Development of Rubber-Based Flexible Sensor Sheet for Care-Related Apparatus

Shijie GUO*, Yo KATO, Hiroaki ITO and Toshiharu MUKAI

With a record-low birthrate and rapidly-growing elderly population, Japan faces a severe demographic challenge compounded by a chronic lack of nursing-care staff. High-function welfare apparatuses are attracting attention as effective tools to reduce the burden of caregivers and to compensate for the lack of nursing care staff. Related research and development have been widely conducted, and as a result, the necessity of flexible tactile sensors as human-machine interfaces is increasing. We have developed a smart rubber tactile sensor sheet made entirely of rubber, to achieve a soft and easy contact with humans. The sensor sheet, which uses electric capacitance to measure pressures, consists of a three-layered structure, with a dielectric layer sandwiched by two electrode layers. Each electrode layer has a number of parallel ribbon-like electrodes and the electrodes on the two layers are oriented orthogonally to form a sensor sheet. This paper describes the sensing principle and the manufacturing method of the sensor sheet, and the development of its microcontrollers, as well as applications in nursing-care assistant robot RIBA-II, and pressure ulcer prevention mattresses.

Keywords: smart rubber sensor, flexible tactile sensor, conductive rubber, nursing-care assistant robot, pressure ulcer prevention

1. Introduction

In Japan, the number of people who require care is increasing with the rapidly growing elderly population. The number of these people was estimated to be 3,920,000 in 2005 and is expected to increase to 5,690,000 in 2015 and to 6,440,000 in 2020(1). Accordingly, the need for high-functionality care-related apparatus is increasing, and research and development of such apparatus has been intensively carried out(2)-(6). In 2007, Tokai Rubber Industries, Ltd. started joint research and development with RIKEN into nursing-care assistant robots, and in 2009 released a robot RIBA (Robot for Interactive Body Assistance), the first-ever two-armed robot that can help transfer a person between a bed and a wheelchair. In 2011, RIBA-II, an improved version of RIBA with enhanced practicality and operational safety, was released. In addition, Tokai Rubber Industries developed an active mattress with the aim of preventing pressure ulcers (bed sores) jointly with Kyushu University, and presented the prototype at the Home Care & Rehabilitation Exhibition in October 2011. Currently, Tokai Rubber Industries is conducting field tests on the active mattress and further developing its products.

Large-area flexible tactile sensors with high reliability are required for the interfaces with humans for the above-mentioned robots and apparatus. To meet this requirement, various tactile sensors have been proposed, studied, and developed. Such sensors include tactile sensors that employ discrete semiconductors(7), contact resistance(8), (9), conductive rubber(10), (11), piezoelectric polymers(12), and capacitance(13), (14). Our research group has carried out research and development on tactile sensors by integrating semiconductor sensors and mounting them on the soft exterior of the robot RIBA. This enabled the operation of the robot based on the human sense of touch and the detection of contact(15), (16). However, it is practically difficult to cover the entire body of the robot with such tactile sensors because semiconductor sensors, which exhibit high measurement accuracy, are expensive. Sensor sheets that employ contact resistance and piezoelectric polymers have bending flexibility but low compatibility with humans; it is necessary for humans to feel that the sensor sheets are pleasant to touch, a property exhibited by cloth and rubber. Also, fashioning such sensor sheets into complicated shapes is difficult. To solve the problems of the above-mentioned existing traditional sensor sheets, our research group has developed a capacitive soft sensor sheet made of rubber over the last few years. In this paper, we describe the principles, manufacturing method, and characteristics of the sensor sheet as well as its application to the care assistant robot RIBA-II and a mattress for preventing pressure ulcers.

