operated. Chapter 5 presents distribution of residual shear stress at the frequent sites for pressure injury during manipulation of the backrest of nursing bed. Finally, the conclusion in Chapter 6 summarizes the entire study based on the results obtained in experiments so far.

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CHAPTER 2. Film sensor for triaxial contact stress measurements on the human body

2.1 Introduction

Contact stress on the human body has been measured by inserting soft but thick sensors with a large measurement point area [1], pressure-sensitive films [2] and hard sensors [3,4] into the contact interface and by embedding sensor in the contact object [5-7]. However, most of these are limited to measuring body pressure distribution. As for the developed sensor, which measured the shear stress on contact surface, there were hard and soft sensors. However, there is only thick sensor. A thick pressure sensitive layer may disturb the contact interface. Furthermore, if the area of sensing point is large, the measurement may be affected by the unevenness of the contact surface. Therefore, the evaluation accuracy is likely to be insufficient. Flexible and very thin to measure the contact stress acting locally, including the projection of the bone of the human body, a sensor having small area of the sensing point was needed. Recently, a tactile sensing system using small, thin, and flexible sensors was developed by Sasagawa et al. [8-10]. This system can measure the contact pressure and biaxial shear stress. However, the following problems were encountered in the used sensors. The sensor had a structure in which the upper and lower electrodes overlapped. However, the adhesion between the upper and lower electrodes was insufficient, resulting in a lack of stability during low-stress measurements. Also, when measuring contact stress on bone protrusions, the measurement area of the sensor was large. This study aims to address these problems and enhance the functionality of the sensors developed in a previous study.

2.2 Materials and methods

2.2.1 Basic structure of the sensor

The basic structure of the sensor used in this research is shown below. The sensor, which is thin and flexible, can simultaneously measure the contact pressure and shear stress on the contact interface. The sensor is made of a pressure-sensitive conductive material and a copper-clad laminate film. The thickness of the sensor is approximately 82 μm. The electrical resistance of the pressure-sensitive conductive ink decreases as the applied pressure increases. The copper-clad laminate is used as the sensor electrode. The copper films are etched using conventional photolithography. The sensor structure is simple, with a pressure-sensitive conductive layer sandwiched between copper film electrodes. The electrical resistance of the pressure-sensitive layer sandwich between the top and bottom electrodes decreases with compression. Figure 2.1 shows the mechanism of contact pressure measurement. When a vertical load, that is contact pressure, is applied to the sensor, the pressure-sensitive layer is compressed, and the electrical resistance between the top and bottom electrodes decreased. Figure 2.2 shows the measurement mechanism of the shear stress. Suppose the shear stress acts on the sensor surface, the top and bottom electrodes displaced and the overlapped area overlap between the top and bottom electrodes increased, resulting in a decrease in the electrical resistance between the electrodes. On the other hand, the electrical resistance between the electrodes increases when the shear stress is applied so as to reduce the overlapped area.

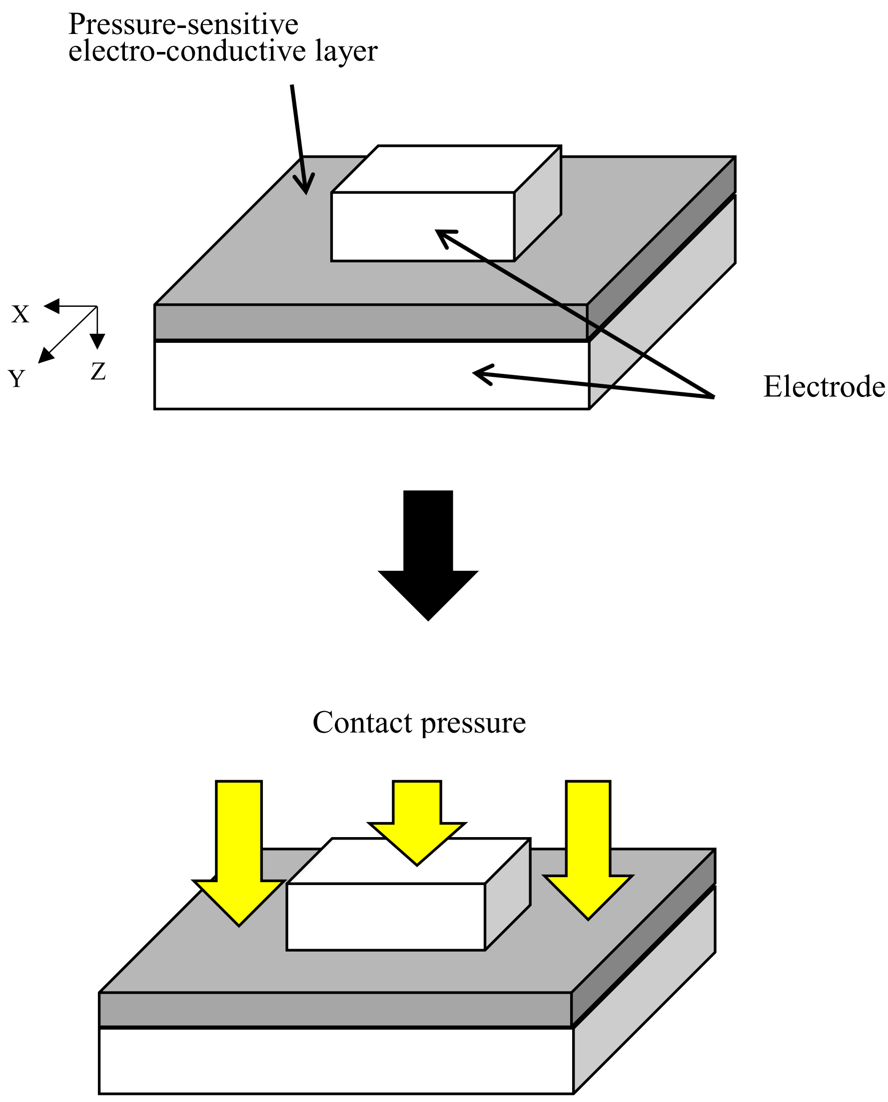


Fig. 2.1 Measuring mechanism of contact pressure (Z axis)

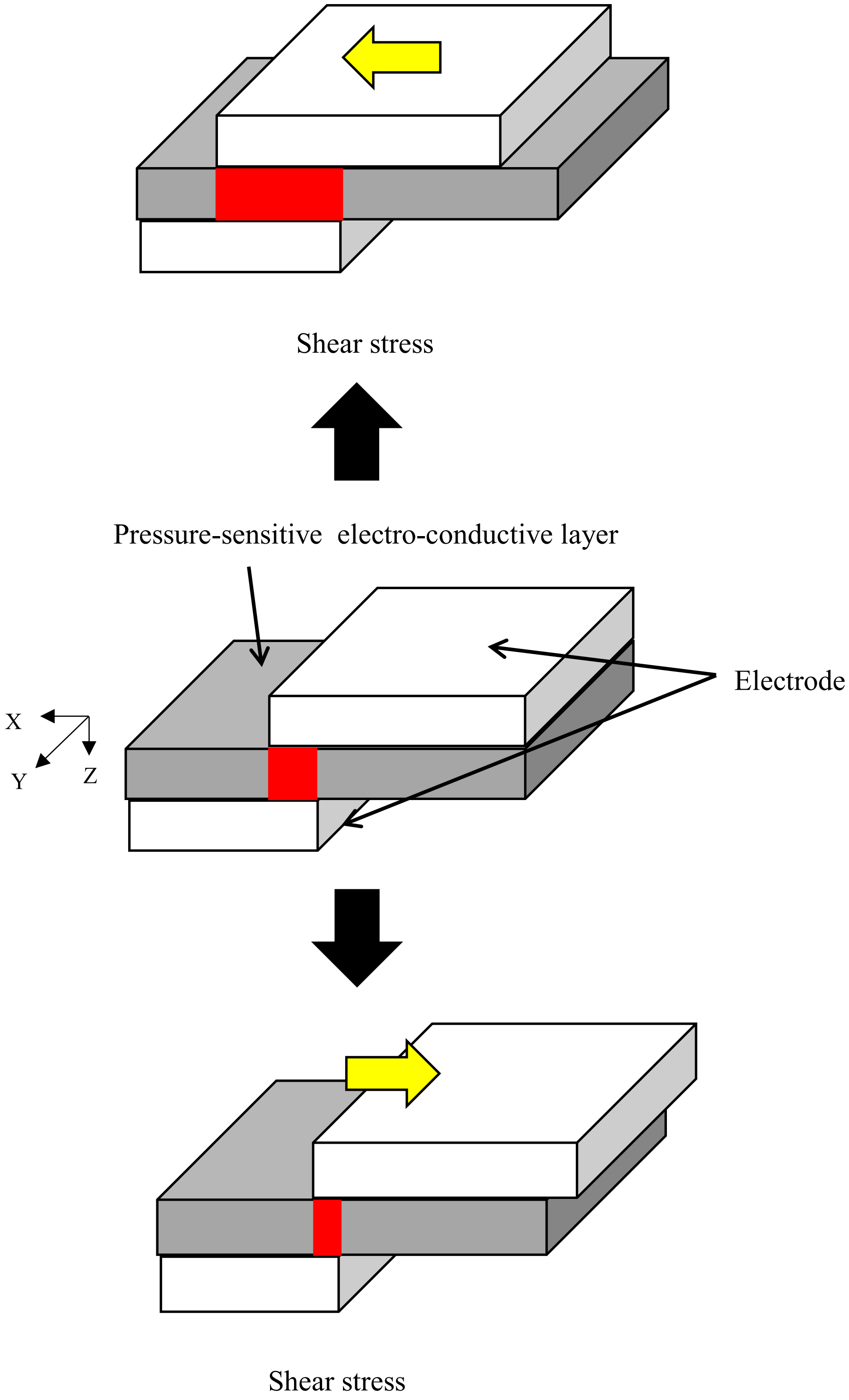
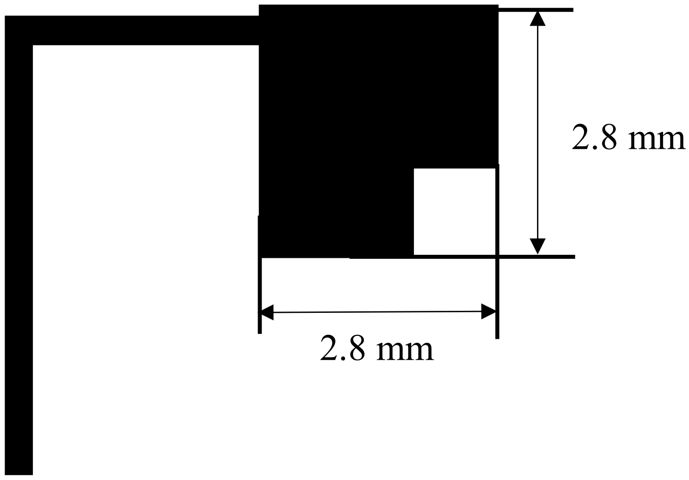
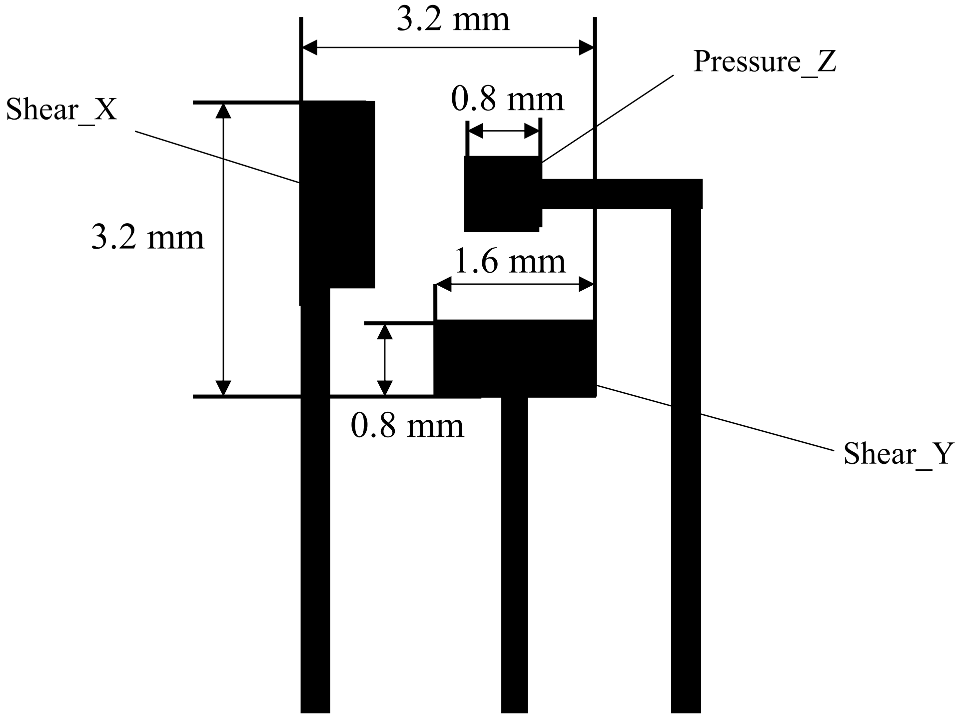


Fig. 2.2 Measuring mechanism of shear stress (X-axis)

Figure2.3 shows the newly designed electrode patterns for measuring the contact pressure and biaxial shear stress. The measurement of parts contact pressure and biaxial shear stress are Pressure_Z, Shear_X, and Shear_Y, respectively. A pressure-sensitive conductive ink was used as the pressure sensitive material in this sensor. In addition to the upper electrode, conductive ink was screen printed on the shear stress measuring parts (Shear_X, Shear_Y) and the contact pressure measuring part (Pressure_Z) of the lower electrodes. Thereafter, it was cured at 120℃ for 20 min. Figure 2.4 shows the upper and lower electrodes after screen printing conductive ink. As shown in Figure 2.5, the upper and lower electrodes were stacked and fixed such that their conductive ink layers (pressure sensitive electro conductive layers) are facing each other. Finally, the sensor was sealed with a waterproof film (Polyurethane film) to protect it. Figure 2.6 shows the fabricated sensor. The change in electrical resistance was converted to voltage via a bridge circuit.

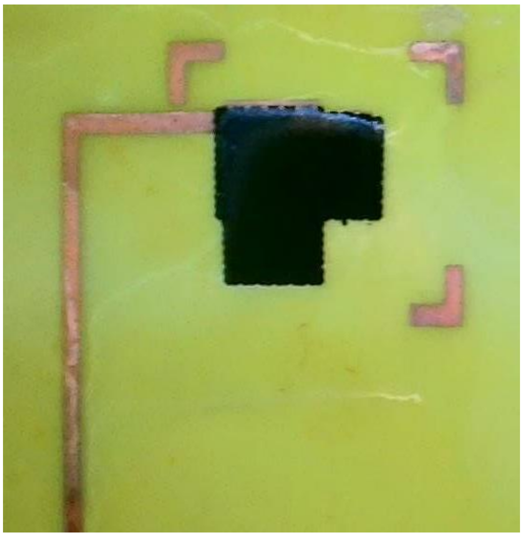


(a) Upper electrode pattern

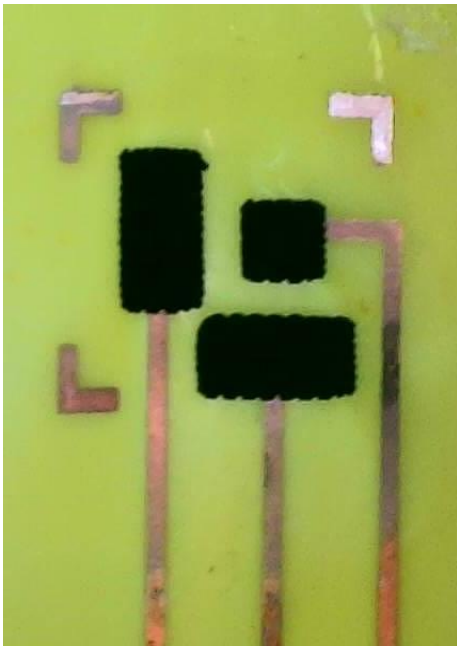


(b) Lower electrode pattern

Fig. 2.3 Electrode pattern for measuring shear stress and contact pressure



(a) Upper electrode



(b) Lower electrode

Fig. 2.4 Conductive ink-coated electrode

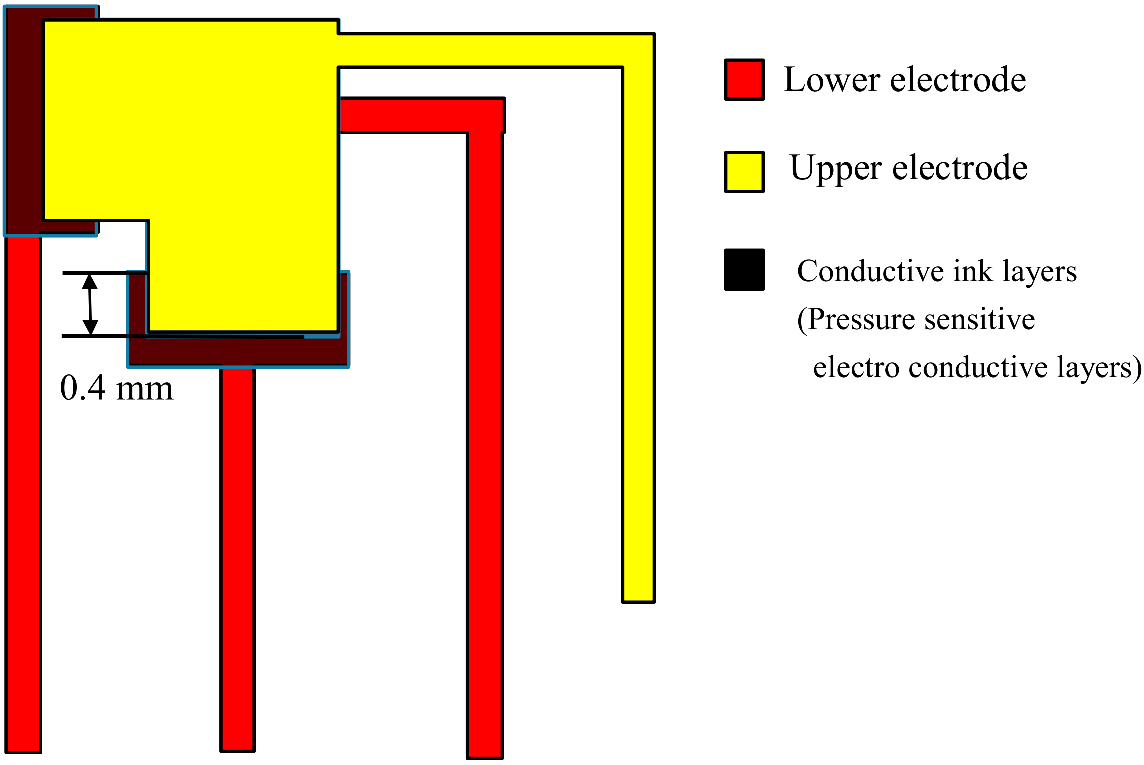


Fig. 2.5 Superposition of upper and lower electrodes

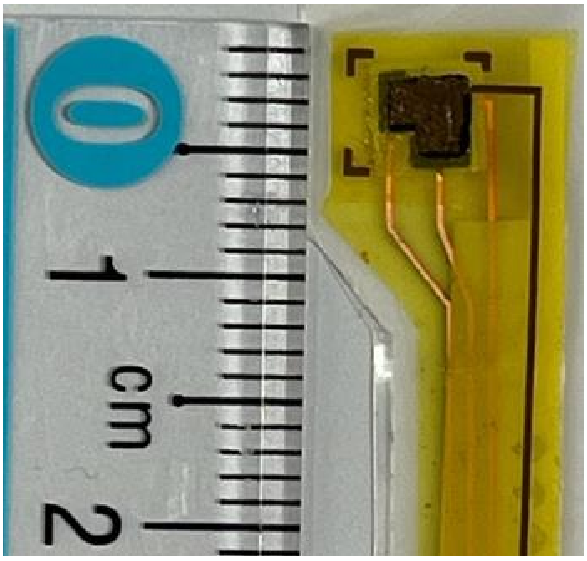
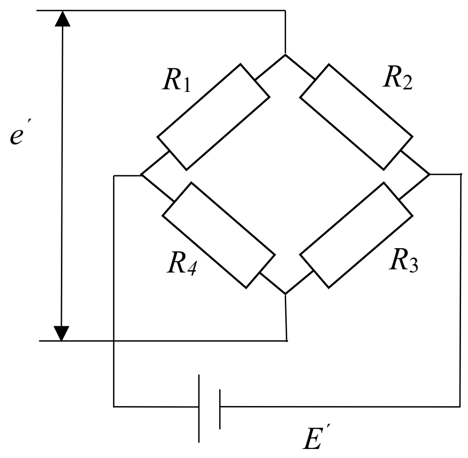


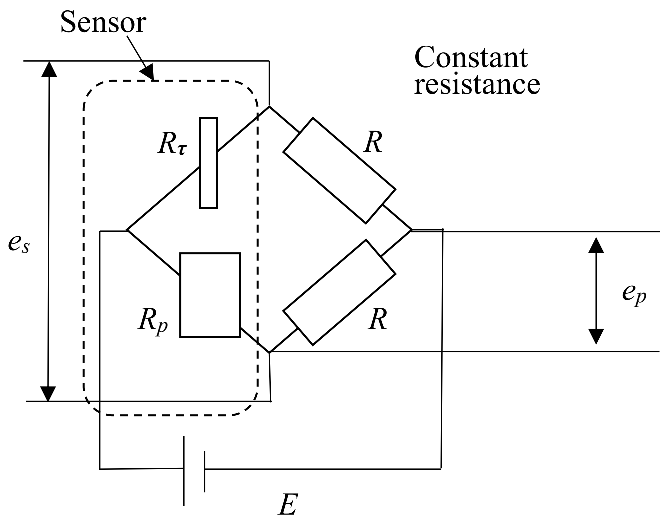
Fig. 2.6 Manufactured thin 3-axis stress sensor

2.2.2 Measurement circuit

The electrical resistance between the upper and lower electrodes changes when contact stress is applied to the sensor. The bridge circuit can detect changes in the electrical resistance as voltage changes. The detected voltage is associated with the applied contact pressure and shear stress. Because the resistance change in the shear stress measurement section includes the change in electrical resistance owing to the contact pressure, the change due to shear stress should be extracted by subtracting the change in resistance due to contact pressure from the resistance change in the shear stress measuring section. To remove the effect of contact pressure on resistance of shear stress measuring part, the principle of the four-gauge method of Wheatstone bridge circuit was used. As shown in Figure 2.7, R_τ and R_p are the resistances between the sensor electrodes for the shear stress and contact pressure measurements, respectively, and R is the value of the constant resistances fixed on the circuit. The electrodes for each stress component were designed to ensure that the electrical resistances of all measuring parts were equal under stress-free conditions. Furthermore, R is set to be equal to R_τ and R_p. All resistances in the bridge circuit are the same, R, under pressure- and shear stress-free conditions, and the bridge circuit is in an equilibrium state. The relationship between the voltage E input to sensor and the output voltage e_s of the bridge circuit is represented by the as following equation [10].



(a) Four-gauge method



(b) Sensor circuit

Fig. 2.7 Correspondence between a general four-gauge bridge circuit (a) and the sensing components of contact pressure and shear stress in the sensor (b).

$$e_s = \frac{1}{4}\left(\frac{\Delta R_\tau - \Delta R_p}{R}\right)E \quad (1)$$

where ΔR_τ and ΔR_p indicate the amount of change in R_τ and R_p, respectively, from the initial state R. Denoting the change in electrical resistance only due to the applied contact pressure by ΔR_A and the amount of change in electrical resistance only due to the applied shear stress by ΔR_B, the quantities ΔR_τ and ΔR_p are expressed as:

$$\Delta R_\tau = \Delta R_A + \Delta R_B$$
$$\Delta R_P = \Delta R_A \quad (2)$$

By substituting Eq. (2) into Eq. (1), the change in electric resistance due to shear stress is extracted as:

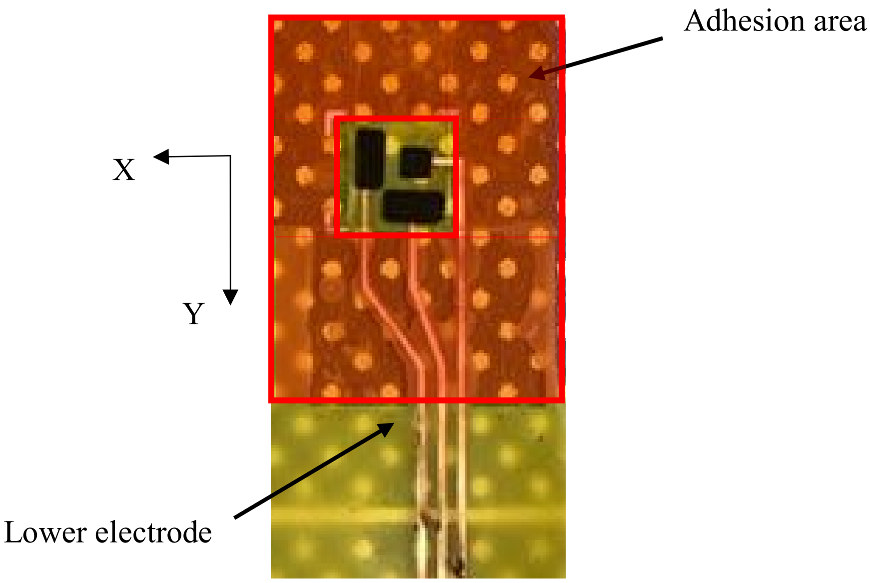
$$e_s = \frac{1}{4}\frac{\Delta R_B}{R}E \quad (3)$$

The contact pressure was measured as the change in voltage across R. This voltage e_p is given by Eq. (4).

$$e_p = \frac{R}{R + R_p} E = \frac{R}{2R + \Delta R_A} E \tag{4}$$

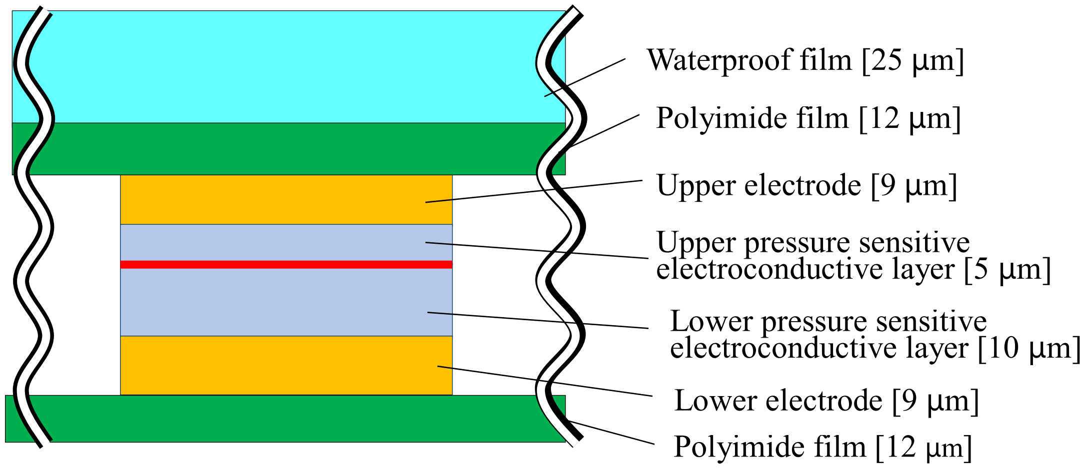
2.2.3 Improvement in sensor system issues

In the conventional sensor structure for contact stress measurement [10], the upper and lower electrodes formed on polyimide film substrate were covered with pressure-sensitive layers. The polyimide substrates were overlapped so that pressure-sensitive layers face each other, and the assembly was then sealed with a waterproof film. Therefore, the adhesion between the pressure-sensitive layer on the top and bottom electrodes was weak. Thus, unstable measurement in the low-stress range was a problem with conventional sensors. Then, an adhesion layer was introduced to attach the top and bottom polyimide film substrates to improve the adhesiveness of the pressure-sensitive layers on the top and bottom electrodes before sealing them with a waterproof film. As shown in Figure 2.8 (a), a very thin double-sided tape used as the adhesion layer was placed around the stress measurement area on the lower electrode, and the upper electrode was overlapped and compressed on the top. The thickness of the double-sided tape used was 20 μm. Figure 2.8 (b) shows cross sections of the conventional sensor and the improved sensor.

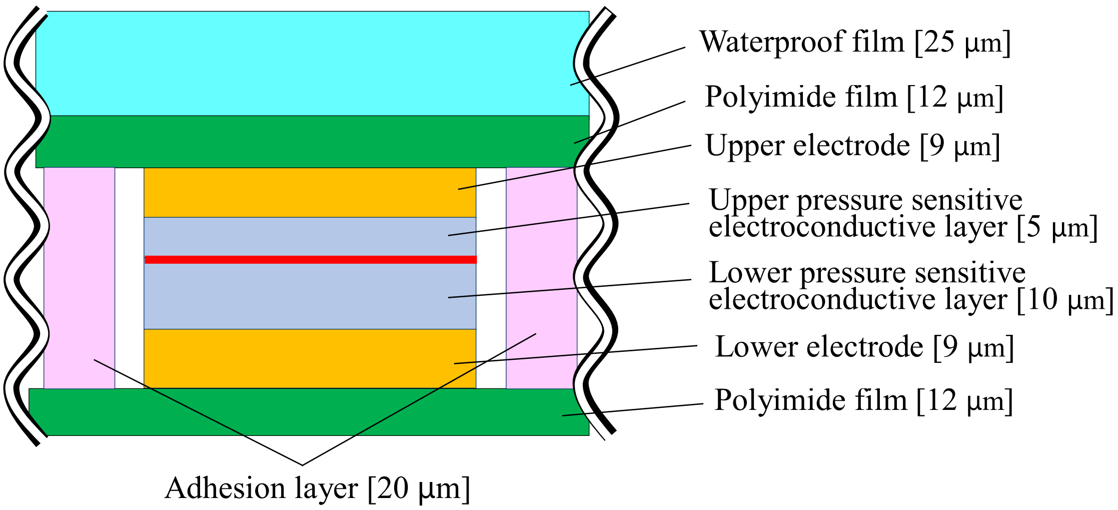


(a) Placement of adhesion layer

Fig. 2.8 Adhesion layer arrangement and sensor cross section



(b-1) Conventional sensor

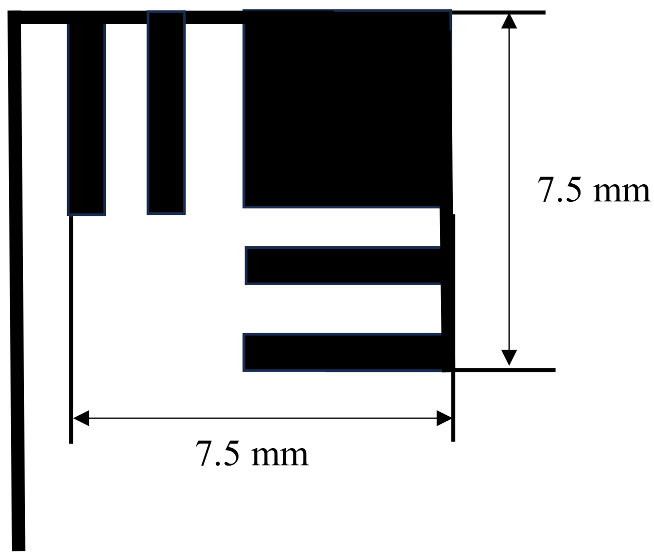


(b-2) Improved sensor

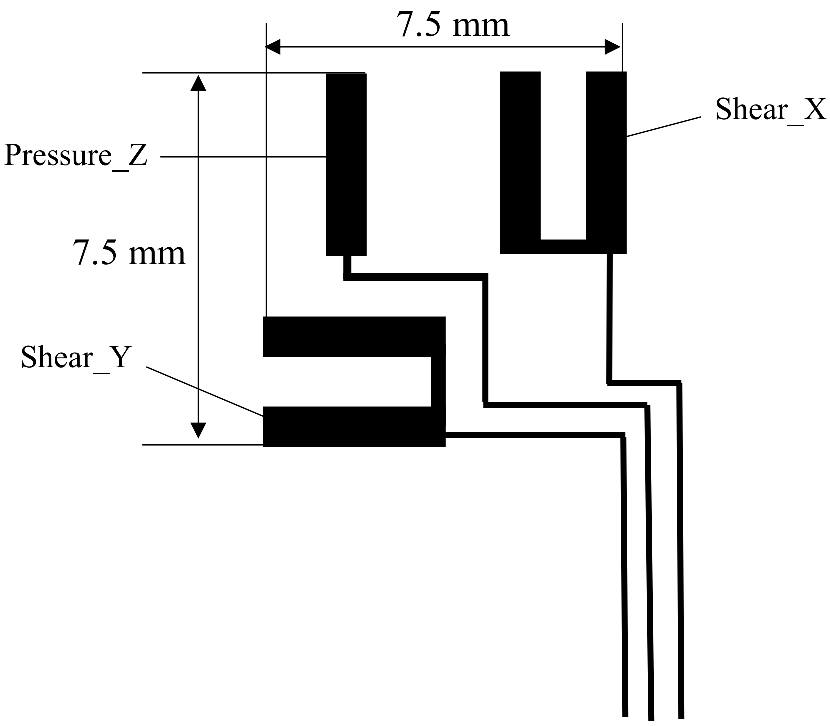
(b) Cross section of sensor

Fig. 2.8 Adhesion layer arrangement and sensor cross section

Furthermore, three improvements were made. First, the shape of the electrodes was changed to reduce the size of the sensor. Figure 2.9 shows, the measurement area of the conventional sensor was 7.5 mm × 7.5 mm. But Figure 2.3 shows, the improved sensor has a measurement area of 3.2 mm × 3.2 mm, enabling further miniaturization and integration. Second, the signal stability and accuracy of the sensor were enhanced by eliminating parasitic current along the lateral direction in the pressure-sensitive layer. Only the contact pressure measurement section (Pressure_Z) and the two-axis shear stress measurement sections (Shear_X, Y) were covered with pressure-sensitive conductive ink by screen printing, as shown in Figure 2.4 (b), although the three measurement sections were covered in the previous sensor. Third, as a sensor device for measuring the contact stress acting on the human body, the measuring area of the sensor surface in contact with clothing was coated with an ultra-soft gel (5 mm × 5 mm in size, approximately 70 μm in thickness) to close the friction condition of the human skin surface. Figure 2.10 shows the area coated with ultra-soft gel.



(a) Upper electrode pattern



(b) Lower electrode pattern

Fig. 2.9 The electrode pattern of a conventional sensor

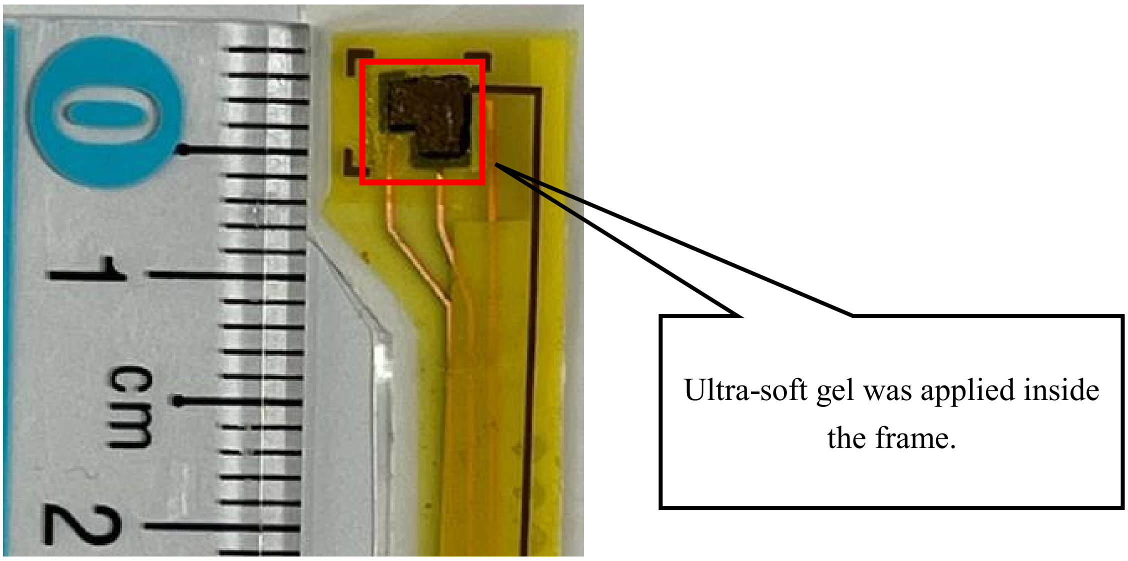


Fig. 2.10 The area coated with ultra-soft gel

2.2.4 Calibration test methods

Calibration experiments were conducted to convert the electrical signals from the sensor system into contact pressure and shear stress values. The contact pressure calibration system is illustrated in Figure 2.11. Contact pressure was applied to the sensor using a material testing machine via an acrylic punch (5 mm × 5 mm × 2 mm), sponge rubber (5 mm × 5 mm × 3 mm), and the compressive force was measured using a six-axis load cell. The load range for the applied contact pressure was 0-30 kPa.

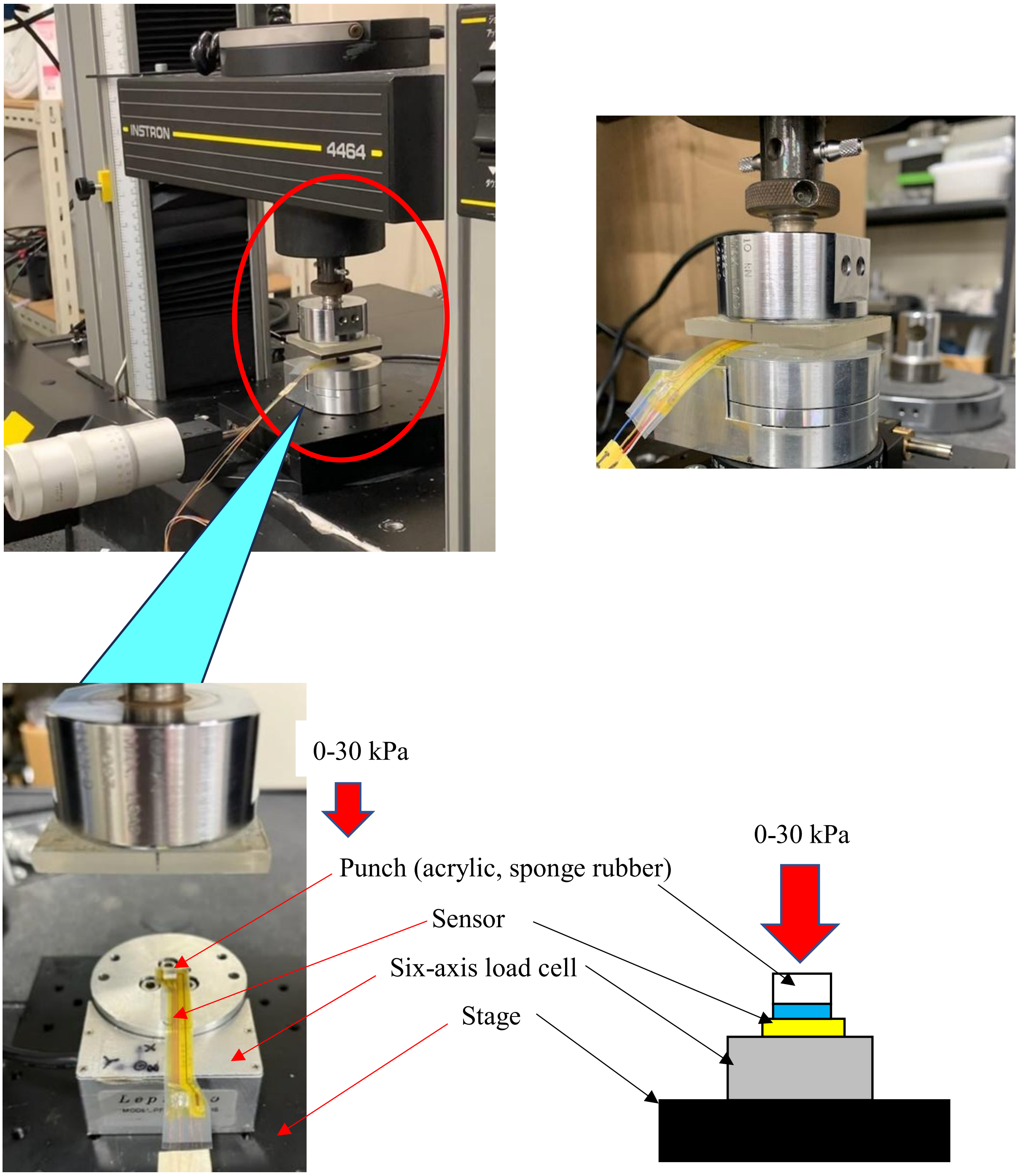
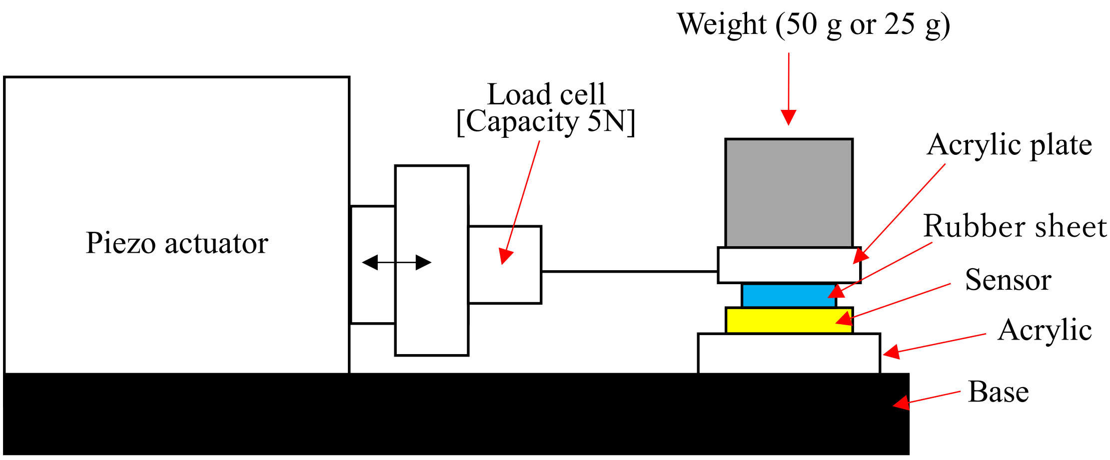
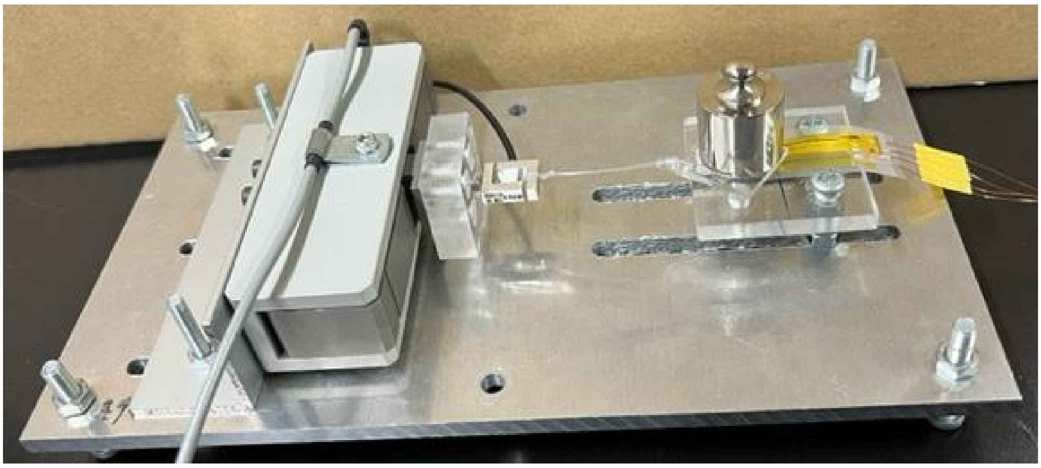


Fig. 2.11 Schematic diagram of contact pressure calibration

Figure 2.12 shows the shear stress calibration system. The sensor was fixed on the base, and a weight was placed on the sensor through an acrylic plate and a rubber sheet. The acrylic plate was connected to the piezo actuator via a load cell and a wire. Shear stress can then be applied to the sensor by controlling the displacement of the piezoelectric actuator. Two types of contact pressures, 10 and 20 kPa, were applied during the shear stress test, and the applied shear stress ranged from -2 to 2 kPa for 10 kPa and from -7 to 7 kPa for 20 kPa compressive loading. Calibration experiments were conducted for two directions of shear stress: Shear_X, Y. The voltage values from the measurement circuit and load cell were measured using an A/D converter.



(a) Schematic diagram of shear stress calibration

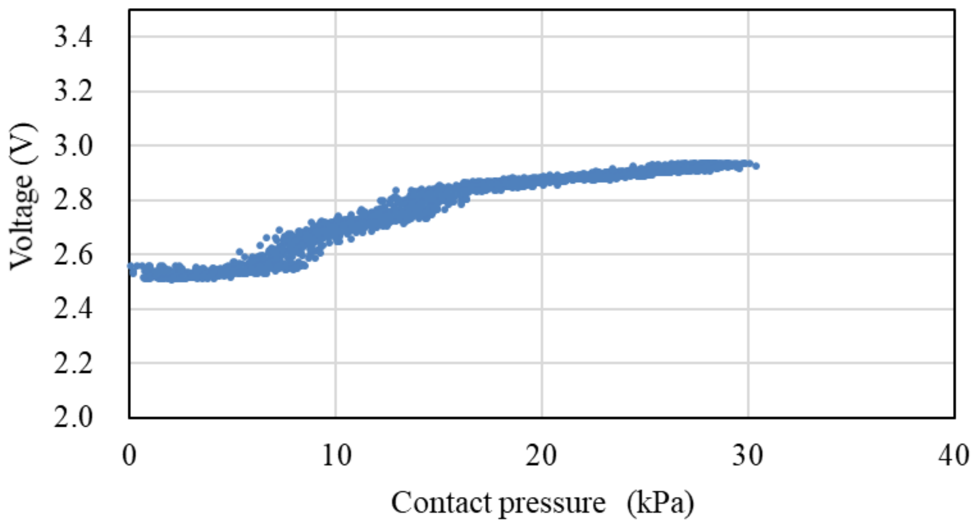


(b) Shear stress calibration device

Fig. 2.12 Shear stress calibration system

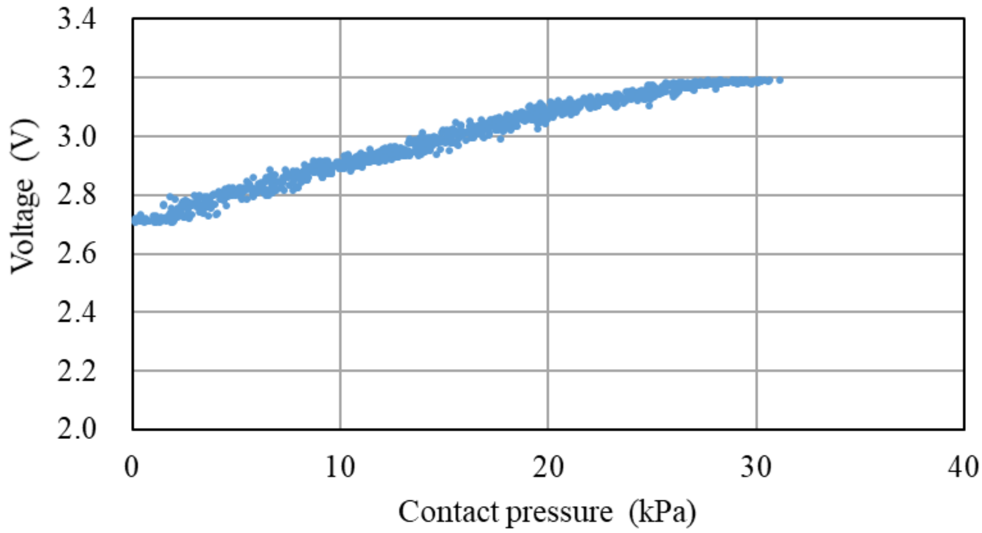
2.3 Results

Figure 2.13 shows the contact pressure calibration results for the self-made conventional sensor and the improved sensor. The relationship between the contact pressure and output voltage was examined under contact pressures of 0–30 kPa. The output voltage increased with increasing contact pressure, as shown by the monotonically increasing curve.



(a) Conventional sensor

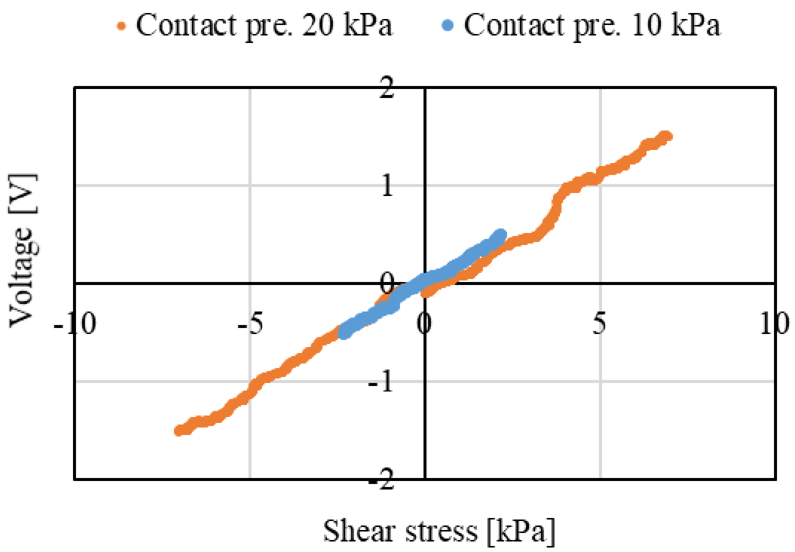
Fig. 2.13 Calibration curve of contact pressure from 0-30 kPa.



(b) Improved sensor

Fig. 2.13 Calibration curve of contact pressure from 0-30 kPa.

An example of the calibration results for the shear stress along the X- and Y-directions of the sensor is shown in Figure 2.14. The output voltage was measured in the range of −2 to 2 kPa in shear stress under a contact pressure of 10 kPa and in the range of −7 to 7 kPa in shear stress under a contact pressure of 20 kPa. Under every condition, the voltage changed linearly with increasing shear stress. The same linear relationship was observed even under different contact pressures.



(a) X-direction

(b) Y-direction

Fig. 2.14 Calibration lines of shear stress measured along the X and Y-directions.

2.4 Discussion

The thin and flexible contact stress sensor was improved on the geometry of the conventional sensor [10] to achieve a smaller measurement area and higher integration of the measuring point. The revised sensor was calibration tested, and it was found that the sensor had appropriate relationships among the contact pressure, shear stress, and output voltage, even under a low-stress range. The previous sensor cannot perform measurements stably in a low stress range. However, stable contact stress measurement has become possible even in the low stress region of 1 kPa or less. The relationship between shear stress and output voltage was maintained even under different contact pressures. It can be seen that shear stress can be measured appropriately without being affected by contact pressure.

2.5 Conclusion

In this study, the fabrication process of conventional sensors was revised, and the electrode design was improved to reduce the measurement area further and achieve higher integration. The revised sensor was calibrated and found to have appropriate relationships between the output voltage and contact pressure, and between the output voltage and shear stress, even in the low-stress range of less than 1 kPa.