2. Development of Smart Rubber Sensor

2-1 Structure and principle

The tactile sensor sheet we developed is based on capacitive sensors, and all components of the sensor, including the wires, are made of only rubber-based materials without the use of metal parts; hence, the sensor is referred to as a smart rubber sensor. The structure of the smart rubber sensor is simple (**Fig. 1**): a thin dielectric layer is sandwiched by two electrode layers. Each electrode layer has a number of parallel electrodes separated by a gap. The electrodes in the two layers are oriented orthogonally to each other so that independent capacitive sensor cells are formed by the intersection of the two orthogonal electrode layers. When the numbers of electrodes in the upper and lower layers are m and n, respectively, $m \times n$ capacitive sensor cells are formed on a sensor sheet. Such a structure has been proposed previously and sensor sheets that employ metal electrodes are commercially available(13). In the application of sensor sheets to care-related apparatus including care assistant robots, however, there are still problems such as their low stretchability and high cost. To solve these problems, we have devised a method of forming electrode layers by printing conductive rubber onto a flexible rubber sheet to form a flexible and stretchable sensor sheet. This method can also be applied to sensors with a complicated shape and is suitable for the fabrication of sensors on large-area substrates at a low cost. The conductive rubber paste developed for this purpose is suitable for screen printing, and its volume resistivity does not increase even when an electrode is stretched by 50%(17).

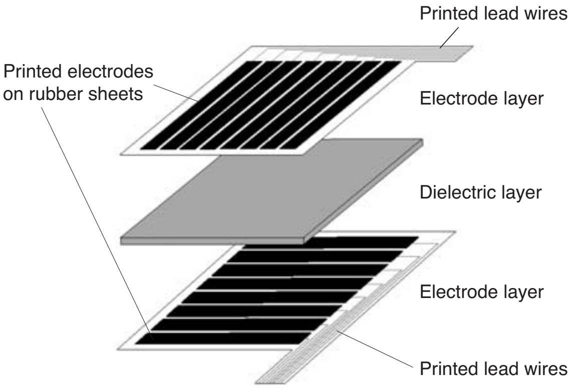


Fig. 1. Schematic structure of smart rubber sensor

The capacitance of the cell formed by the intersection of the *i*th electrode of one electrode layer and the *j*th electrode of the other electrode layer, $C(i,j)$, is given by

$$C(i,j)=\varepsilon_0\varepsilon_r\frac{s(i,j)}{d(i,j)} \qquad (i=1,2,\cdots,m;\quad j=1,2,\cdots,n) \qquad \cdots\cdots\cdots\cdots\cdots (1)$$

Here, ε_0 is the permittivity in vacuum, ε_1 is the relative permittivity of the dielectric layer, and $d(i,j)$ and $s(i,j)$ are the interelectrode distance (i.e., the thickness of the dielectric layer) and the area of the cell (i,j), respectively. When $C(i,j)$ is measured for all cells by switching on the electrodes in the two layers and $d(i,j)$ is calculated using **eq. (1)**, we obtain the pressure applied to each cell, $p(i,j)$, as follows.

$$p(i,j)=Y\frac{d_0-d(i,j)}{d_0} \qquad \cdots\cdots\cdots\cdots\cdots (2)$$

Here, Y is the Young's modulus of the dielectric layer and d_0 is the interelectrode distance when no pressure is applied to the cell (i.e., the interelectrode distance before deformation). Calculating the pressures applied to all $m \times n$ cells will determine the distribution of pressure applied on the sensor sheet. As shown in **Fig. 2**, it is assumed that the pressure is uniformly applied inside a cell and that the cell is uniformly deformed. Sensor sheets with such a structure are fundamentally designed on the basis of this assumption.

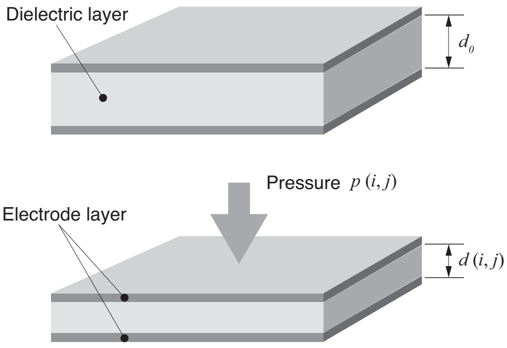


Fig. 2. Deformation of a sensor cell subjected to a normal pressure

2-2 Development of microcontrollers

Soft tactile sensor sheets used for care-related apparatus must not only have high flexibility, feel pleasant to the touch, and have high productivity to enable low-cost fabrication on large-area substrates, but also employ microcontrollers that are highly resistant to electromagnetic noise and small enough to be mounted on the sensor sheets or inside the apparatus. Although there are various methods for detecting capacitance(18), we developed two microcontrollers (circuit boards) with different measurement methods to meet the needs of various applications: one employs a simple method of measuring the current flowing through the capacitance cells (charge-based method), and the other employs a method based on the measurement of electrical impedance with high responsiveness (impedance-based method).