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CHAPTER 3. Measurement of contact stress at the frequent sites for pressure injury when operating the backrest of a nursing bed

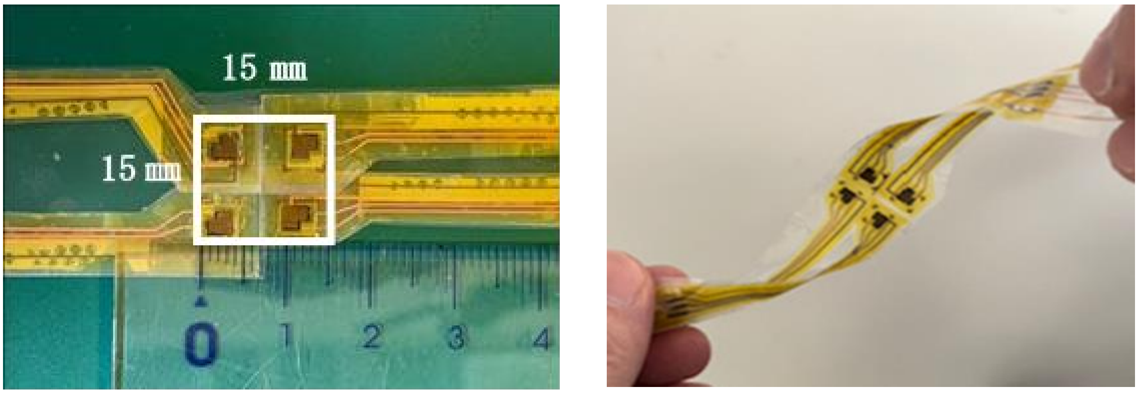
3.1 Introduction

The development process of pressure injury is as follows. When a person lies in bed, body weight concentrates on the bony prominences of the back of the human body. The blood flow of muscle, subcutaneous tissue, and skin owing to compression becomes worse. Severe cases lead to cell necrosis [1-4]. Patients who spend a considerable amount of time in bed by illness or disability have at high risk of developing pressure injury. Pressure injuries tend to occur at bony protrusions area in the human body. When a person lies supine in bed, pressure injury tends to develop on the occipital tuberosity, scapula, sacrum, and heels [5]. Regarding the external force that causes pressure injury, it has been pointed out that in addition to contact pressure, the action of shear stress further exacerbates the symptoms [6].

Recently, a tactile sensing system using a small, thin, and flexible sensor was developed by Sasagawa et al. [7-9]. This system can measure the contact pressure and biaxial shear stress. In Chapter 2, the fabrication process of conventional sensors was revised, and the electrode geometry was improved to reduce the measurement area further and achieve higher integration. From these efforts, successfully fabricated a small, thin, and flexible triaxial stress sensor for pressure injury inspection. The purpose of Chapter 3 is to clarify the correspondence between the change in contact stress due to the manipulation of the backrest of the bed and the displacement of the body due to the manipulation of the bed.

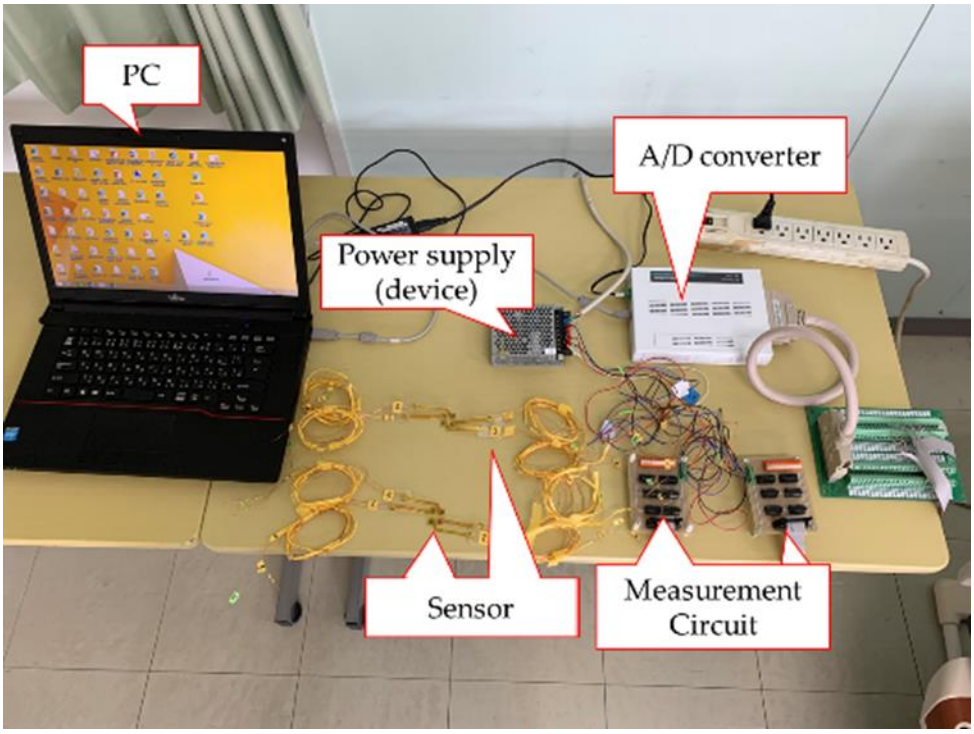
3.2 Methods

The subject was a healthy adult male, 174 cm and 65 kg. This experiment was conducted in accordance with the Helsinki Declaration. The subject was given a thorough explanation of the primary purpose and methods of the experiment, orally and in writing, prior to the experiment, and his consent was obtained. In this study, our focus was on the scapula and sacrum areas. Bone protrusions on the subject's back (scapula, sacrum) were confirmed by touching the skin. A triaxial stress sensor was attached to the skin of the bony protrusion using double-sided tape. Four sensors were placed on each scapula and sacrum. Figure 3.1 shows the overall image of the experimental setup. Figure 3.2 shows the sensor installation location and measurement experiment scene. As shown in Figure 3.2(b), the subject's clothing consisted of a T-shirt for the upper body and pajamas for the lower body. For the measurement of shear stress, the focus will be on the vertical action. The subject was asked to maintain a supine posture in bed, and the posture of the subject was changed by raising the bed backrest from 0 deg. to a maximum value of 75 deg. “backrest up” and continuously lowering the bed backrest from the maximum value of 75 deg. to 0 deg. “backrest down”. The experiment was conducted three times consecutively. Note that contact stress measurements were continuously performed while the backrest of the bed was being operated. The sampling frequency was 10 Hz.



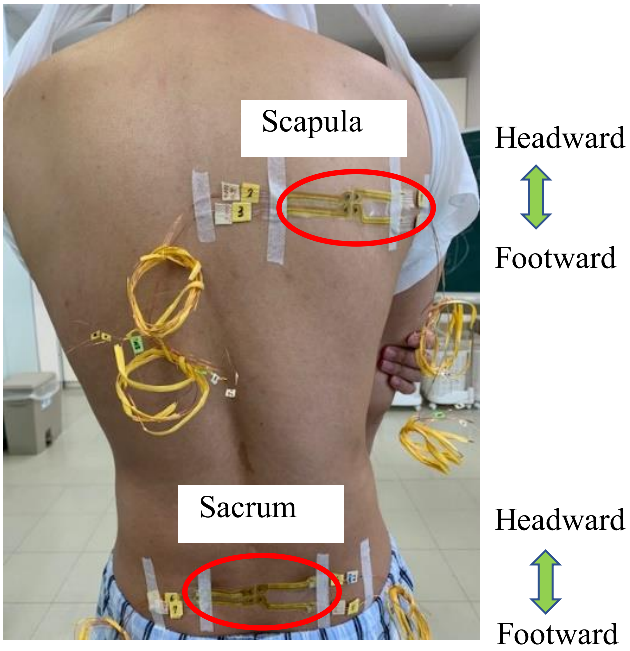
(a) Thin 3-axis stress sensor

Fig. 3.1 Overview of sensors and experimental equipment



(b) Measurement system

Fig. 3.1 Overview of sensors and experimental equipment



(a) Location of sensor installation

(b) Scene of measurement experiment

Fig. 3.2 Sensor position and scene of measurement experiment

The bed used was a commercially available nursing care bed. As the backrest moves up and down, the knees also rise in synchronization. When the backrest up begins, the “knee lift-up” begins immediately. The knee lift-up reaches up to 30 deg. in maximum. When the angle of the backrest reaches 40 deg., the knee lift-up gradually begins to disappear. When the backrest angle reached its maximum angle of 75 deg., the knee lift-up was completely eliminated. When the backrest down begins, the “knee lift-up” begins immediately. The knee lift-up reaches up to 30 deg. in maximum. When the angle of the backrest reaches around 20 deg., the knee lift-up gradually begins to disappear. Once the backrest is lowered, the knee lift-up is completely eliminated. The time required from the start of backrest up until the inclination angle of the backrest was 75 deg. was 40 s. The time required from the start of backrest down to the bed inclination angle of 0 deg. was 38 s. The mattress, which was made of polyester, was 80 mm thick. In this measurement, the initial position of the subject's body to the mattress was unified. The backrest operation with knee lift-up from backrest up to backrest down was repeated twice in a row. Thereafter, the body position of the subject was taken as the initial position at the start of the measurement. And, additional experiments were conducted as shown in Figure 3.3. The displacement of the body relative to the mattress when the backrest was operated was measured. Markers were affixed to four locations on the sides of the subject's body (acromion, lumbar region, knees, and ankles) and at the mattress contact position (side surface) of the subject prior to measurement. The displacement of the mattress and markers affixed to the subject was recorded by video camera while the bed was being operated. Then, still images were created from the images for every 10 deg. of inclination angle of the backrest. The displacement of the body relative to the mattress was measured.

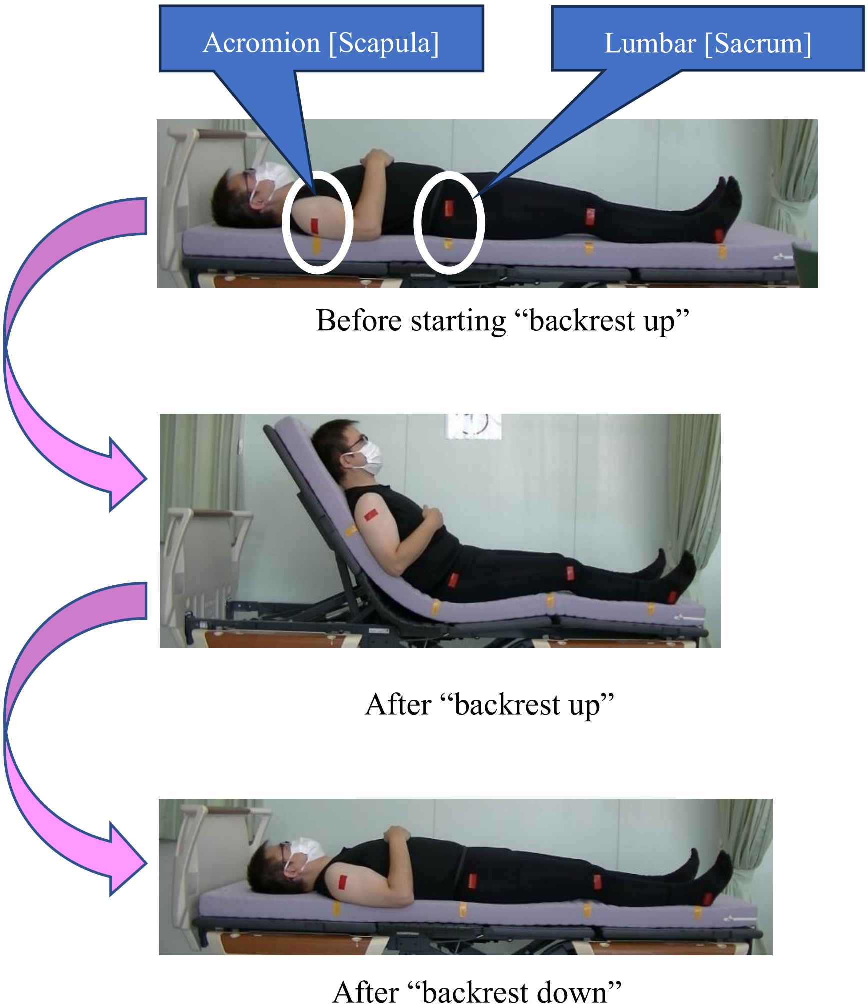
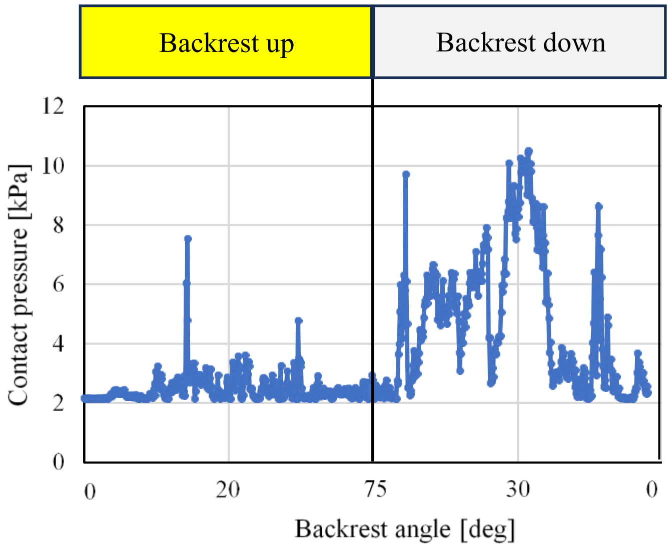


Fig. 3.3 Measurement of the displacement between the bed and the body when the backrest was operated.

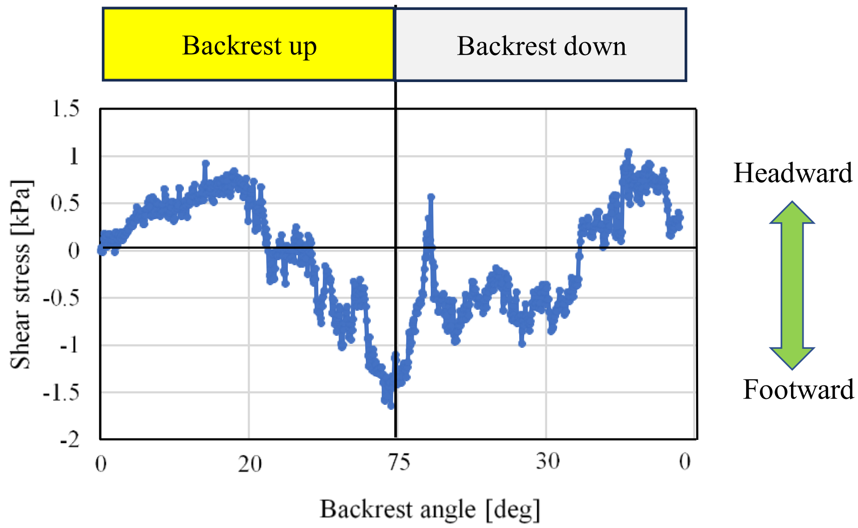
3.3 Results

3.3.1 Contact stress on scapula

Figures 3.4(a) and (b) shows the results of measuring contact stress on the scapula. Four sensors were placed on the shoulder blade. This is data from one sensor that was in contact with the mattress. Contact pressure measurements showed that when the backrest was up, contact pressure of approximately 2–3 kPa persisted even if the inclination angle of the backrest increased. However, no large changes were observed. When the backrest was down, an increase in contact pressure of up to 10 kPa was confirmed when the inclination angle of the backrest was 70–30 deg. Shear stress measurements showed that when the backrest was up, footward shear stress tended to be approximately 1.5 kPa at most. When the backrest was down, the footward shear stress tended to decrease. When the inclination angle of the backrest was around 10 deg., the headward shear stress increased to approximately 1 kPa. Then, even when the inclination angle of the backrest reached 0 deg., it did not return to its initial value.



(a) Contact pressure on scapula

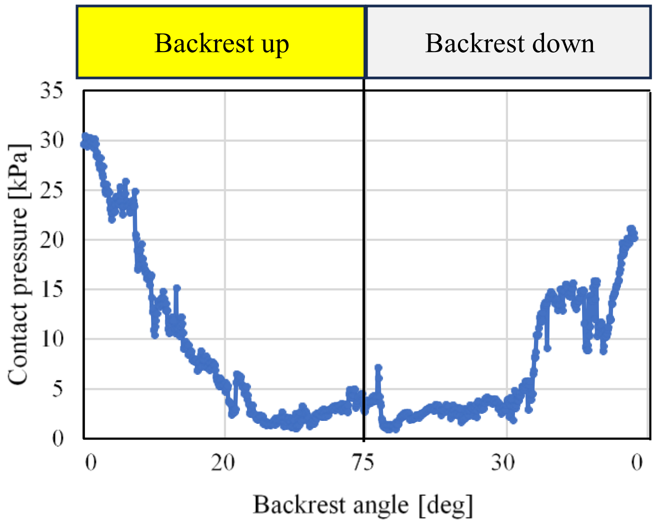


(b) Shear stress on scapula

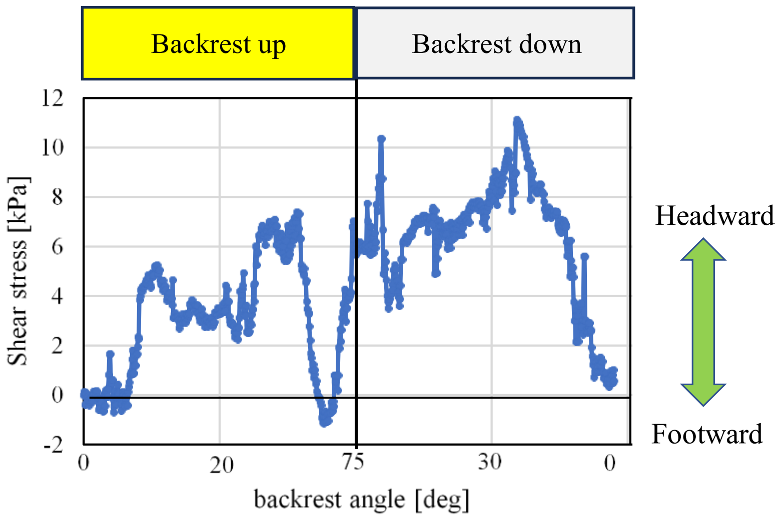
Fig. 3.4 Results of measuring contact stress on the scapula

3.3.2 Contact stress on sacrum

Figures 3.5 (a) and (b) show the results of measuring contact stress on the sacrum. Four sensors were placed in the sacrum. This is the average value of the two sensors that were in contact with the mattress. The contact pressure measurements showed that when the backrest was up, the contact pressure decreased from about 30 to 1 kPa as the inclination angle of the backrest increased. When the backrest was down, the contact pressure increased to about 20 kPa as the inclination angle of the backrest decreased. Measurements of shear stress showed that when the backrest was up, headward shear stress of about 7 kPa was observed as the inclination angle of the backrest increased. When the backrest was down, headward shear stress was applied up to an inclination angle of 30 deg. Then, it gradually decreased. Even after the backrest was down and the inclination angle of the backrest became 0 deg., the shear stress value did not return to its initial value. Headward shear stress of approximately 1 kPa was measured.



(a) Contact pressure on sacrum



(b) Shear stress on sacrum

Fig. 3.5 Results of measuring contact stress on the sacrum

3.3.3 Results of measuring the displacement of the body when operating the backrest

Figures 3.6 and 3.7 show the results of measuring the displacements of the acromion and lumbar when the backrest of the bed was operated. The headward deviation of the acromion relative to the mattress increased as the backrest inclination angle increased. Then, the headward shift decreased as the inclination angle of the backrest decreased. As for the lumbar, footward displacement relative to the mattress increased as the backrest inclination angle increased. Even if the inclination angle of the backrest decreased, the footward shift was maintained. The footward deviation decreased from around the inclination angle of 30 deg.

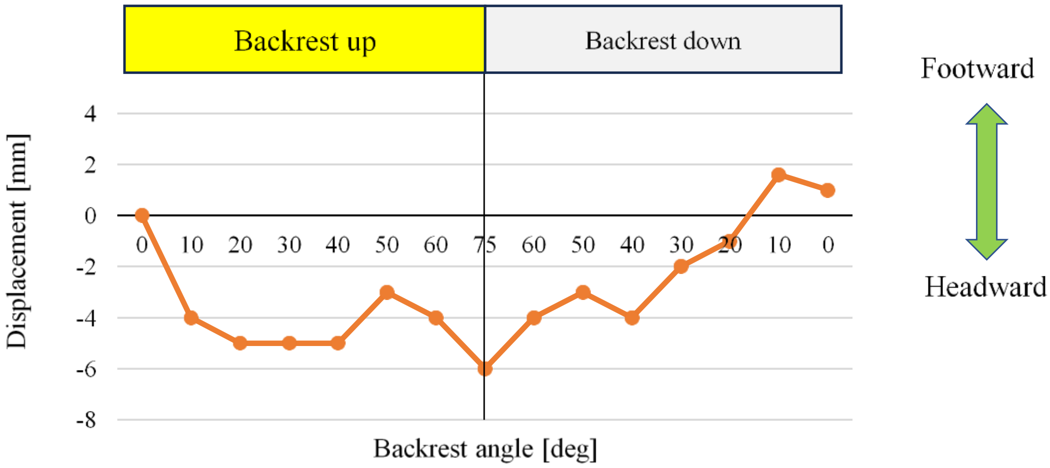


Fig. 3.6 Measurement results of acromion deviation

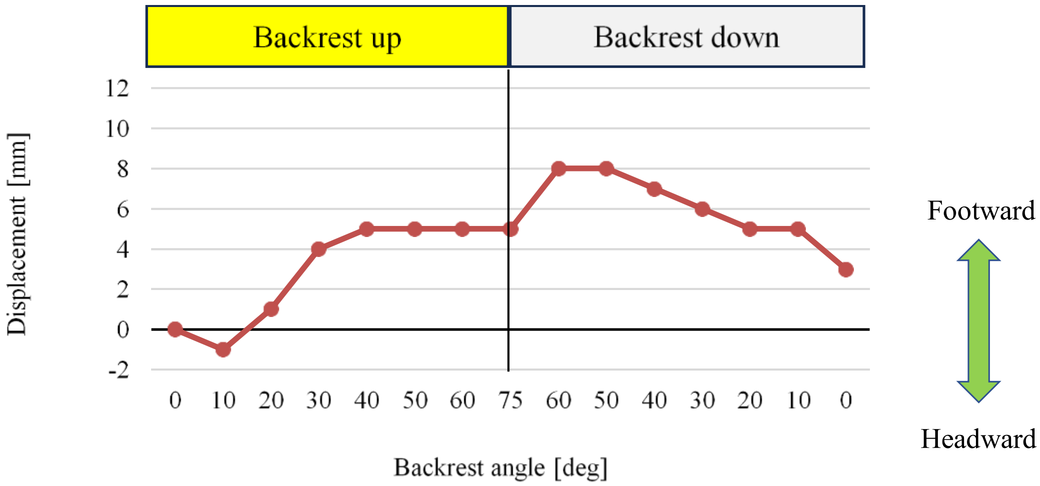


Fig. 3.7 Measurement results of lumber deviation

3.4 Discussion

3.4.1 Contact stress of scapula

In contact pressure measurements, the inclination angle of the backrest was varied between 70 deg. and 30 deg. when the backrest was down. Focusing on the changes in the posture of the subject at this time. As the knee lift-up function was linked to the backrest down position, the posture of the subject became bent in a "V" shape with the lumbar as the fulcrum. It is speculated that this caused the area around the shoulder blades to be pressed against the backrest, increasing the contact pressure. Later, the contact pressure seemed to decrease as the "V" posture was resolved. Regarding the measurement of shear stress, when the backrest was up, the area around the shoulder blades shifted upward relative to the mattress as the inclination angle of the backrest increased. Therefore, footward shear stress was generated. When the backrest was down, the headward displacement of the shoulder blades decreased as the inclination angle of the backrest decreased. Therefore, the effect of the footward shear stress was weakened. As the inclination angle further increased, the shoulder began to shift footward. Therefore, it was assumed that headward shear stress started to act. Moreover, when the backrest is down, the knee lift-up returns to its original state when the inclination angle of the backrest is around 10 deg. Then, as the body shifted headward again, headward shear stress decreased.

3.4.2 Contact stress of sacrum

When measuring the contact pressure in the sacral region, the contact pressure decreased as the inclination angle of the backrest increased. The contact pressure increased as the inclination angle of the backrest decreased. Thus, when the backrest was up, the posture of the subject gradually changed from lying to sitting. Then, the contact area with the mattress moved from the sacrum to the ischial bones. Therefore, the contact pressure in the sacral region was reduced. In backrest down position, the posture changes from sitting to lying. Thus, it was inferred that the point of contact with the mattress moved from the ischia to the sacrum, and the contact pressure in the sacral region gradually increased. The relationship between the change in shear stress due to the operation of the backrest of the bed and the displacement of the body due to the operation of the bed is as follows. When the backrest was up, the lumbar shifts downward relative to the mattress as the inclination angle of the backrest increases. Therefore, headward shear stress acts. When the backrest was down, immediately after the backrest angle decreased, the lumbar moved downward relative to the mattress. Therefore, headward shear stress acts. Later, when the inclination angle of the backrest decreased, the knee lift-up began. This reduced the downward shift of the lumbar region. Therefore, the headward shear stress was reduced. When the backrest is down, the acromion and lumbar region shift footward relative to the mattress. Therefore, it is possible that headward shear stress is acting on both. In actual measurements, it was confirmed that some shear stress remained in the headward direction after the backrest was down.

3.4.3 Comparison of measurement results of this study and results of previous studies

Mimura et al. [10] measured contact stress of a person on a nursing care bed during manipulating the backrest. The results were compared with the results obtained in this experiment. Previous research utilized sensing using devices fluid pressure. The pressure-sensitive mechanism was thick and had a large area. The measurement part of the sensor was 70 mm × 96 mm oval and 2 mm thick. Sensors were attached to the subject's scapula, sacrum, coccyx, and back of the thigh. Contact stress measurements were taken continuously while the backrest of the bed was being manipulated. The sampling frequency was 2Hz. Figure 3.8 shows the measurement results of contact stress in previous research. Focus on the results of the sacral measurements.