Figure 3 shows the equivalent circuit of a sensor cell. The quantities to be measured are denoted with a subscript x for convenience. In **Fig. 3**, C_x is the capacitance of a cell and R_x is the resistance of the electrodes and wires of the cell. The electrodes also serve as the wires to a cell. R_x depends on the cell because the length of the electrodes depends on the location of a cell.

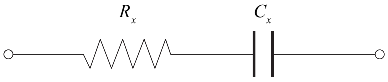


Fig. 3. Equivalent circuit of a sensor cell

In the charge-based method, a pulse with a certain voltage is applied to a sensor cell (the equivalent circuit in **Fig. 3**), and the current flowing through the cell is converted into voltage and measured. As the amount of electric charges in the sensor is measured, this is named the charge-based method. The resistance of the electrodes and wires is negligible because charges are measured as voltage. Moreover, the signal-to-noise (SN) ratio can be increased when the amount of charge with respect to the noise components is set to a high value, enabling measurement with a relatively simple circuit. In the impedance-based method, a voltage with a sinusoidal or cosine waveform with a certain amplitude is applied to the sensor cell, and the amplitude and phase (phase difference with respect to voltage) of the current flowing in the cell are measured to obtain the capacitance. The measurement speed is high, and C_x and R_x can be simultaneously measured. However, a drawback is the increased size of the measurement circuit, which includes a lock-in amplifier for the generation of harmonic waves.

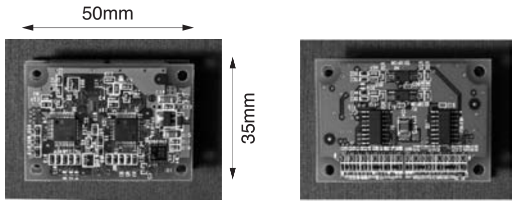
Table 1 summarizes the characteristics of the two methods. The method that should be adopted depends on the purpose and conditions of use. For example, the impedance-based method is preferable for feedback control in the operation of robots, which requires a high response speed, and for applications that require the separation of resistance and capacitance because of large elastic deformation of the sensor. In contrast, the charge-based method is reasonably suitable for mattresses for preventing pressure ulcers, for which low-cost fabrication is more important than high responsiveness.

Table 1. Comparison of impedance- and charge-based methods

Method	Impedance	Charge
Separation of C and R	Possible	Not possible
Response speed	High	Low
Program capacity	Standard	Small
Required memory	High	Low
Cost of low-volume production	High	Low

Microcontrollers using the charge-based method can be fabricated at a relatively low cost and easily downsized because of the small size of the circuits. In contrast, microcontrollers using the impedance-based method require multipliers to measure the ratio of the amplitude of an observation waveform (the flowing current) to that of a reference waveform (the applied voltage) and their phase difference. Although analog circuits using, for example, operational amplifiers are often used, measurement results are easily affected by phase differences, the cost becomes high because of the need for high-accuracy time measurement circuits, and the correction of temperature in a wide range is required. Therefore, we mounted a digital lock-in amplifier onto the microcontrollers and integrated the analog parts into a single chip, reducing the size and cost. As signals observed by the impedance-based method may include noise, the components with frequencies other than that of the applied voltage are detected using a lock-in amplifier and removed.