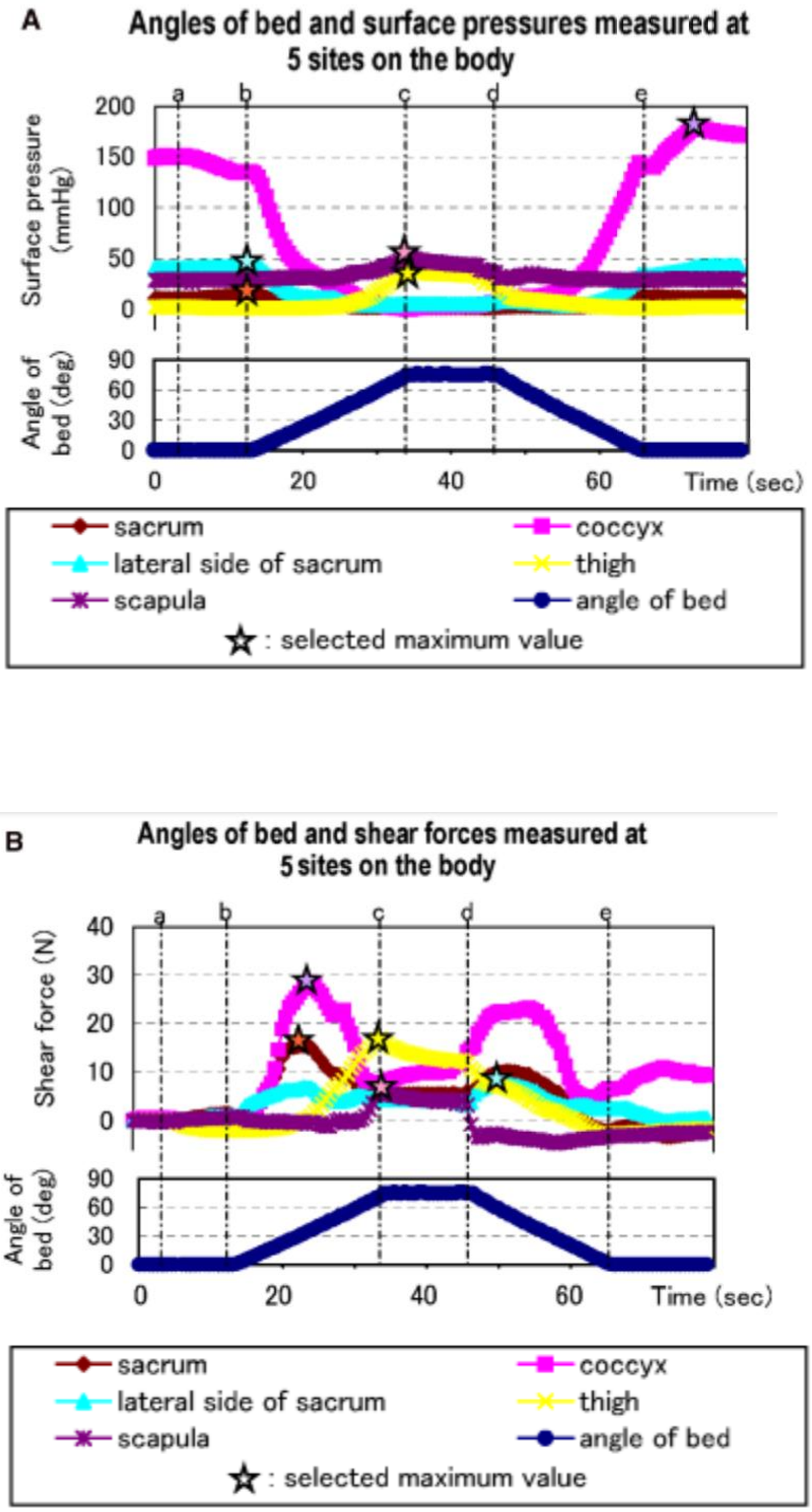


Fig.3.8 The measurement results of contact stress in a previous study [10].

The measurement results of this study (Figure 3.5) and the measurement results of the previous study which the sensor installed in the coccygeal region were similar. There were commonalities in the measured values and change trends of contact pressure and shear stress for both. This was because the shape of the sensor used in previous research was wide, 70 mm × 96 mm, and thick. Therefore, it was thought that the measurement results included measurements of not only the coccygeal region but also the sacral region. Although the trends of changes in contact stress were similar, this study confirmed a non-periodic increase and decrease in shear stress. This is due to the fact that the sampling frequency in this study was higher than in previous studies. The frequency was 10 Hz in this study and 2 Hz in previous studies. The present study captured the release of shear stress due to intermittent body shifts associated with the operation of the backrest of the bed.

When a person lies on a nursing care bed, their posture changes in a complex manner, not only owing to the operation of the backrest, but also owing to the activation of the knee lift-up function. The effect of contact stress also changes in a complicated manner. This study revealed a relationship between shear stress changes due to bed backrest manipulation and body displacement due to bed manipulation.

3.5 Conclusion

In Chapter 3, contact stress was measured of at the frequent sites for pressure injury when operating the backrest of a nursing bed. Thus, for measuring shear stress, an headward stress was exerted on the sacrum as the backrest was operated. The stress on scapula showed a tendency to act footward. The effect of shear stress was confirmed even after the patient returned to the lying position on the backrest. Therefore, residual shear stress may have occurred. It was also suggested that the knee lift-up function, which is activated when the backrest of the bed is operated, may affect changes in contact stress.

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CHAPTER 4. Effect of the knee lift-up function on changes in sacrum contact stress when the backrest of a nursing bed is operated

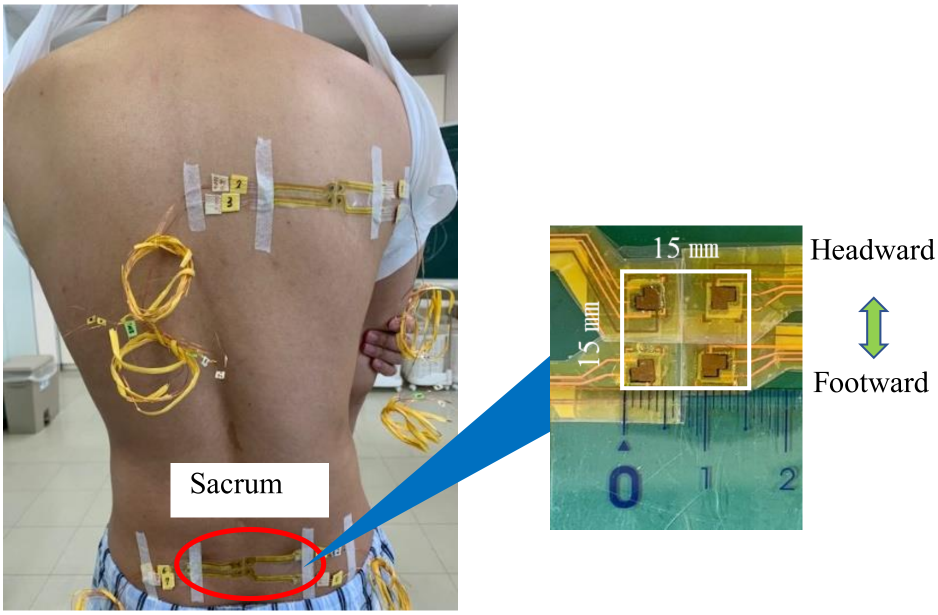
4.1 Introduction

In Chapter 3, an experiment was conducted to measure contact stress on the human body using the home-made sensor [1] created in Chapter 2. Subjects were asked to lie on their backs on a nursing bed, assuming an actual nursing care situation. Then, contact stress was measured at the frequent sites for pressure injury when operating the backrest of a nursing bed. When a person lies supine in bed, pressure injury tends to develop on the occipital tuberosity, scapula, sacrum, and heels [2]. In Chapter 3, sensors were pasted on the skin of the scapula and sacrum. As a result of the contact stress measurements, the following trends were revealed regarding the characteristics of the shear stress. In the sacrum, shear stress showed a tendency to act headward. In the scapula, shear stress showed a tendency to act footward. It was also confirmed that shear stress appeared at measurement points even after the backrest returned to the lying position. This suggests the possibility that shear stress remains on the skin. And, it was suggested that not only the reclining function of the nursing bed but also the knee lift-up function may affect changes in contact stress. In Chapter 4, contact stresses were measured with and without the knee lift-up activated, and the results were compared. The purpose of

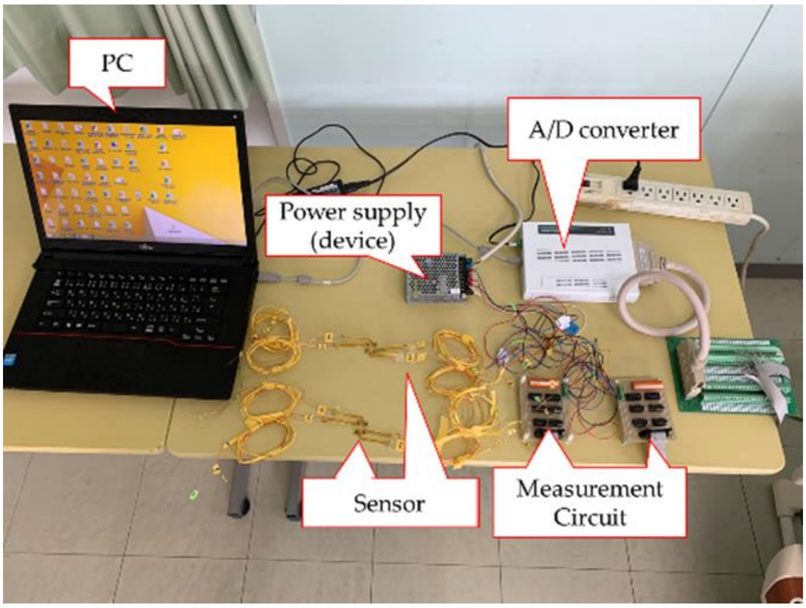
Chapter 4 is to clarify the effect of knee lift-up on changes in contact stress. The focus was on contact stress changes in the sacral region.

4.2 Methods

The subject was a healthy adult male, 174 cm and 65 kg. This experiment was conducted in accordance with the Helsinki Declaration. The subject was given a thorough explanation of the primary purpose and methods of the experiment, orally and in writing, prior to the experiment, and their consent was obtained. The location sacral region was confirmed by touching the skin, and a triaxial stress sensor was pasted on the skin over the bony prominence, as shown in Figure 4.1 (a). Figures 4.1 (b) and (c) show the sensor and measurement system, and Figure 4.1 (d) shows a picture of the measurement experiment.

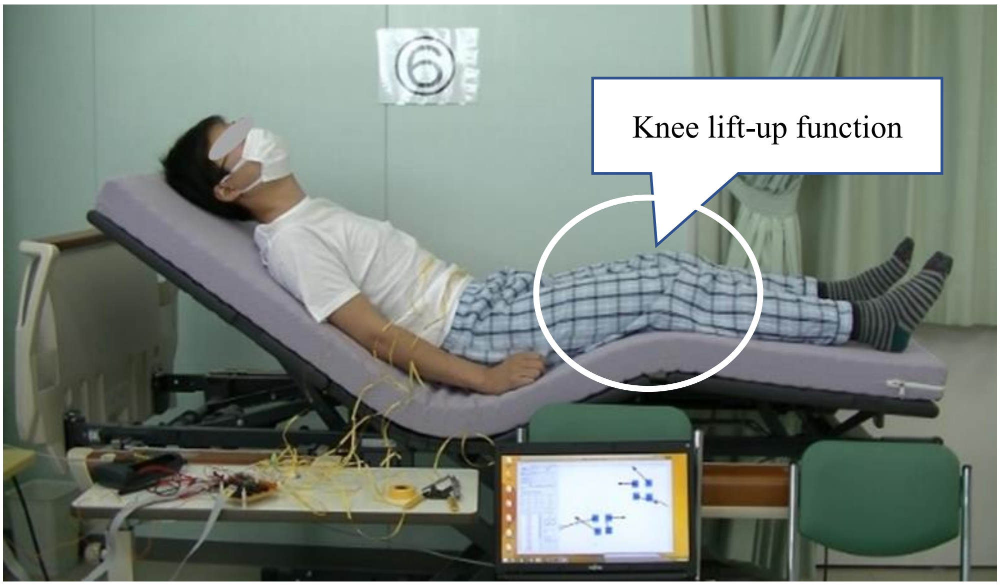


(a) Location of sensor installation (b) Thin 3-axis stress sensor



(c) Measurement systems

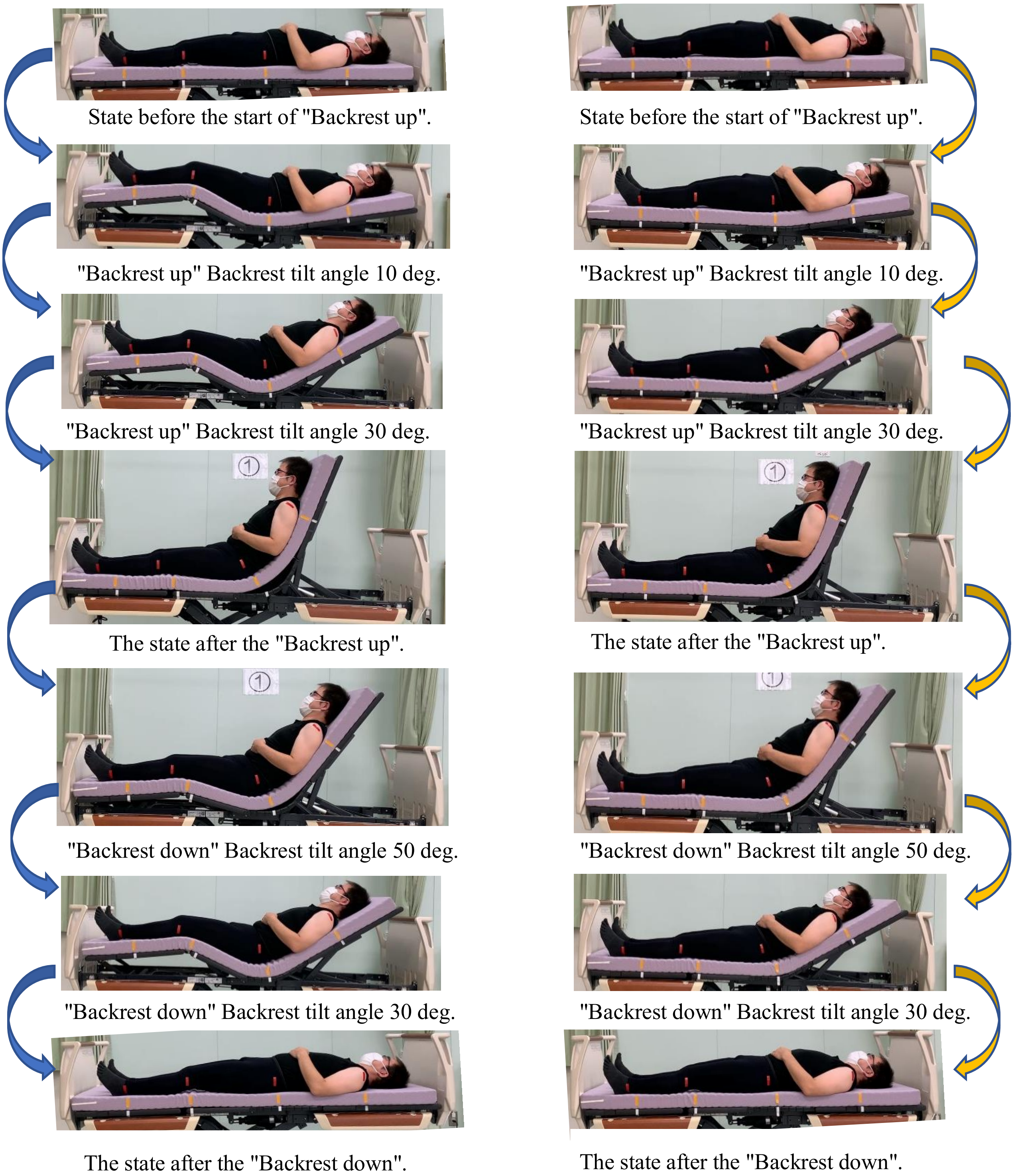
Fig. 4.1 Sensor position and picture of the measurement experiment



(d) Measurement experiment

Fig. 4.1 Sensor position and picture of the measurement experiment

The subject was asked to maintain a supine posture in bed, and the posture of the subject was changed by raising the bed backrest from 0 deg. to a maximum value of 75 deg., “backrest up” and continuously lowering the bed backrest from the maximum value of 75 deg. to 0 deg., “backrest down”. The experiment was conducted three times successively for each condition. Contact stress measurements were conducted with and without the knee lift-up. Figure 4.1 (d) shows how the knee lift-up is activated when the backrest is operated. The knee lift-up is operated in synchronization with the up and down movement of the backrest. The operation or non-operation of the knee lift-up was controlled using the controller attached to the bed. This study focused on the change in vertical shear stress acting on the sacrum when the back of the bed is manipulated. For all measurements, the initial positions of the subject body to the mattress was unified. Before each measurement, the movement from backrest up to backrest down with knee lift-up was repeated twice in succession. Thereafter, the body position of the subject was taken as the initial position at the start of the measurement of contact stress. And, additional experiments were conducted as shown in Figure 4.2. The displacement of the body relative to the mattress was measured when the backrest was operated. As shown in Figure 4.2, markers were putted to four locations on the sides of the subject's body (acromion, lumbar region, knees, and ankles) and at the contacting position on mattress their (side surface) prior to measurement. The displacement of markers putted on the subject to the mattress was recorded by video camera while the bed was being operated. Then, still images were created from the recorded video for every 10 deg. of inclination angle of the backrest. The displacement of the body relative to the mattress was measured. Measurements of body displacement were also conducted with and without the knee lift-up.



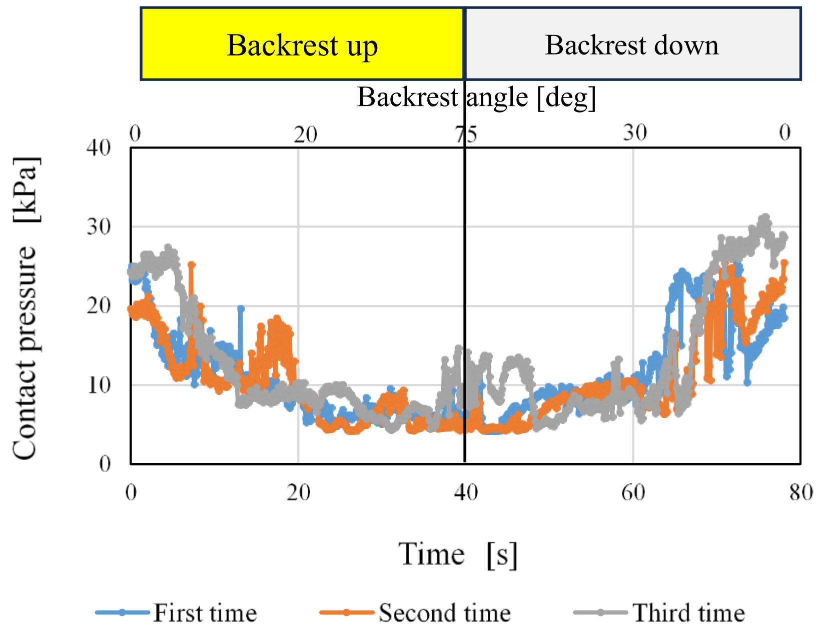
(a) With knee lift-up function (b) Without knee lift-up function

Fig. 4.2 Steps showing the backrest being lowered and raised

4.3 Results

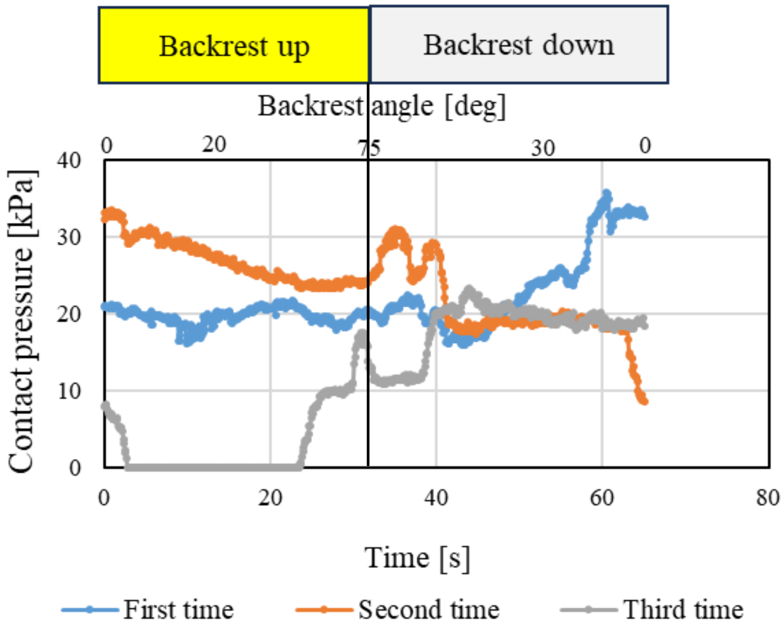
4.3.1 Comparison of contact pressure in the sacrum region with and without knee lift-up

The contact pressure measurement results are shown in Figures 4.3 (a) and (b). In the case with the knee lift-up, the pressure decreased from 25 kPa to 5 kPa as the inclination angle of the backrest increased. Then, when the inclination angle of the backrest decreased, the pressure increased to 30 kPa. A similar trend was confirmed in the three trials. In the case without the knee lift-up, there was no uniformity in the change in contact pressure among the three measurements.



(a) With knee lift-up

Fig. 4.3 Contact pressure of sacrum

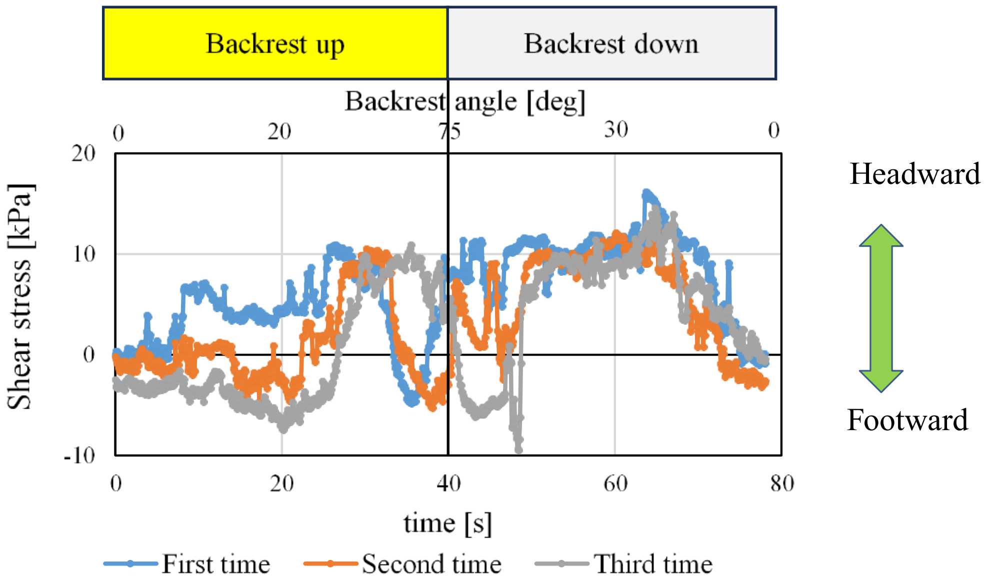


(b) Without knee lift-up

Fig. 4.3 Contact pressure of sacrum

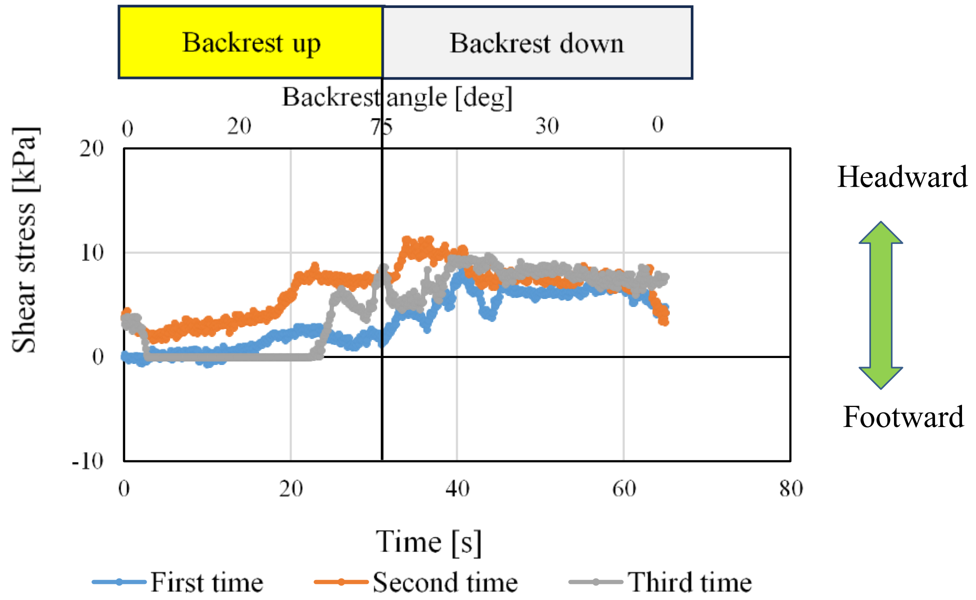
4.3.2 Comparison of shear stress in the sacrum region with and without knee lift-up

The measurement results of vertical shear stress are shown in Figures 4.4 (a) and (b). In the case with the knee lift-up, the headward of shear stress was applied up to a maximum of about 10 kPa as the inclination angle of the backrest increased. When the inclination angle of the backrest decreased, the headward shear stress was maintained up to an inclination angle of around 30 deg., which gradually decreased later. In the case without the knee lift-up, as the inclination angle of the backrest increased, the shear stress of headward direction was increased up to approximately 8 kPa. Even when the inclination angle decreased, the shear stress remained. And when the bed inclination angle reached 0 deg., it did not return to its initial value. At that time, an headward shear stress of 4–8 kPa was acting. When the knee lift-up, intermittent increases and decreases in shear stress were observed. However, this was not observed when the without knee lift-up.



(a) With knee lift-up

Fig. 4.4 Shear stress of sacrum

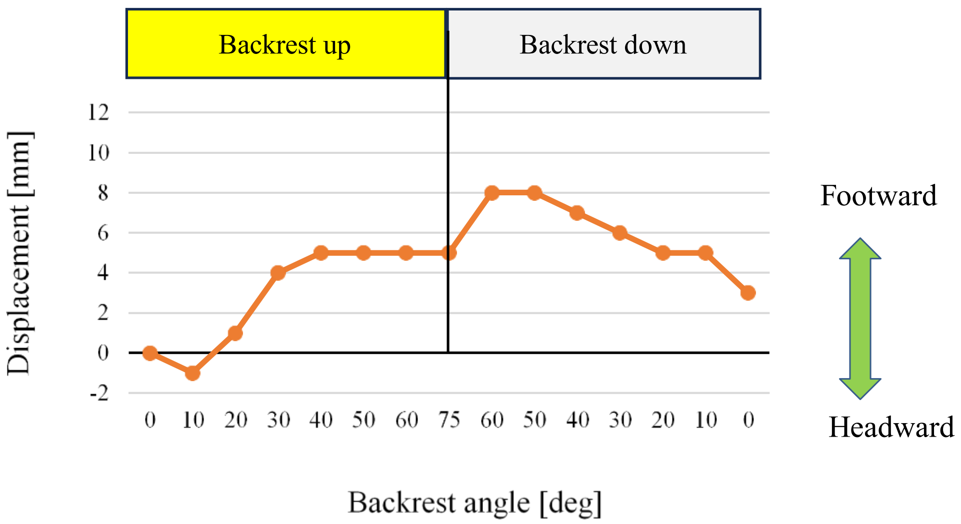


(b) Without knee lift-up

Fig. 4.4 Shear stress of sacrum

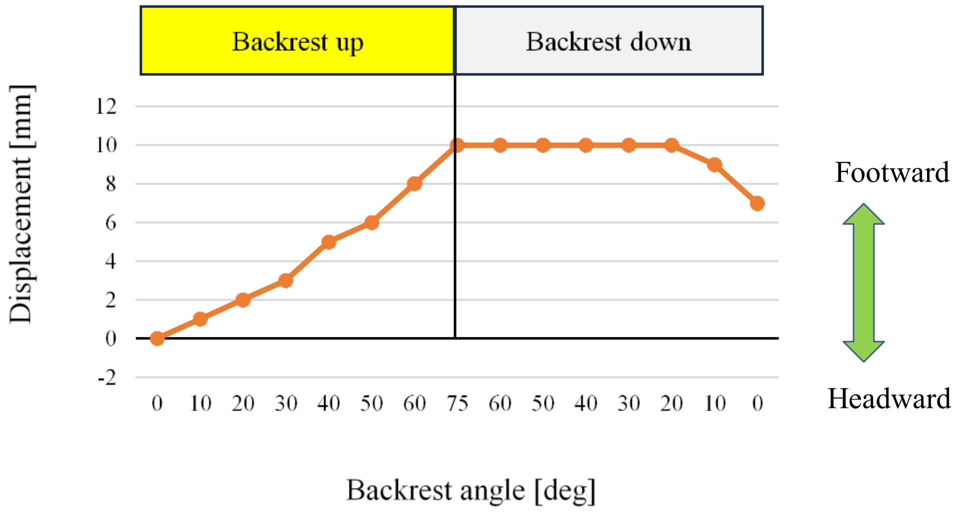
4.3.3 Results of measuring the displacement of lumber when operating the backrest

Figures 4.5 (a) and (b) show the results of measuring the displacement of the lumbar region when the backrest of the bed was operated. When the knee lift-up functioned, the lumbar region shifted footward direction by 5 mm as the inclination angle of the backrest increased. When the inclination angle of the backrest began to decrease, the displacement of the lumbar region increased to 8 mm. When the inclination angle decreased to less than 50 deg., the displacement toward footward direction of the lumbar region gradually decreased. In the case without the knee lift-up, the lumbar region shifted footward direction by 10 mm as the inclination angle of the backrest increased. Even when the inclination angle of the backrest decreased, there was no change in the amount of footward displacement of the lumbar region. Below 20 deg., the displacement toward footward direction of the lumbar region becomes slightly decreased.



(a) With knee lift-up

Fig. 4.5 Displacement measurement results



(b) Without knee lift-up

Fig. 4.5 Displacement measurement results

4.4 Discussion

4.4.1 Contact pressure of sacrum

Let us compare the changes in contact stress applied to the sacrum when operating the backrest of a bed with and without a knee lift-up. Regarding contact pressure, when the knee lift-up was activated, the contact pressure decreased as the inclination angle of the backrest increased. After that, the contact pressure increased as the inclination angle of the backrest decreased. This was thought to be due to the contact area moving from the sacral region to the ischial region and to the sacral region again as the posture of the subject changed from lying to sitting to lying down. When the without knee lift-up, the tendency of change in the contact pressure was different for all three times and was not consistent. Even if the backrest was repeatedly operated, the same tendency of change in contact pressure as in the case with the knee lift-up could not be confirmed. The reason for this is shown in Figure 4.5, and is thought to be because the lumbar region moved significantly footward in one operation of the backrest without the knee lift-up. Through the three backrest operations during stress measurement, the lumbar region continued to displace footward, and this was thought to be because the contact area between the sacral region and the mattress was not constant. Regarding contact pressure that causes pressure injury, Kosiak [3] states that if a pressure of 9.3–13.3 kPa is applied to the skin for 2 h, signs of pressure damage will appear in the tissue. On the other hand, Sakai et al. [4] measured the contact pressure acting on the sacral region of multiple subjects lying on bed and reported that contact stress of 20 kPa or more was applied to some people. In this study, contact pressure of 20 kPa or more was observed in the sacral region when the subject was in a lying position, regardless of the presence or absence of the activation of knee lift-up. Although individual differences seem to have a large effect on the measured values, pressure values comparable to those in previous studies were obtained.

4.4.2 Shear stress of sacrum

The relationship between changes in shear stress caused by manipulating the backrest of the bed or knee lift-up and the displacement of the lumber relative to the mattress is as follows. In the case of the knee lift-up activation, as the inclination angle of the backrest increases, the displacement toward footward direction was observed, as shown in Figure 4.5 (a). Thus, it can be assumed that shear stress of headward direction is applied. However, as shown in Figure 4.4 (a), it was confirmed that the shear stress of headward direction temporarily decreases around 50 deg.–60 deg. at the first time of backrest operation. When measuring the displacement of the lumbar region, there was no downward displacement of the lumbar region when the inclination angle of the backrest was around 50 deg.−60 deg. This study may capture the release of shear stress associated with intermittent lumber displacement caused by backrest motion. A similar phenomenon to the 1st shear stress measurement was confirmed in each the 2nd and 3rd measurements as shown in Figure 4.4 (a), although there were some differences in the timing of occurrence. When the inclination angle of the backrest decreased, the amount of footward displacement of the lumbar region decreased, which is thought to have decreased the headward shear stress. In the case without the knee lift-up, the lumbar region continuously shifted footward as the inclination angle of the backrest increased, as shown in Figure 4.5

(b). Therefore, it is assumed that the shear stress of headward gradually increased, as shown in Figure 4.4 (b). The displacement caused by increasing the inclination angle of the backrest remained even when the inclination angle decreased, as shown in Figure 4.5 (b). Therefore, it is believed that the shear stress was maintained. Furthermore, it was confirmed that when the without knee lift-up, the headward shear stress remained even if the subject returned to the supine position after backrest down. From this, it is thought that for the case without knee lift-up, shear stress is more likely to remain after the subject returns to the lying position, which may induce the development of pressure injury.

4.4.3 Comparison of shear stress in sitting position after "backrest up" operation and in lying position after "backrest down" operation

Let us compare the shear stress state of the subject while sitting between the cases with and without knee lift-up. As a result, greater shear stress was confirmed with the knee lift-up than without the knee lift-up. The reason for this is that for the case without the knee lift-up, the sacrum continuously slips footward during backrest up. Therefore, a friction force equal to the dynamic friction force is generated while sitting position. On the other hand, when the knee lift-up is activated, footward displacement of the sacrum is restrained. It is thought that a large shear stress was measured because static friction force, which is larger than dynamic friction force, acts with releasing intermittently. Let us compare the shear stress state of the subject while lying after backrest operation between with and without knee lift-up. A greater shear stress was confirmed without the knee lift-up than with the knee lift-up. The reason for this is that the downward displacement of the lumber is suppressed by the activation of the knee lift-up function. Therefore, the headward shear stress is decreased. However, without knee lift-up, the downward shift of the lumber remains during backrest down. Therefore, the headward shear stress also remained. The shear stress was confirmed even after the backrest returned to the lying position. This suggested that residual shear stress was occurring. Reger et al. [5] reported that even if the back of the bed returns to its original position, shear stress is applied to human back. However, the details have not been revealed. In this study, it was confirmed that residual shear stress acts significantly when without the knee lift-up, and important findings were obtained from the perspective of preventing pressure injury. The results of this study suggest that the knee lift-up prevents the human body from shifting footward when operating the bed backrest, compared to a case without the knee lift-up. Furthermore, it was found that residual shear stress was less likely to occur when the subject returned to the supine position. These results suggest that the small, thin, and flexible sensor used in this study enabled us to understand in detail the influence of the knee lift-up function on the change in contact stress in the sacrum when operating the backrest of the bed.

4.5 Conclusion

In this study, contact stress was measured with and without the knee lift-up. The effect of backrest manipulation on contact stress change in the sacral region was investigated. As the result regarding the shear stress, there was a common tendency to act headward when the backrest was raised, regardless of the presence or absence of the knee lift-up. When the backrest was down, the shear stress of headward gradually decreased when the knee lift-up was activated. Without the knee lift-up, the headward shear stress generated when the backrest up, tended to remain. Additionally, the shear stress was confirmed even after the backrest returned to the lying position. This suggested the possibility that residual shear stress was occurring.

References

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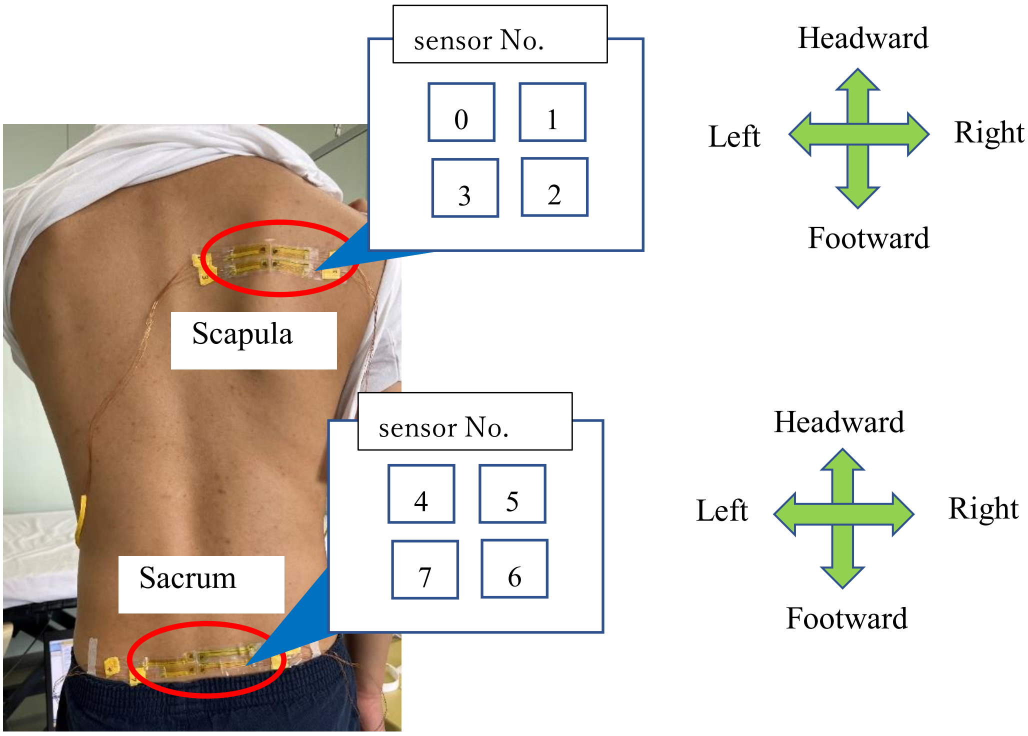
CHAPTER 5. Distribution of residual shear stress at frequent sites of pressure injury after manipulation of nursing bed backrest

5.1 Introduction

When a person lies in bed in the supine position, pressure injuries tend to develop in the occipital tuberosity, scapula, sacrum, and heels [1]. Chapter 4 focused on contact stress changes in the sacral region. The purpose of Chapter 4 was to clarify the effect of knee lift-up on changes in contact stress. The sensor described in Chapter 2 [2] was fabricated and used to measure the contact stress in the sacral region. Regarding shear stress, it tended to act headward when the backrest was raised, regardless of the presence or absence of knee lift-up. During the backrest was down, the shear stress in the headward direction gradually decreased when knee lift-up was activated. In the case without the knee lift-up, the headward shear stress generated when the backrest was up tended not to change. When knee lift-up was activated, footward displacement of the sacrum relative to the mattress was suppressed, which also reduces the residual shear stress after the backrest is returned. However, residual shear stress did not completely disappear. Chapter 5 focuses on the residual shear stress when the subject is in a supine position after the backrest is down. Four sensors were pasted on the skin of subject's scapula and sacrum respectively. The distribution of residual shear stress is clarified with and without knee lift-up.

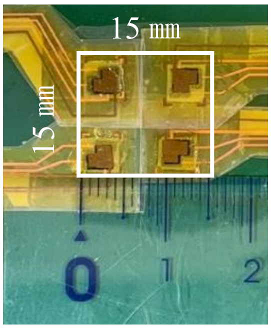
5.2 Methods

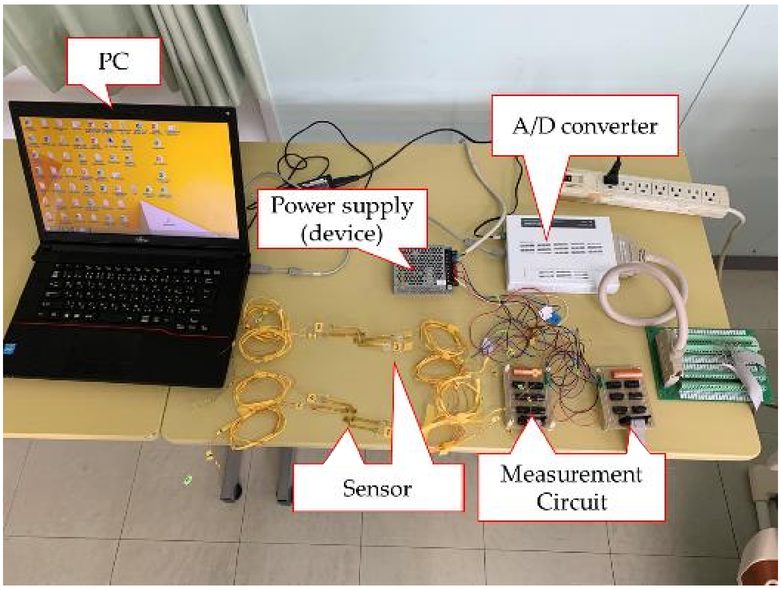
The subject was a healthy 24 years old male with height 173 cm and weight 65 kg. This study was approved by the Research Ethics Committee of the Graduate School of Science and Technology, Hirosaki University, Japan. The reception number was 23-001. Approval was also obtained from the Research Ethics Committee of Hirosaki University of Health and Welfare Junior College. The reception number was 22-04. This experiment was conducted in accordance with the Helsinki Declaration. Prior to the experiment, the subject was given a thorough explanation of the primary purpose and methods of the experiment, both orally and in writing, and informed consent was obtained. The sacral and scapular regions were confirmed by touching the skin. The triaxial stress sensors were attached to the skin over the bony prominence, as shown in Figure 5.1 (a). Four sensors were installed on the scapula, sensor No. 0-3, and four on the sacrum, sensor No. 4-7. In the subject's back, it was possible to measure the shear stress acting in the vertical and lateral directions. Figures 5.1 (b) and (c) show the sensor and measurement system, respectively, and Figure 5.1 (d) shows the scene of the measurement experiment. A commercially available bed (Paramount Bed) was used. A cotton sheet was placed on the mattress of the bed. The subject wore a T-shirt on the upper body and shorts on the lower body. The subject was asked to maintain a supine posture in bed, and the posture of the subject was changed by raising the bed backrest from 0 deg. to a maximum value of 75 deg. “backrest up”; the bed backrest was continuously lowered from the maximum value of 75 deg. to 0 deg. “backrest down.” The sampling frequency was 10 Hz.



(a) Location of sensor installation

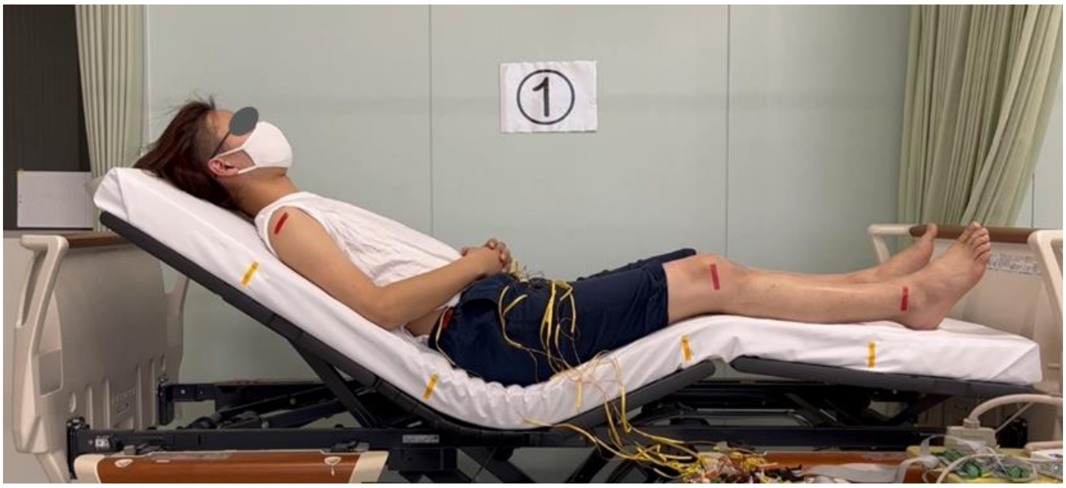
Fig. 5.1 Sensor position and scene of measurement experiment





(b) Thin 3-axis stress sensor

(c) Measurement systems



(d) Scene of measurement experiment

Fig. 5.1 Sensor position and scene of measurement experiment

In each measurement, the backrest was moved up and down three times in a row without any rest intervals. Contact stress measurements were conducted three times with and without knee lift-up. Chapter 5 focuses on the initial measurement results. Figure 5.1 (d) shows how the knee lift-up was activated when operating the backrest. The knee lift-up was performed in synchronization with the upward and downward movements of the backrest. The operation of the knee lift-up was controlled using a controller attached to the bed. For all measurements, the initial positions of the subject's body to the mattress were standardized. Before each measurement, the backrest supporting the subject was moved up and down twice in succession with knee lift-up. Then, the body position of the subject was taken as the initial position in the measurement of contact stress. Concurrent with the contact stress measurement, the displacement of the body was measured relative to the mattress when the backrest was in operation. As shown in Figure 5.2, markers were placed at four locations on the sides of the subject's body (acromion, lumbar, knees, and ankles) and at their contact position on the mattress (side surface). The displacement of each marker attached on the subject, relative to the mattress, was recorded using a video camera while the back of the bed was manipulated. Still frames were created from the recorded videos, at every 10-deg. inclination angle of the backrest. The displacement of the body relative to the mattress was measured. Body displacement measurements were also conducted with and without knee lift-up.

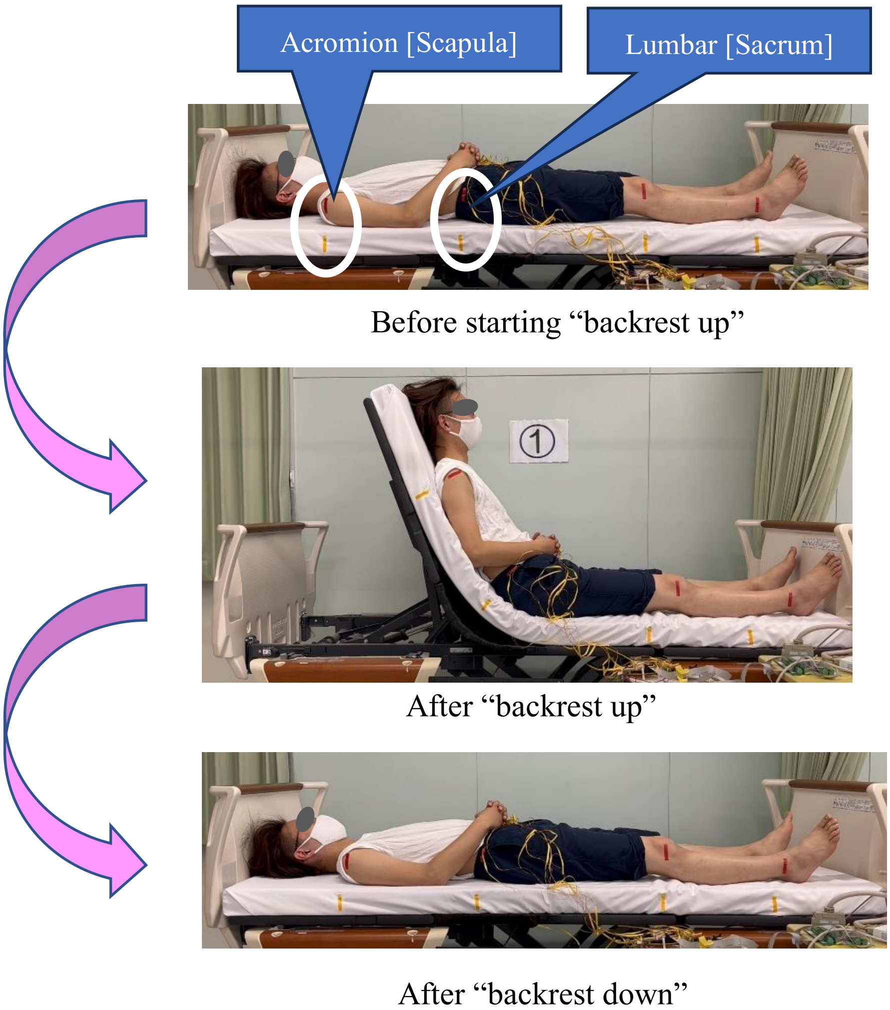
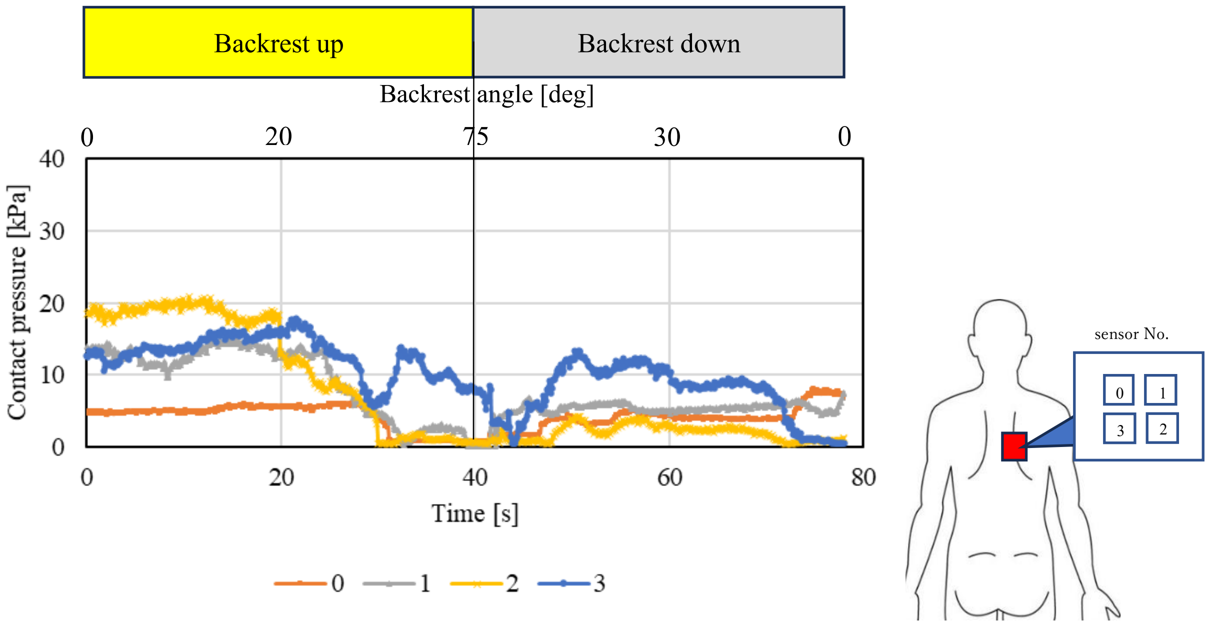


Fig. 5.2 Measurement of the displacement between the bed and body with backrest in operation

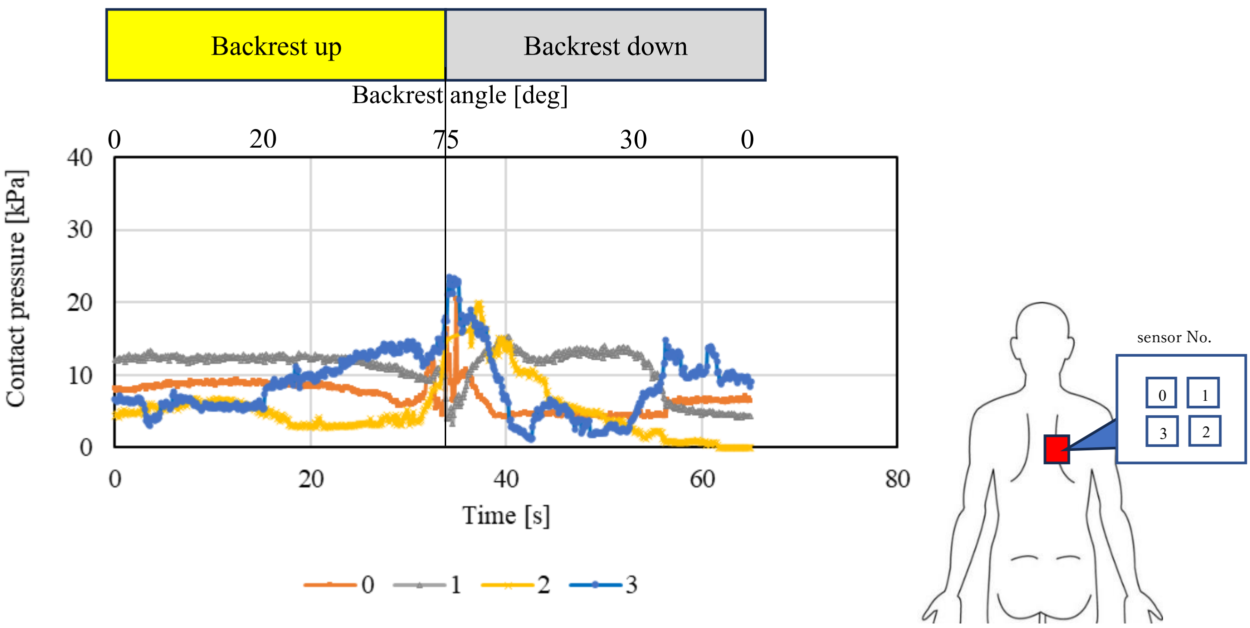
5.3 Results

5.3.1 Comparison of contact pressure in the scapula region with and without knee lift-up

The results of contact pressure measurement are shown in Figures 5.3 (a) and (b). In the case with the knee lift-up, the contact pressure increased at Sensors 1 and 3 at an inclination angle of 10–20 deg. when the backrest up. Thereafter, when the inclination angle of the backrest increased, the contact pressures of all sensors tended to decrease. When the backrest down, it was confirmed that the contact pressures at all sensors tended to increase with decrease in tilt angle. In the case without the knee lift-up, the contact pressures of Sensors 0, 2, and 3 increased as the backrest up. The contact pressure decreased as the backrest was lowered.