Photo 1 shows the 16 ch × 16 ch microcontrollers developed for robot and mattress applications. They are designed to have a two-ply structure: one is the signal processing substrate and the other is the communication substrate. The analog parts of the microcontroller using the impedance-based method are mounted on a semicustomized chip to limit the size. Both kinds of microcontroller are designed to have the same dimensions: 50 mm × 35 mm, to accommodate the two methods as necessary by exchanging the signal processing substrate. **Photo 2** shows the distribution of pressure measured by pressing the palm of a hand onto the sensor sheet. There are no differences between the two methods in terms of the measured pressure.



(a) Impedance-based method **(b) Charge-based method**

Photo 1. Microcontrollers (16 ch × 16 ch)

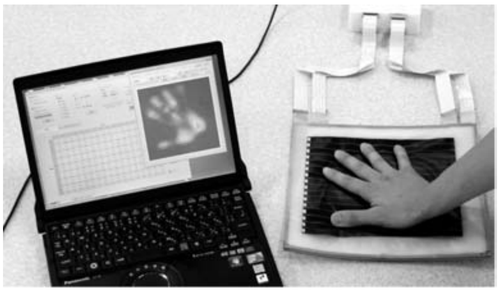


Photo 2. Distribution of pressure measured by pressing palm of hand onto sensor sheet

3. Application to Care Support Robot

The task that may pose the greatest burden on a caregiver is to lift and transfer a person who cannot move by him/herself between a bed or the floor and a wheelchair(19). This burden causes more than half of caregivers who work at nursing facilities to suffer from back pain(20). Tokai Rubber Industries and RIKEN have jointly carried out research and development on a two-armed robot with multiple joints, aiming at practical realization of care assistant robots that can be easily and safely operated and require no time for setting up and operation. **Photo 3** shows successive movements of RIBA-II, released in August 2011, in assisting a caregiver to lift a person from the floor to a

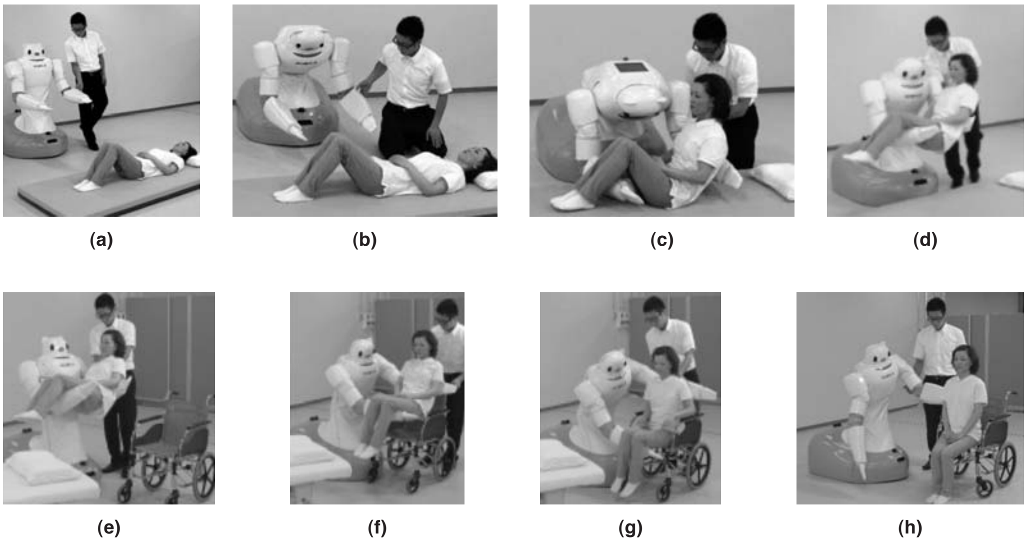

(a) (b) (c) (d)
(e) (f) (g) (h)