(a) With knee lift-up

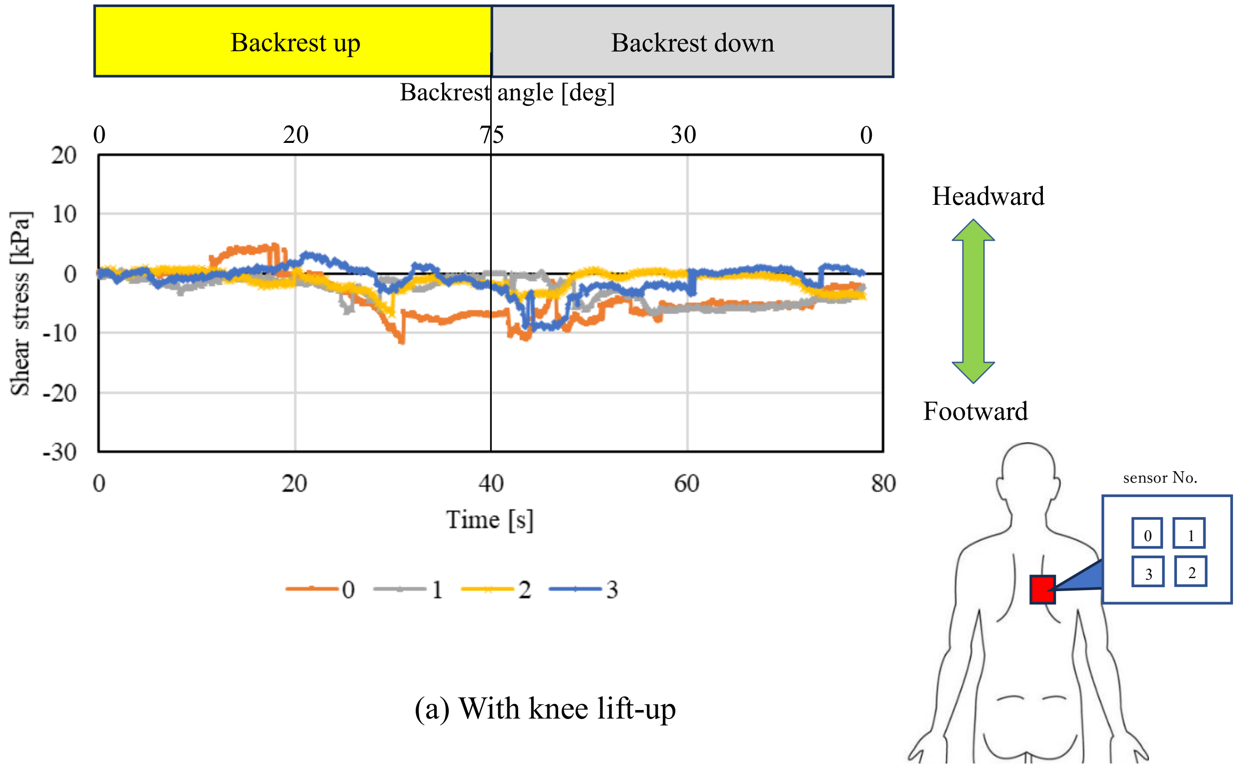


(b) Without knee lift-up

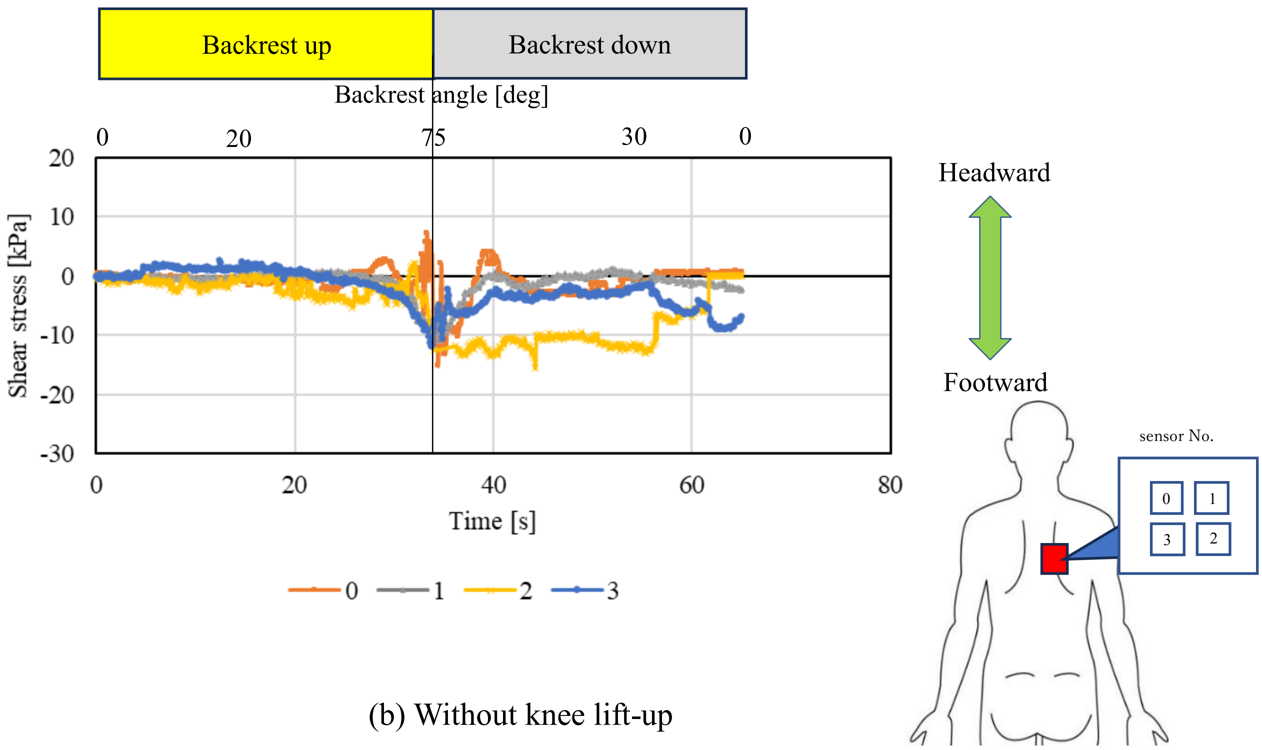
Fig.5.3 Contact pressure of scapula

5.3.2 Comparison of shear stress in the scapula region with and without knee lift-up

The measurement results of the vertical shear stress are shown in Figures 5.4 (a) and (b). The measurement results of the shear stress in the lateral direction are shown in Figures 5.5 (a) and (b). Vertical shear stress tended to act in the footward direction when the backrest up independent of the knee lift-up. As the backrest up, the footward shear stress increased. As the backrest down, the footward shear stress decreased. This trend was observed both with and without knee lift-up. In the case with the knee lift-up, the footward shear stress increased by up to 12 kPa. In the case without the knee lift-up, the footward shear stress increased by up to 15 kPa. The trends in shear stress in the lateral direction were as follows: In the case with the knee lift-up, shear stress at Sensor 3 increased up to 7 kPa in the left direction when the backrest up. Subsequently, the shear stress in the left direction decreased with an increase in the backrest inclination angle. When the backrest down, the shear stress in the left direction at Sensor 1 increased up to 8 kPa. Subsequently, the shear stress in the left direction decreased with decreasing backrest inclination angle. In the case without the knee lift-up, the shear stress in the left direction tended to increase up to 12 kPa immediately after backrest up was completed. When the backrest down, the shear stress in the left direction tended to decrease.

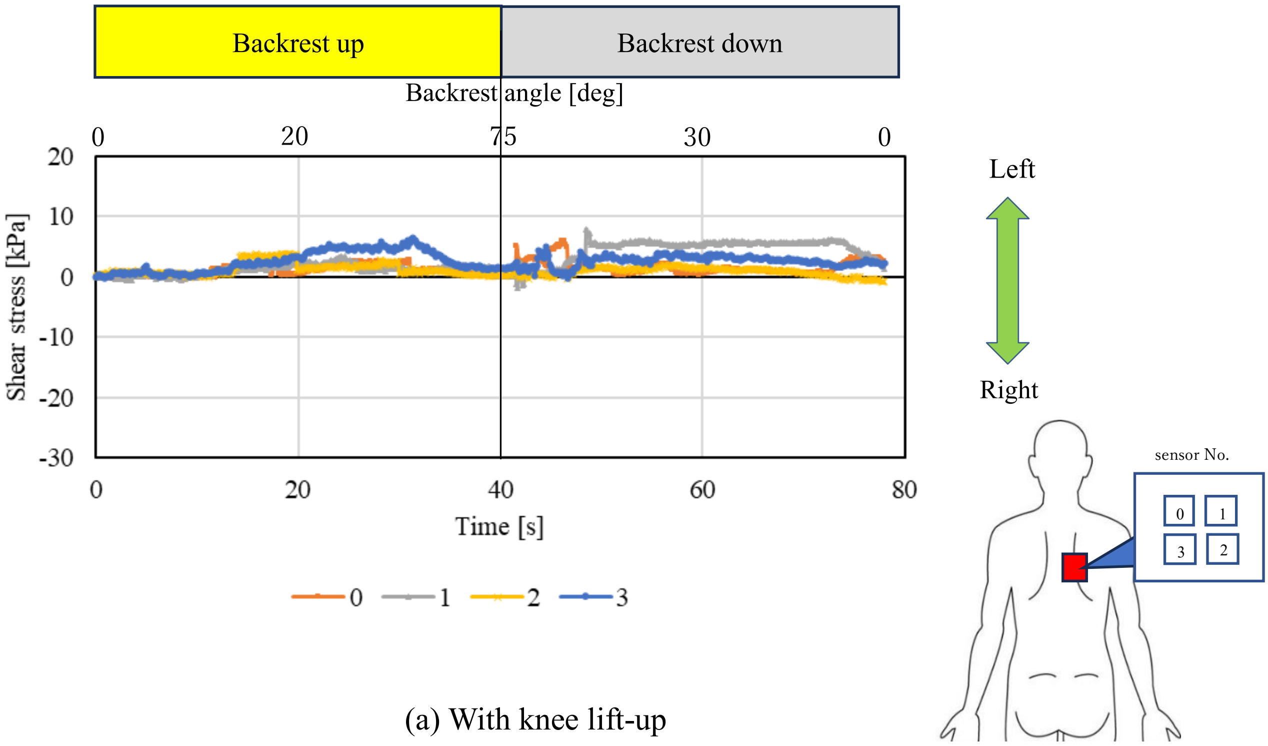


(a) With knee lift-up

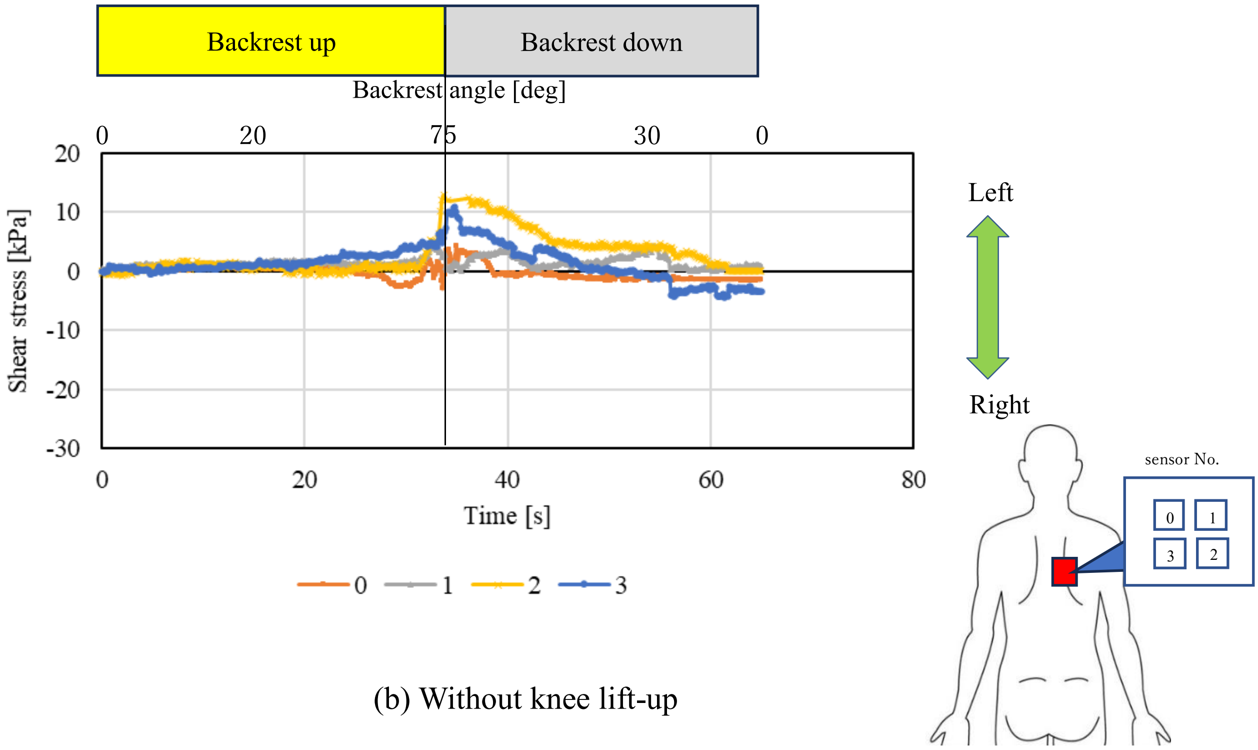


(b) Without knee lift-up

Fig.5.4 Shear stress of scapula in vertical direction



(a) With knee lift-up



(b) Without knee lift-up

Fig.5.5 Shear stress of scapula in lateral direction

5.3.3 Distribution of residual shear stress acting on the scapula

Chapter 5 focuses on the distribution of shear stress in the vertical direction when the subject is in a sitting position after backrest up and residual shear stress after backrest down. The results were compared with and without knee lift-up. Figure 5.6 shows the distribution of shear stress when the subject is in a sitting position. Figure 5.7 shows the distribution of the residual shear stress when the subject returns to the supine position after the backrest down. The maximum value in the sitting position was 9.1 kPa without knee lift-up and 7.1 kPa with knee lift-up. The average shear stress at the four points was 6.6 kPa without knee lift-up and 2.8 kPa with knee lift-up. Footward shear stress was distributed in the measurement area of the scapula. This trend was observed both with and without knee lift-up. The maximum values in the supine position were 6.6 kPa without knee lift-up and 3.9 kPa with knee lift-up. The average residual shear stress at the four points was 2.0 kPa regardless of whether the knee was lifted. Footward shear stress was distributed in the measurement area of the scapula.

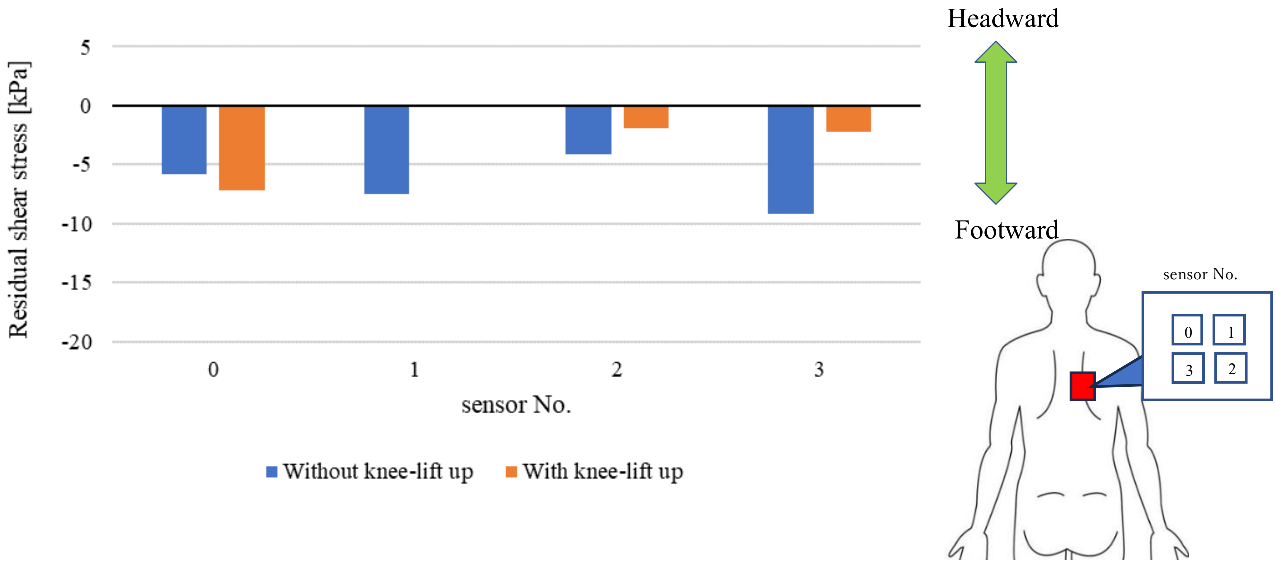


Fig. 5.6 Distribution of shear stress when sitting [Scapula: vertical direction]

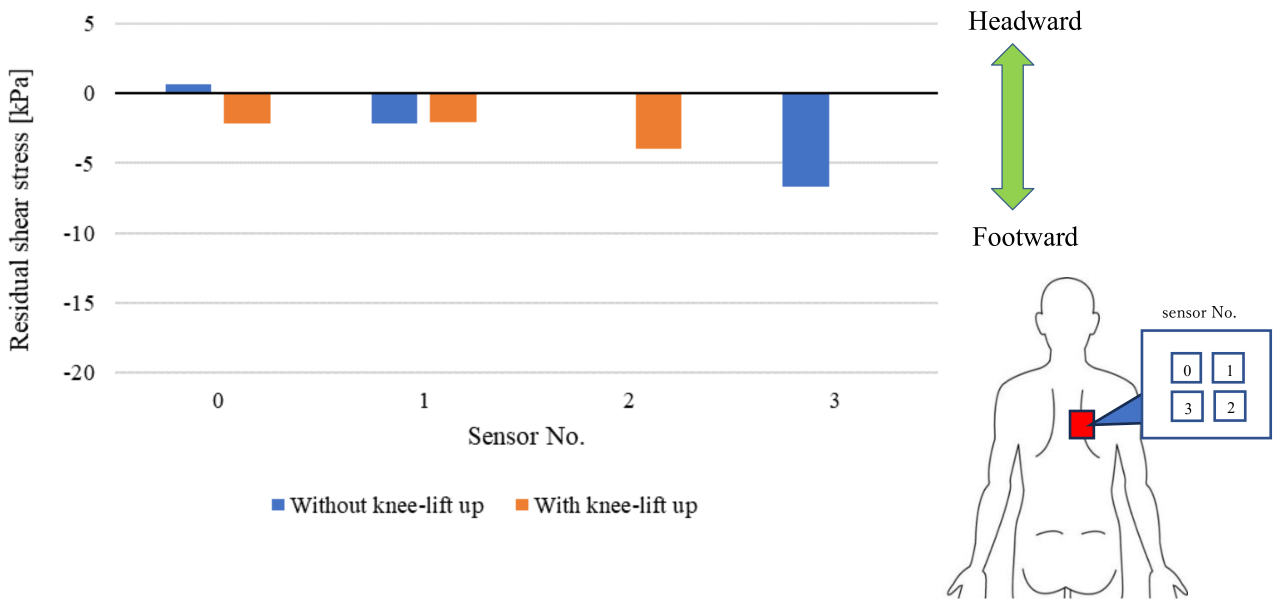
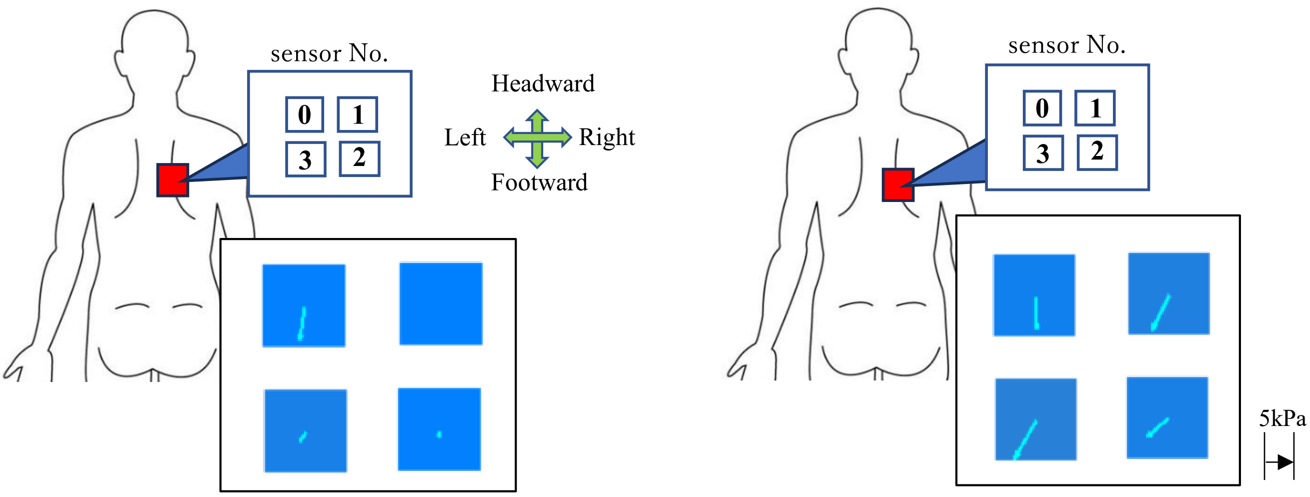


Fig. 5.7 Distribution of residual shear stress when supine position

[Scapula: vertical direction]

Based on these measurement results, the distribution of shear stress was visualized using an application software that indicates the direction and the amount of the measured shear stress with arrows. Figure 5.8 shows the distribution of shear stress acting on the scapula when the subject is in a seated position. Figure 5.9 shows the distribution of shear stress acting on the scapula after completely lowering the backrest with the subject lying in supine position. Comparing the results with and without knee lift-up, the shear stress acting on the scapula without knee lift-up tended to be greater. The arrow indicates the shear stress in vector, whose the direction and its length show the direction and the magnitude of the shear stress. In the indication of the direction and size of the arrows, the measurement results of not only vertical shear stress but also lateral shear stress.