Photo 3. Successive movements of RIBA-II in lifting and transferring a person from the floor to a wheelchair

wheelchair. RIBA-II can lift and transfer a person weighing up to 80 kg between the floor, a bed, and a wheelchair, meaning that it can handle most care-receivers. Two caregivers are generally required to lift a care-receiver of care level three or higher in nursing facilities. If care assistant robots are introduced in such facilities, a single caregiver will be able to perform this task in cooperation with a robot, which is the goal of our research and development. The entire body of RIBA-II, including its joints, is covered with flexible materials that feel pleasant to touch. The materials used for the surface were selected to be easily cleaned by wiping, highly waterproof, and not to give a cold feeling to the persons who touch the body. Robots with a mechanical appearance would not be suitable for nursing facilities, and humanoid robots may cause care-receivers to feel uncomfortable and patients with dementia may confuse them with real humans (almost half the people receiving care have dementia(1)). As a result, RIBA-II has been designed to have the appearance of a stuffed white bear to portray friendliness and cleanliness.

Ensuring the safe operation of care assistant robots is very important because they come into direct contact with humans. The use of smart rubber sensors plays a significant role in the safe operation and functioning of RIBA-II. **Photo 4** shows a front view of RIBA-II. Smart rubber sensors are installed on the two arms and chest to control the operation of RIBA-II by touch and to detect pressure when the robot lifts a person. Many care-receivers at nursing facilities have fragile skin and easily bleed internally, meaning that great care is required so as not to injure them during lifting. The pressure is detected in real time by tactile sensors attached to the arms of the robot; once the robot has been set up, it can automatically stop the operation when the detected pressure reaches a predetermined value or higher. RIBA-II can measure the weight of a care-receiver while lifting the person and can automatically sound an alarm and stop the operation if the detected weight exceeds the limit of its load-bearing ability.

Caregivers can operate RIBA-II by touching the tactile sensors. Although remote controllers and joysticks may be used to operate the robot, operation by touch is less restrictive for caregivers and more suitable for accurately instructing RIBA-II to perform operations while confirming the safety of the environment around the person being lifted(16). **Figure 4** shows a schematic of the operation of RIBA-II by touch. The bogie of the robot moves forward when the caregiver strokes the back of the upper arm towards the elbow joint, whereas it moves backward when he/she strokes the back of the upper arm in the opposite direction [arrow 1 in **Fig. 4(a)**]. When the back of the upper arm is stroked in the circumferential direction, the bogie laterally moves in the stroking direction [arrow 2 in **Fig. 4(a)**]. Pushing the back of the left upper arm rotates the bogie clockwise [arrow 1 in **Fig. 4(b)**], whereas pushing the inner side of the left upper arm rotates the bogie counterclockwise [arrow 2 in **Fig. 4(b)**]; a reverse rotation can be obtained by pushing the right upper arm. Stroking the upper arm and forearm in the circumferential direction rotates them around the longitudinal centerline in the stroking direc-

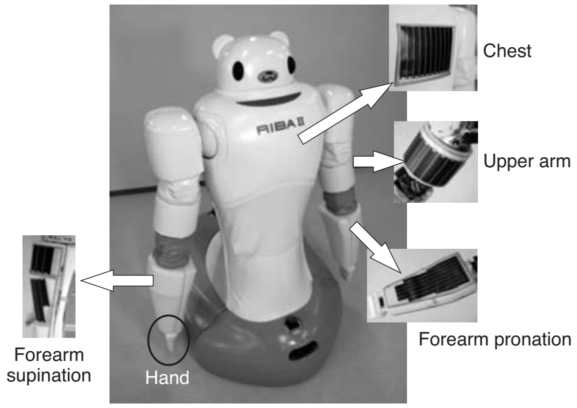
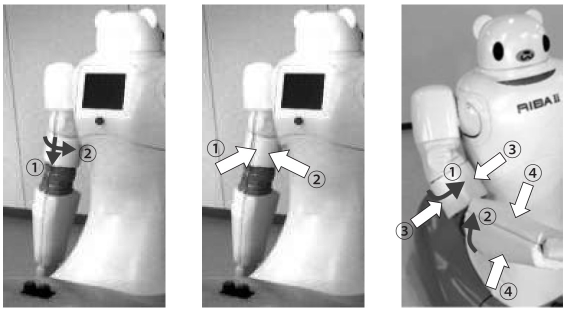