With knee lift-up

Without knee lift-up

Fig. 5.8 Distribution of shear stress on the scapula when sitting [vector display]

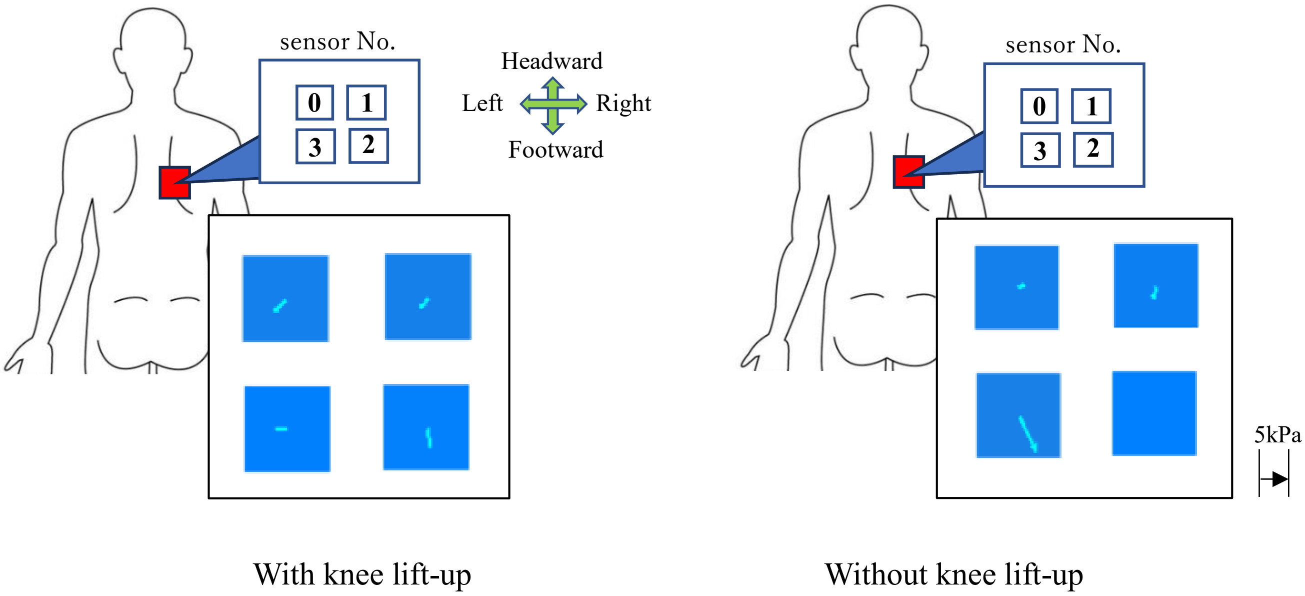
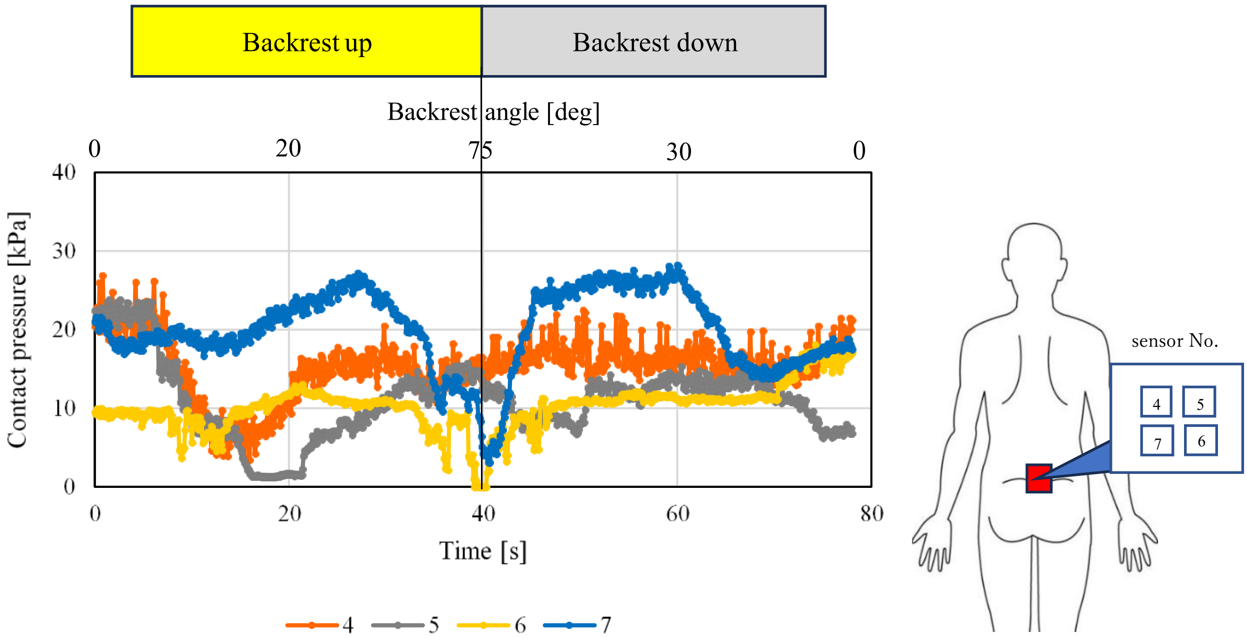


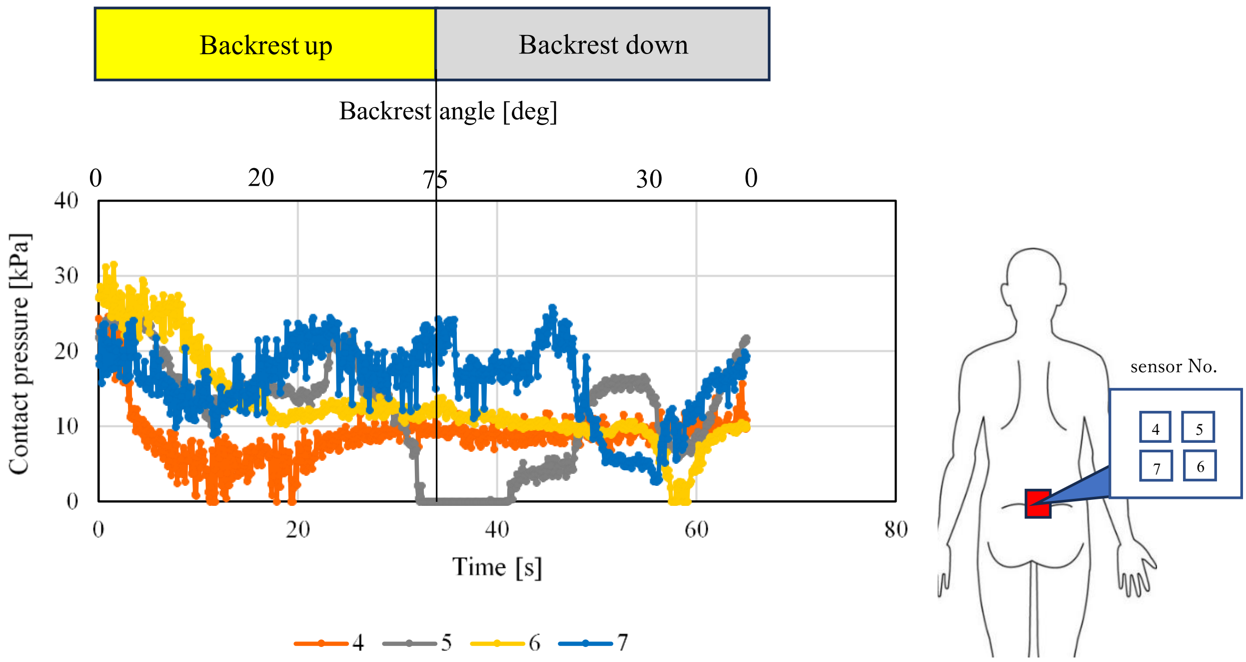
Fig. 5.9 Distribution of residual shear stress in the scapula [vector display]

5.3.4 Comparison of contact pressure in the sacrum region with and without knee lift-up

The results of contact pressure measurement are shown in Figures 5.10 (a) and (b). The focus will be on Sensors 6 and 7, where a particularly characteristic change was observed. In the case with the knee lift-up, Sensor 6 showed a decrease in contact pressure at around 75 deg. of backrest up. A similar trend was observed with Sensor 7. However, in the case of Sensors 6 and 7 without knee lift-up, a decrease in contact pressure was not observed at around 75 deg. of backrest up.



(a) With knee lift-up

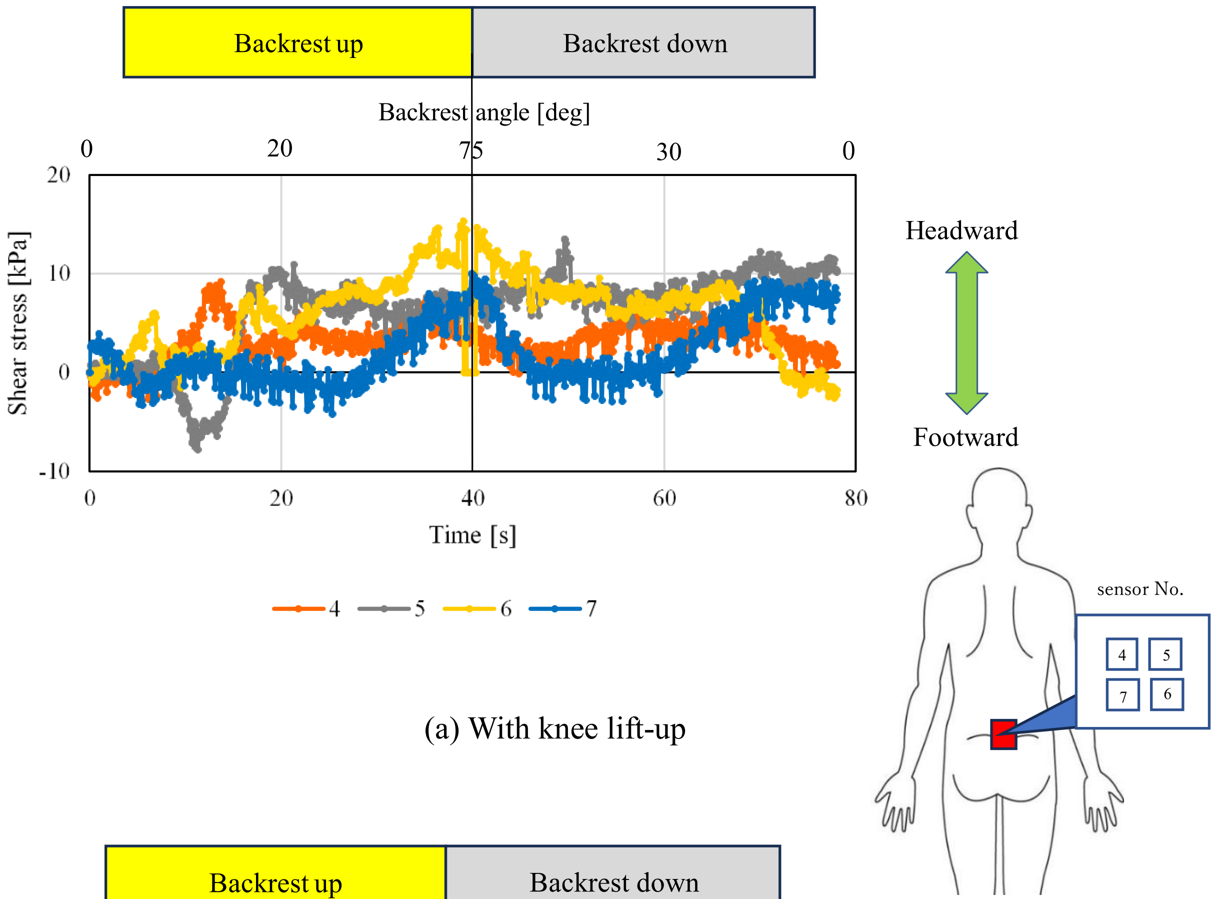


(b) Without knee lift-up

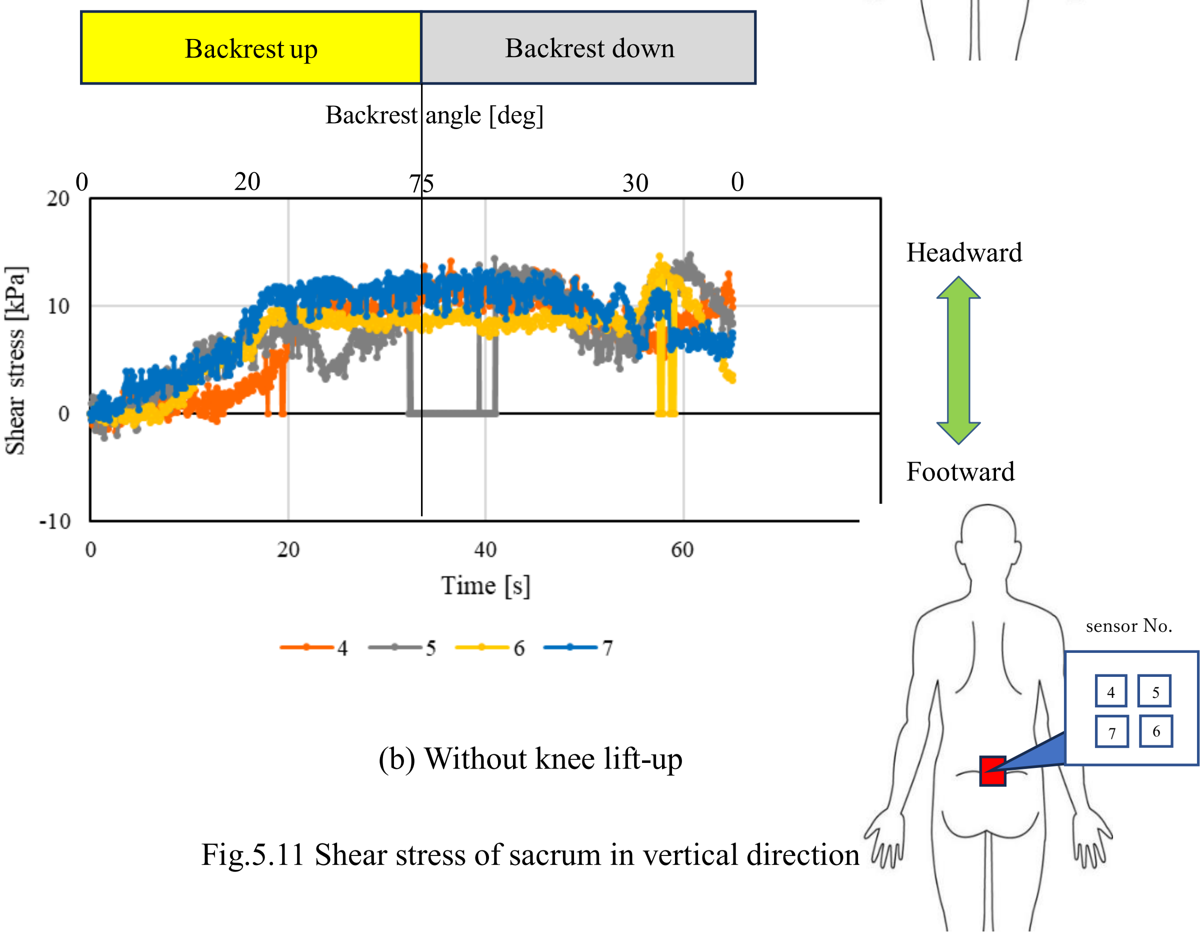
Fig.5.10 Contact pressure of sacrum

5.3.5 Comparison of shear stress in the sacrum region with and without knee lift-up

The measurement results of the vertical shear stress are shown in Figures 5.11 (a) and (b). The measurement results of the shear stress in the lateral direction are shown in Figures 5.12 (a) and (b). The trends in shear stress in the vertical direction were as follows: In the case with the knee lift-up, headward shear stress was increased during backrest up. Sensor 6 showed a maximum of approximately 15 kPa. In the backrest down, the headward shear stress at Sensors 4 and 6 decreased after 20 deg. In the case without the knee lift-up, headward shear stress was increased during backrest up. Sensor 4 showed a maximum of approximately 13 kPa. In the backrest down, headward shear stress was maintained at all sensors. At Sensor 4, the residual shear stress was about 10 kPa. The trends in shear stress in the lateral direction were as follows: In the case of knee lift-up, the shear stress in the left direction of Sensor 7 increased a maximum of approximately 7 kPa at until 20 deg. in the backrest up. At that time, the shear stress in the right direction of Sensor 5 increased a maximum of approximately 8 kPa. No characteristic changes were observed in the case of backrest down. In the case without the knee lift-up, the shear stress in the left direction of Sensors 4 and 7 increased approximately 10 kPa at until 30 deg. in the backrest up. In the backrest down, the shear stress in the left direction of Sensors 4 and 7 decreased gradually.

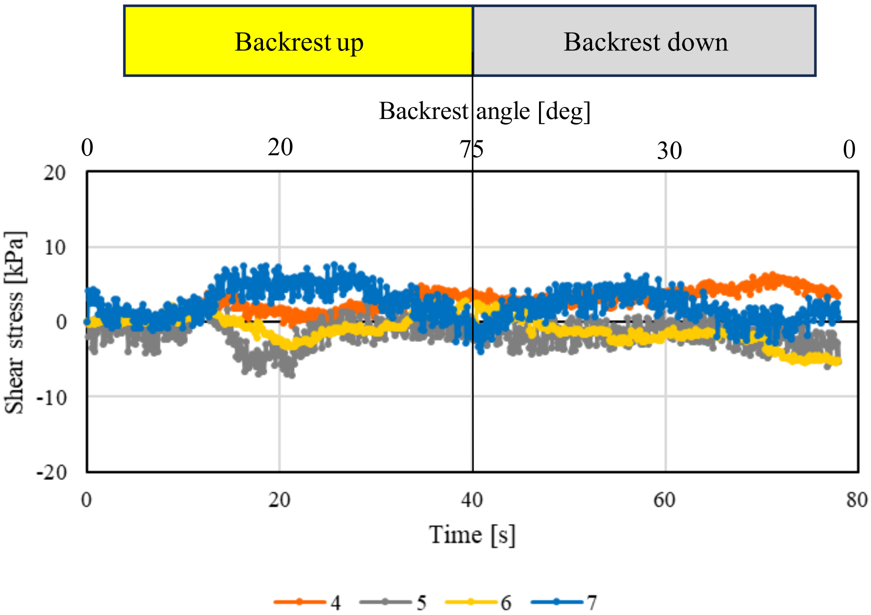


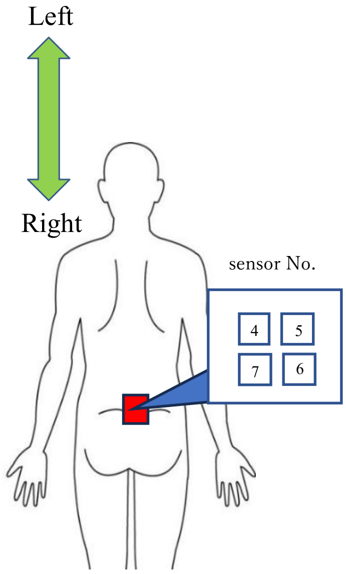
(a) With knee lift-up



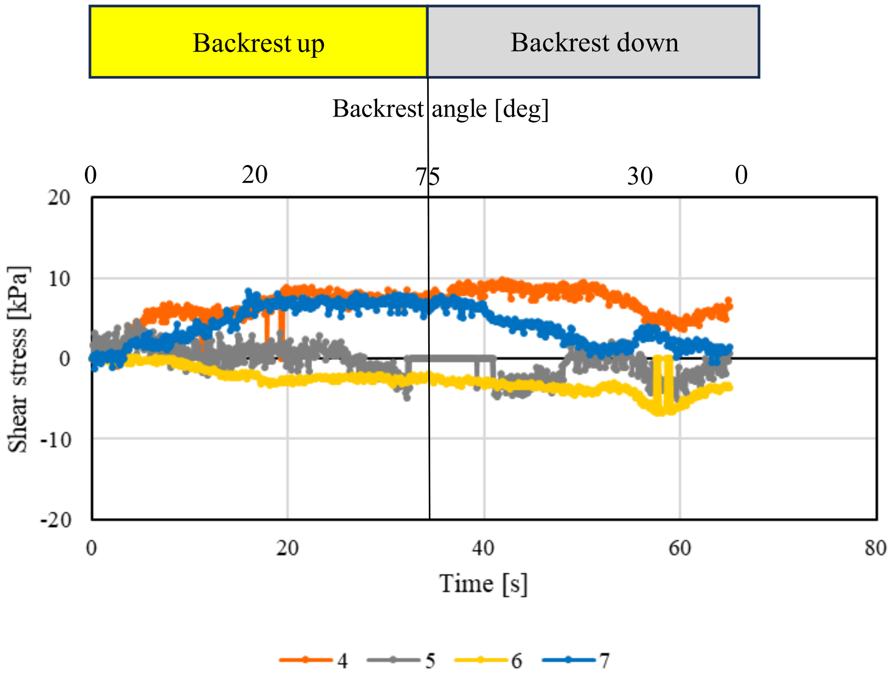
(b) Without knee lift-up

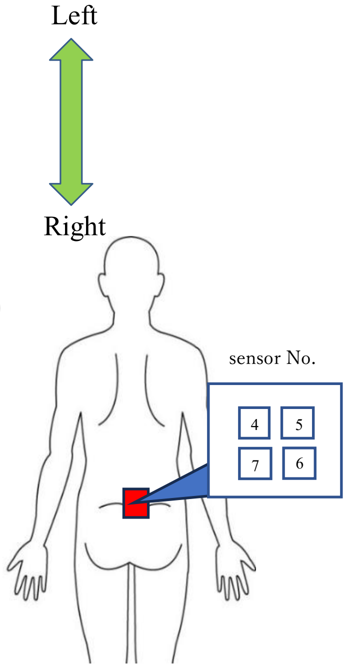
Fig.5.11 Shear stress of sacrum in vertical direction





(a) With knee lift-up



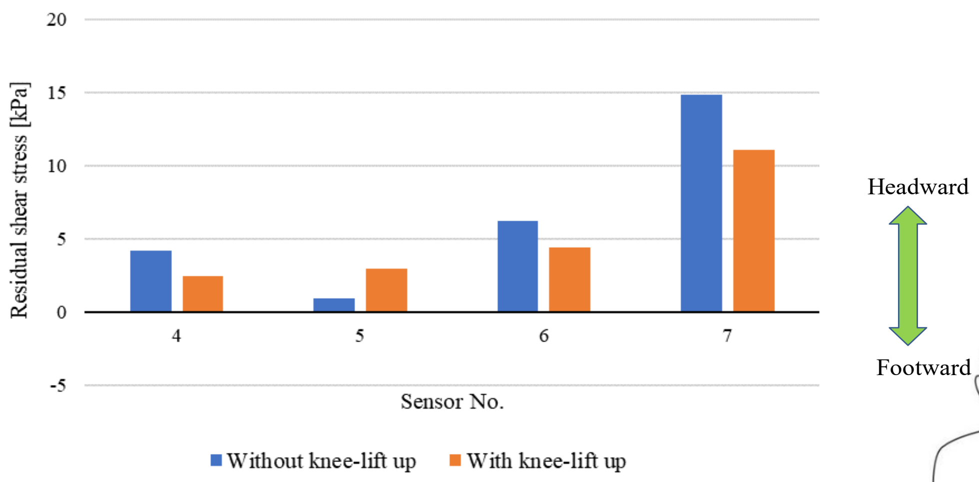


(b) Without knee lift-up

Fig.5.12 Shear stress of sacrum in lateral direction

5.3.6 Distribution of residual shear stress acting on the sacrum

Figure 5.13 shows the distribution of shear stress when the subject is in a sitting position, backrest angle 75 deg. Figure 5.14 shows the distribution of the residual shear stress when the subject returns to the supine position after the backrest operation. The maximum value in the sitting position was 14.8 kPa without knee lift-up and 11.0 kPa with knee lift-up. The average shear stress at the four measurement points was 6.5 kPa without knee lift-up and 2.8 kPa with knee lift-up. Headward shear stress was distributed in the measurement area of the sacrum. The maximum value in the supine position was 13.1 kPa without knee lift-up and 3.5 kPa with knee lift-up. The average residual shear stress at the four measurement points was 8.7 kPa without knee lift-up and 2.2 kPa with knee lift-up. Headward shear stress was distributed in the measurement area of the sacrum. In comparisons with and without knee lift-up, all sensors had a higher residual shear stress without knee lift-up than that with knee lift-up.



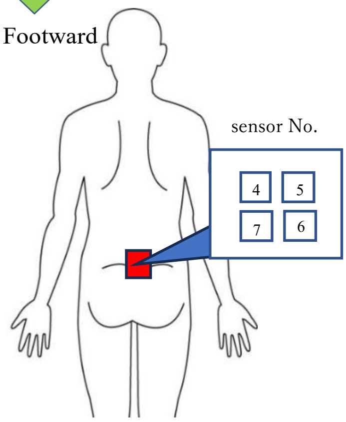
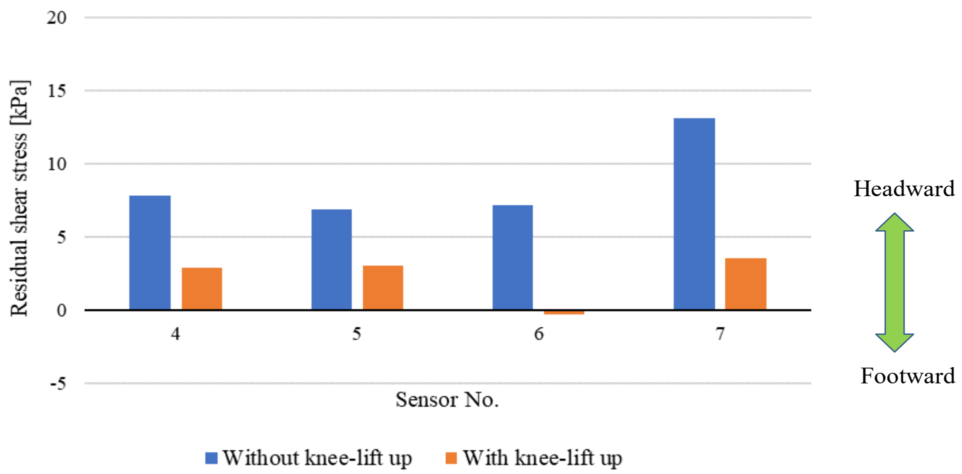


Fig. 5.13 Distribution of shear stress when sitting

[Sacrum: vertical direction]



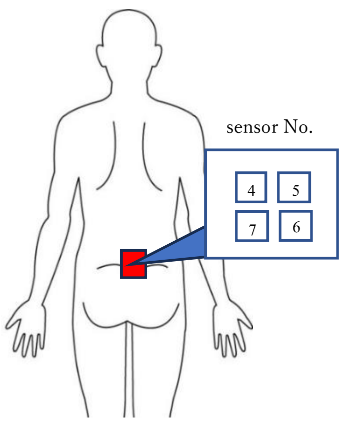


Fig. 5.14 Distribution of residual shear stress when supine position

[Sacrum: vertical direction]

Figure 5.15 shows the distribution of the shear stress acting on the sacrum when the subject is in a seated position. Figure 5.16 shows the distribution of shear stress acting on the sacrum after completely lowering the backrest, with the subject lying in supine position. Comparing the results with and without knee lift-up, the shear stress acting on the sacrum without knee lift-up tended to be greater.