Photo 4. Appearance of RIBA-II and positions of smart rubber sensors installed



(a) Movement of cart in a straight line **(b) Turning of cart** **(c) Motion of arms**

Fig. 4. Schematic of operation of RIBA-II by touch

tion. Pushing the upper arm and forearm moves them in the pushing direction. To ensure safety, however, the robot only performs the operation designed for the person being lifted and is prohibited from performing arbitrary operations during lifting, although the operation speed can be controlled. Operation patterns are designed for all the care-receivers who are lifted by the robot and the corresponding pattern is called up by inputting the care-receiver's name before the transfer task. The robot is designed to operate only upon manipulation by touch and to stop when the caregiver releases his or her hand from the robot. Stroking the supination of the forearm towards the elbow joint reverses the operation of the robot during stroking if the caregiver considers such an operation necessary.

4. Application to Nursing-Care Mattresses

According to the Comprehensive Survey of Living Conditions (Ministry of Health, Labour and Welfare), people who are bedridden, requiring support in their daily lives, account for approximately 15.5% of the elderly population(21), (22). Bedridden patients who maintain a fixed posture for a long time easily develop pressure ulcers. Pressure ulcers are one of the most painful disorders, are difficult to cure, and cause other diseases. Therefore, the prevention of pressure ulcers is a key task, and repositioning the patient is generally performed as a means of preventing pressure ulcers in care and nursing sites. Supporting the repositioning of the patient every 2-3 hours is physically and mentally stressful for not only caregivers and nursing staff in nursing facilities and hospitals but also caregivers at home.

According to the National Pressure Ulcer Advisory Panel (NPUAP), pressure ulcers are defined as local tissue necrosis that occurs when prolonged pressure is applied to the soft tissue between projections of bones of the body and the supporting plane of the bed(23); compression is considered to be the main cause of pressure ulcers. In recent studies, it has been clarified that the mechanism by which pressure ulcers develop is complicated and associated with various factors, such as shear stress (friction), poor circulation, malnutrition, sweat, body waste, a decrease in arterial pressure, and irregular projections of bones as well as pressure(24). Although there are various causes of pressure ulcers, pressure is the main cause. Various types of mattress that disperse body pressure have been developed and commercialized with the aim of reducing the frequency of repositioning the patient and the burden on caregivers. Here, the dispersion of body pressure means that the weight of a person is evenly applied to the entire body. There are two types of body-pressure dispersion mattress: passive and active mattresses. Passive mattresses disperse the body pressure using low-repulsion flexible materials and fluids (*e.g.*, gels, water, air) without controllers. No external power is required, there are few safety-related issues, and the manufacturing cost is relatively low. However, passive mattresses are difficult to use with patients with special requirements and make it difficult for patients to move in bed (*e.g.*, roll over) and sit up in bed because they have uniform flexibility. Moreover, passive mattresses containing water and gels are heavy. On the other hand, many active mattresses, which use active control, employ air cells and disperse the body pressure by increasing or decreasing the air pressure. Active mattresses are relatively light and have improved functions compared with those of passive mattresses. However, most conventional body-pressure dispersion active mattresses cannot sense the body pressure but just switch the pressure with a certain time interval. Although the switching time is changeable, it is difficult to use such active mattresses in a personalized manner in accordance with the body shape and the locations of lesions of each patient. To cope with the above problems, Tokai Rubber Industries has proposed and developed a mattress that exhibits novel functions owing to the independent control of multiple air cells based on the signals of the smart rubber sensors.

A large number of independent air cells are incorporated into the mattress, and a valve is attached to each air cell. Thus, the pressure is controlled by electromagnetically opening and closing the valves. **Photo 5** shows the prototype mattress and the smart rubber sensors placed on the mattress. Many air cells are arranged in parallel in the mattress, as shown in the schematic in **Fig. 5**. An air pump is used to supply air. Pressure applied to the human body can be measured instantly and, if necessary, reduced by opening the valves of the air cells subjected to high pressure. It is also possible to control the pressure of air cells corre-

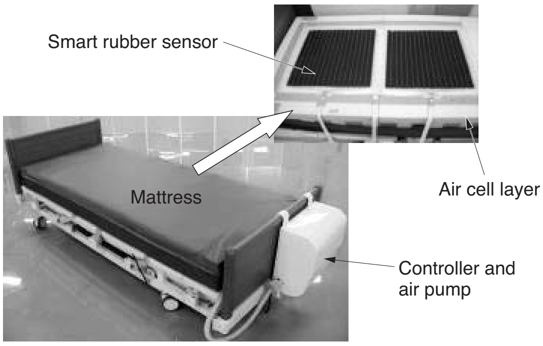


Photo 5. Prototype for preventing pressure ulcers

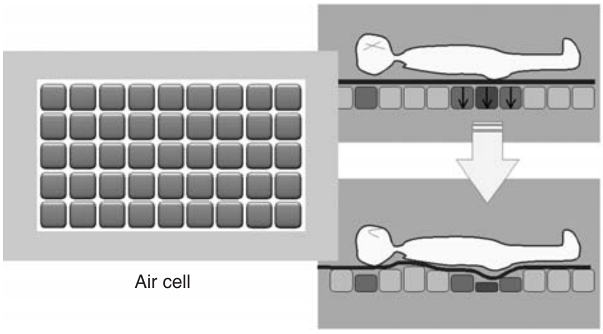


Fig. 5. Schematic of depressurization of mattress by decreasing air pressure in air cells

sponding to particular locations of the patient's body to keep the pressure under a predetermined threshold. Moreover, the mattress does not prevent the patient from moving or sitting up in bed because there is no need to make the entire mattress flexible. **Photo 6** was taken during an experiment to evaluate the mattress. **Figure 6** shows the body pressures before and after the dispersion of pressure as an example of experimental results. The mattress has been developed in a joint research project with Kyushu University, and favorable reports of its use have been received from Kyushu University Hospital⁽²⁵⁾.

Photo 6. Experiment performed to evaluate the prototype mattress

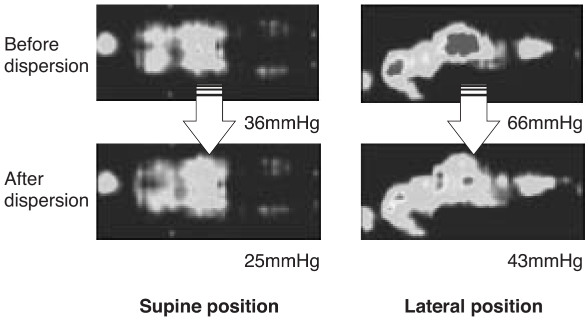


Fig. 6. Dispersion of pressure (experimental result)

5. Conclusion

We developed a tactile sensor sheet called a smart rubber sensor, in which all components including wires are made of rubber-based materials, with the aim of realizing tactile sensors highly suitable for contact with human bodies. The sensor sheet is fabricated by screen-printing conductive rubber paste onto a rubber sheet to form electrodes, and the electrodes can maintain their conductivity even when greatly deformed by stretching. The sensor sheet has a simple structure and it is possible to fabricate such sensors with a complicated shape on large-area substrates at a low cost. We also developed two types of microcontroller with different measurement methods, i.e., impedance- and charge-based methods, to meet the needs of various applications.

As a first step towards their practical applications, smart rubber sensors have been mounted on the care assistant robot RIBA-II currently under development and the mattresses for preventing pressure ulcers. Using the sensors, it is possible to operate RIBA-II through the detection of contact with care-receivers and instruction given by the caregiver through touch. We have experimentally confirmed the practicality and safe operation of RIBA-II by instructing the robot to lift healthy subjects. In the near future, we will further improve the performance of the robot and carry out demonstrative tests on care-receivers. On the other hand, the mattress for preventing pressure ulcers will be commercialized after field tests and monitoring at nursing-care facilities and individual homes.

In the longer term, the smart rubber sensor will be further developed and applied to various care-related apparatus and nursing-care products in addition to care assistant robots and mattresses for preventing pressure ulcers.

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