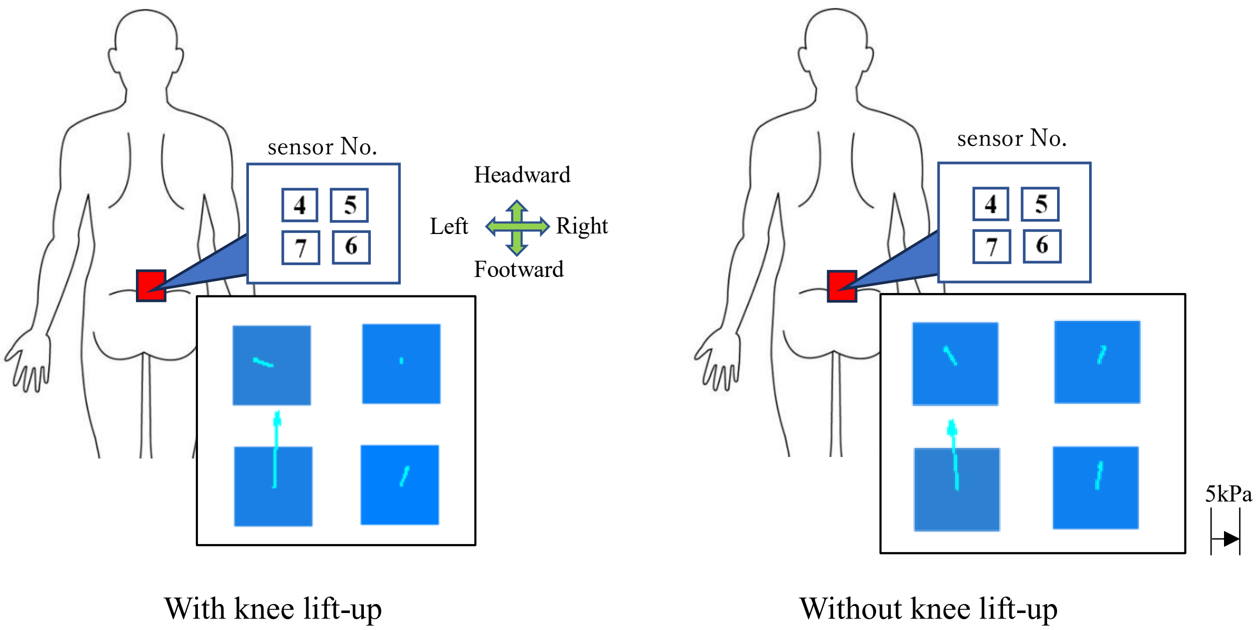


Fig. 5.15 Distribution of shear stress on the sacrum when sitting [vector display]

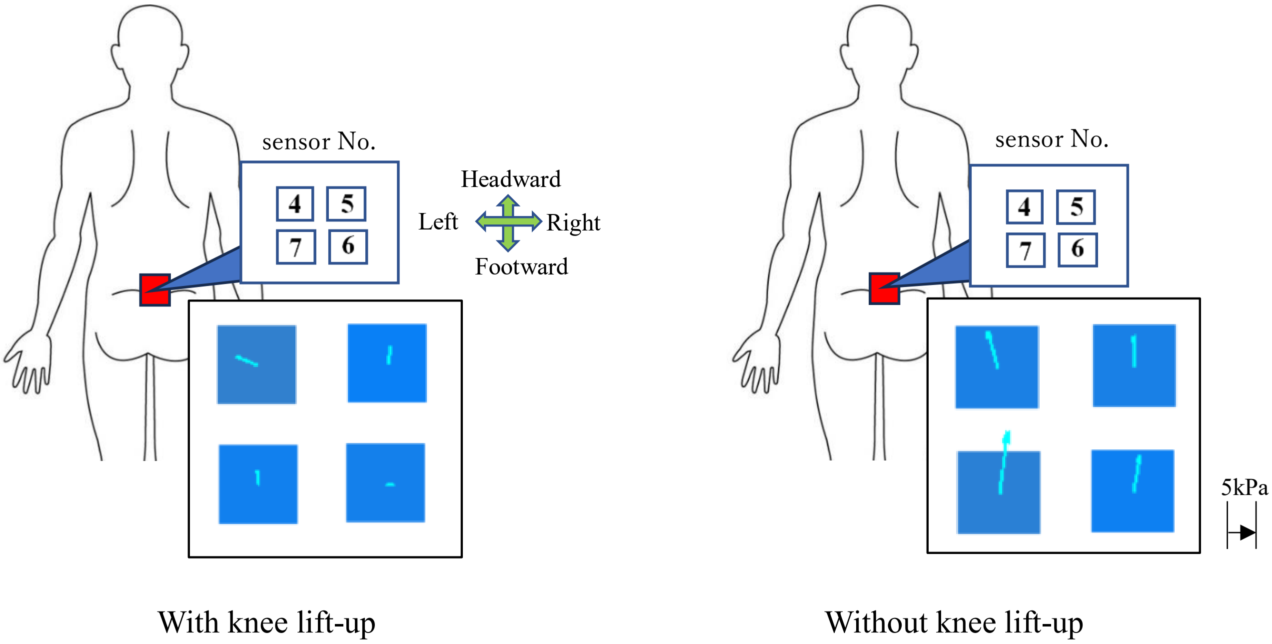
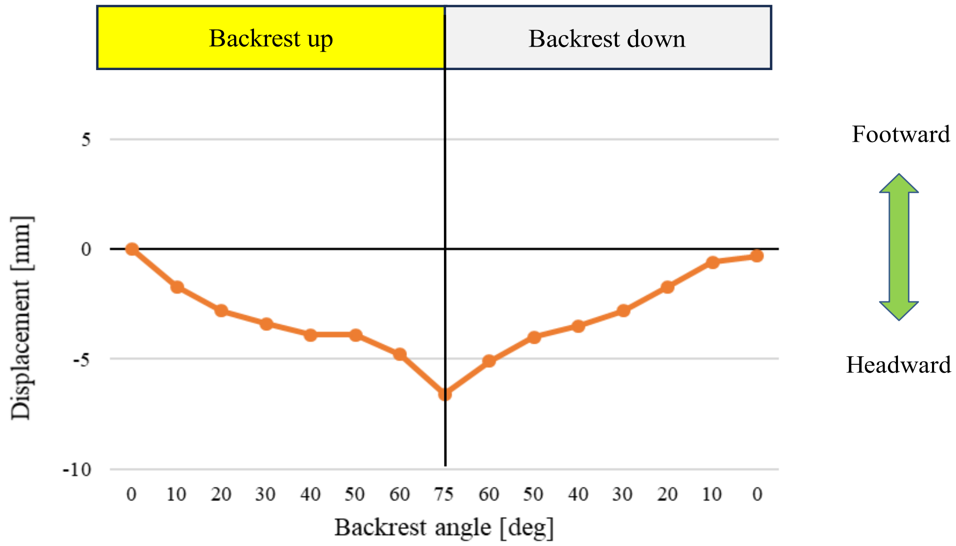


Fig. 5.16 Distribution of residual shear stress in the sacrum [vector display]

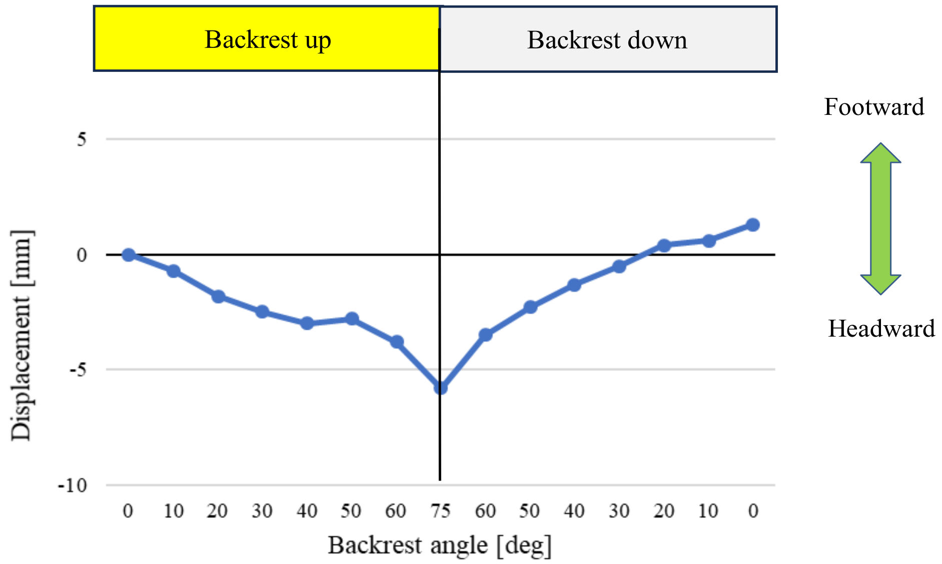
5.3.7 Results of measuring the displacement of the body when operating the backrest

Figures 5.17 and 5.18 show the measured displacements of the acromion and lumbar when the backrest of the bed is in operation with and without knee lift-up. The headward displacement of the acromion relative to the mattress increased with the inclination angle of the backrest. This trend was observed both with and without knee lift-up. In the case with the knee lift-up, the maximum deviation was 6.6 mm. Without knee lift-up, the maximum deviation was 5.8 mm. As the inclination angle of the backrest decreased, the headward shift also decreased. In the case with the knee lift-up, when the backrest returned to its original position, the deviation almost returned to its initial value.

In the case without the knee lift-up, body displacement shifted footward by 1.2 mm.



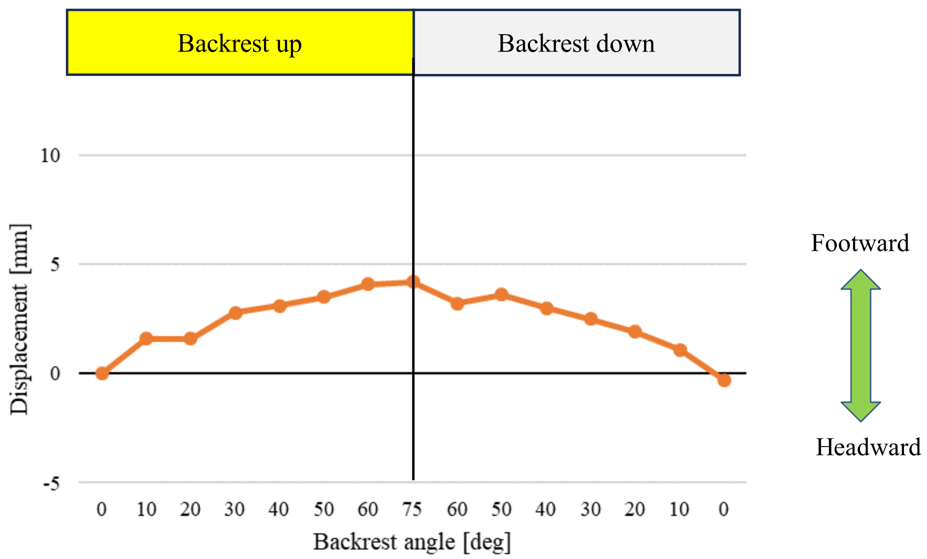
(a) With knee lift-up



(b) Without knee lift-up

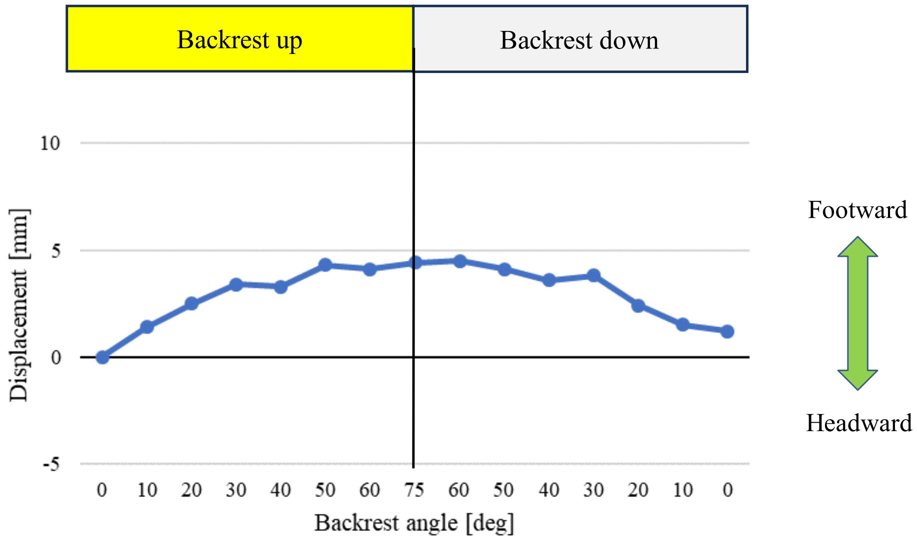
Fig. 5.17 Measurement results of acromion deviation

The footward displacement of the lumbar relative to the mattress increased with the inclination angle of the backrest, regardless of knee lift-up. In the case with the knee lift-up, the maximum deviation was 4.2 mm. Without knee lift-up, the maximum deviation was 4.4 mm. As the inclination angle of the backrest decreased, the footward shift of the lumbar also decreased. In the case with the knee lift-up, when the backrest returned to its original position, the deviation almost returned to its initial value. In the case without the knee lift-up, the lumbar still shifted footward by 1.2 mm.



(a) With knee lift-up

Fig. 5.18 Measurement results of lumbar deviation



(b) Without knee lift-up

Fig. 5.18 Measurement results of lumbar deviation

5.4 Discussion

5.4.1 Contact pressure on scapula

In the case with the knee lift-up, the contact pressure at Sensors 1 and 3 increased at an inclination angle of 10 deg.–20 deg. when the backrest up. When the backrest was down, the contact pressure at multiple sensors increased at an inclination angle of 70 deg.–50 deg. In confirming the changes in the postures of subject on video, the subject's upper bodies were found to have changed to a folded state when the knee lift-up was activated. It is thought that this caused the area around the scapula to be pressed against the backrest, increasing the contact pressure. In the case without the knee lift-up, the contact pressures of Sensors 0, 2, and 3 increased when the backrest was finally raised. This is attributed to the fact that the subject's upper body is pushed forward by the backrest during the process of the posture changing from lying to sitting, which increases the contact between the scapula and backrest. Comparing the results with and without knee lift-up, it was found that the timing of the increase in contact pressure was different.

5.4.2 Shear stress on scapula

Regarding the measurement of shear stress, it had the following features: As the backrest up, the footward shear stress increased. As the inclination angle of the backrest increases, the subject's scapula moves headward relative to the mattress, leading to a footward shear stress. This trend was observed both with and without knee lift-up. As the backrest down, the footward shear stress decreased. The amount of headward shift of the scapula becomes small when the inclination angle of the backrest decreases. Thus, footward shear stress also decreases. This trend was observed both with and without knee lift-up. As for the lateral shear stress, it tended to act in the left direction. This trend was observed both with and without knee lift-up. This suggests that the scapular may have shifted to the right when the mattress and scapular were in close contact.

5.4.3 Contact pressure on sacrum

In the case with the knee lift-up, Sensor 6 showed a decrease in contact pressure around inclination angle 75 deg. of backrest. The similar trend was observed with Sensor 7. This is because the contacting region between the mattress and sacrum moved when the subject's posture changed from lying down to sitting up and back to lying down. However, in the case without the knee lift-up, a decrease in contact pressure of Sensors 6 and 7 was not observed around 75 deg. of backrest. Even if the sacrum has shifted footward during the process of backrest up, the sacrum may have remained in contact with the mattress.

5.4.4 Shear stress on sacrum

The tendency of shear stress in the vertical direction is as follows: In the case with the knee lift-up, the lumber shifts footward with the backrest up, causing headward shear stress. In the backrest down, the headward shear stress at Sensors 4 and 6 decreased after 20 deg. This is because the knee lift-up reduces the amount of footward slippage. As a result, the headward shear stress decreased. These results follow the same trends as those of Chapter 4. In addition, the measurement results of Sensor 6 in measuring sacral shear stress with knee lift-up, shown in Figure 5.11(a), are similar to the results of sacral shear stress measurements in a previous study by Mimura et al. [3]. Figure 5.19 shows the measurement results of previous research. In the case without the knee lift-up, the lumber shifts footward with the backrest up, leading to headward shear stress. When the backrest down, the knee lift-up was not operational. Even when the backrest returned to its original position, the footward deviation of the lumber did not return to its initial value. Therefore, the headward shear stress also persisted. The tendency of shear stress in the lateral direction is as follows: In the case with the knee lift-up, the shear stress at Sensor 7 tended to act in the left direction at approximately 20 deg. to backrest up. At that time, the shear stress at Sensor 5 tended to act in the right direction. In the case without the knee lift-up, from approximately 10 deg. of backrest up, shear stress in the left direction of Sensors 4 and 7 increased. At that time, the shear stress at Sensor 6 tended to act in the right direction. This suggests that the shear stress acts outward when the mattress and sacrum area were in close contact.

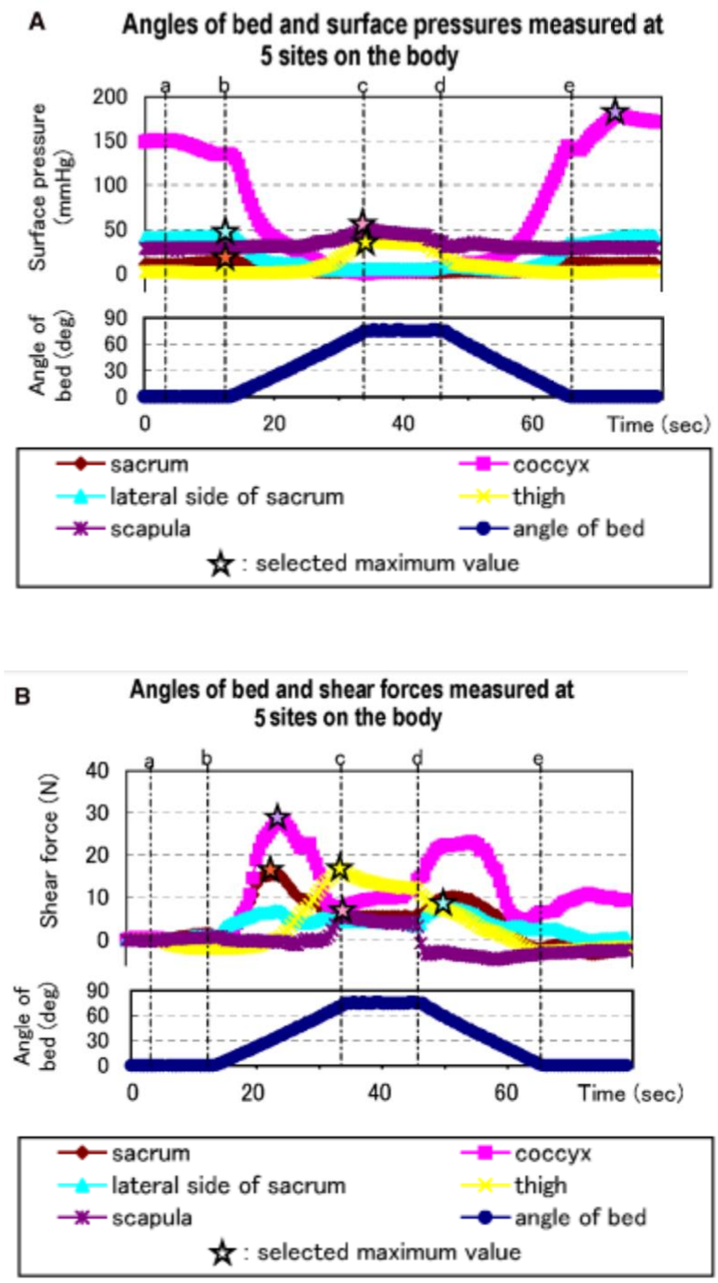


Fig. 5.19 Measurement results of contact stress in a previous study [3].

5.4.5 Distribution of residual shear stress

Measurement experiments confirmed that residual shear stress remained in the scapula and sacrum. In particular, there was a characteristic trend in residual shear stresses in the sacrum. As shown in Figure 14, when comparing the distribution of the residual shear stress with and without knee lift-up, the value was higher without knee lift-up. The difference is remarkable. Based on these facts, knee lift-up is useful as outlined below: Knee lift-ups help prevent the body from shifting when operating the bed backrest. This is also thought to reduce the occurrence of residual shear stress. However, the residual shear stress does not completely disappear. In nursing care settings, shear stress may remain in patient areas where pressure injury is most likely to occur after the bed's backrest is adjusted. Therefore, measures are required to reduce the contact stress that occurs after operating the backrest of the bed. This is an important point in pressure injury prevention measures.

Next, the residual shear stresses acting on the scapula in Figure 5.7 are compared with the residual shear stresses acting on the sacrum in Figure 5.14. Multiple sensors show larger values in the sacrum. Previous studies [4-6] have pointed out that the sacral region is the area where pressure injuries are most likely to develop. The results of this study also suggest that the sacral region is susceptible to residual shear stress and is at high risk of developing pressure injuries. Reger et al. [7] suggested that even if the backrest of the bed returns to its original position, shear stress is applied to the back of the subject. However, the details have not been revealed. In a previous study [3] that used sensors with a large measurement area, the distribution of the residual shear stress was not examined in detail. However, the sensing system described in Section 2 [2], makes it possible to capture the distribution of the residual shear stress. In addition, by using an application software, researchers can successfully visualize the distribution of the residual shear stress acting on areas where pressure injury is likely to occur.

5.5 Conclusion

The trends in residual shear stress acting on the scapula and sacrum are not the same, and indeed they turned out to be different. The distribution of residual shear stress in the scapula had the following characteristics: Footward shear stress was distributed in the measurement area of the scapula. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the scapula without knee lift-up tended to be greater. The distribution of residual shear stress in the sacrum had the following characteristics: Headward shear stress was distributed in the measurement area of the sacrum. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the sacrum without knee lift-up tended to be greater. These results suggest that the knee lift-up function may reduce residual shear stress. In a previous study using sensors on a large measurement area, the distribution of the residual shear stress was not examined in detail. However, contact stress measurements using small, thin, flexible sensors, makes it possible to capture the distribution of the residual shear stress. In addition, by using an application software, researchers can successfully visualize the distribution of the residual shear stress acting on areas where pressure injury is likely to occur.

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CHAPTER 6 Conclusions and Prospects

The measurement of contact stress on the human body has been reported using soft but thick sensors with a large measurement point area inserted into the contact interface. A thick pressure sensitive layer may disturb the contact interface. Furthermore, if the area of sensing point is large, the measurement may be affected by the unevenness of the contact surface. Therefore, the evaluation accuracy is likely to be insufficient. Flexible and very thin to measure the contact stress acting locally, including the projection of the bone of the human body, a sensor having small area of the sensing point was needed. The purpose of this study is to develop a small, thin, and flexible 3-axis stress sensor to investigate pressure injury, and to measure the contact stress acting on subjects' areas where frequent sites of pressure injury when operating the backrest of a nursing care bed.

Chapter 1 presented the background and purpose. Chapter 2 presented the structure of the developed sensor and the measurement system for measuring contact stress that acts locally on bone protrusions of the human body. In this study, a tactile-sensing system using the small, thin, flexible sensor developed by Sasagawa et al. was improved. This system can measure the contact pressure and biaxial shear stress. However, the adhesion between the upper and lower electrodes was insufficient, resulting in a lack of stability during low-stress measurements. To solve this problem, when overlapping the upper and lower electrodes, a 20 μm double-sided tape was used as an adhesive layer to strengthen adhesion, thereby ensuring stability during low-stress measurements. The shape of the electrodes was also improved. The measurement area of the previous sensor was 7.5 mm x 7.5 mm. The improved sensor had a measurement area of 3.2 mm × 3.2 mm, enabling further miniaturization. In addition, the surface of the sensor that came into contact with clothing was coated with an ultra-soft gel (5 mm× 5 mm in plane size, approximately 70 μm in thickness), which is a new procedure. This brings the sensor surface closer to the frictional state of human skin. The improved sensor was calibrated and it was found to show the appropriate relationships between output voltage and contact pressure as well as shear stress, even in the low-stress range of less than 1 kPa. The thickness of the measuring part of the improved sensor was 82 μm. Therefore, measurements using the sensor were almost unaffected by the thickness of the sensor.

Chapter 3 presented the measurement results of contact stress on the human body using the improved sensor. Chapter 3 focused on the contact stress of the subject's scapula and sacrum. As a result of the contact stress measurements, the following trends were revealed regarding the characteristics of the shear stress. In the sacrum, shear stress showed a tendency to act headward. In the scapula, shear stress showed a tendency to act footward. It was also confirmed that shear stress appeared at measurement points even after the backrest returned to the lying position. This suggests the possibility that shear stress remains on the skin. And, it was suggested that not only the reclining function of the nursing bed but also the knee lift-up function may affect changes in contact stress.

In Chapter 4, how the knee lift-up of a nursing bed affected changes in contact stress on the back of the human body was investigated. The contact stress of the sacrum was measured when knee lift-up activated and not activated, and the measurement results ware compared. Regarding the measurement of shear stress, it had the following features: When the backrest up, the headward shear stress increased. This trend was observed both with and without knee lift-up. During the backrest going down, the shear stress of headward gradually decreased when the knee lift-up was activated. However, the shear stress did not decrease when the knee lift-up was not activated. Moreover, it did not vanish when the subjects returned to the supine position. These results suggest that there is a high possibility that shear stress remains after operating backrest when the without knee lift-up.

Chapter 5 focused on the distribution of residual shear stress when the subject returned in a supine position after lowering the backrest. Four sensors were pasted on the skin of the subject's scapula and sacrum, respectively. The distribution of the residual shear stress was clarified with and without knee lift-up. The trends of residual shear stress acting on the scapula and sacrum were different. Footward shear stress was distributed in the measurement area of the scapula. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the scapula without knee lift-up tended to be greater than with knee lift-up. On the other hand, headward shear stress was distributed in the measurement area of the sacrum. This trend was observed both with and without knee lift-up. Comparing the results with and without knee lift-up, the shear stress acting on the sacrum without knee lift-up tended to be greater than with knee lift-up. These results suggest that the knee lift-up function may reduce residual shear stress. In a previous study using sensors with a large measurement area, the distribution of the residual shear stress was not examined in detail. However, using the sensing system described in Chapter 2, the distribution of the residual shear stress could be captured. In addition, by using an application software, the distribution of the residual shear stress acting on areas where pressure injury is likely to occur could be successfully visualized.

The results of this study can be used to improve and develop welfare equipment to prevent the occurrence and deterioration of pressure injuries. Clarifying the actual status of contact stress that causes pressure injury is useful for a detailed investigation on the mechanism of pressure injury development. Furthermore, the contact and residual shear stresses acting on the human body were visualized as the backrest of the nursing bed was operated. This study will serve as a reference for considering effective nursing care methods that decrease contact pressure and shear stress, which are factors that cause pressure injuries in bedridden individuals. A limitation of this study is that the subjects were limited to healthy adult males. Future studies should by the developed triaxial stress sensors clarify the contact stress status for various body types.

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