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FULL PAPER

Dummy humanoid robot simulating several trunk postures and abdominal shapes – Report of element technologies

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ABSTRACT
Development of clothing in consideration of the shape and body function of a person with spinal cord injury is an important task. Then, a dummy robot with a deformation mechanism was developed in this study for evaluating the comfortable level of clothings. Specifically, a trunk joint mechanism and an abdominal mechanism that can realize various deformations of the abdominal area and various trunk poses were developed. The trunk joint mechanism was implemented in order to simulate the seated posture of persons with spinal cord injury. The abdominal deformation mechanism was implemented using linear actuators and rotating servomotors in order to simulate abdominal obesity of persons with spinal cord injury. Further, a tactile sensor system was developed for measuring the clothing pressure on the abdominal area and evaluating the comfort or discomfort of clothing.

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1. Introduction

Spinal cord damage can curtail a person's mobility and other body functions to a significant extent and can lead to muscle weakness and paralysis. Many persons with tetraplegia have great difficulty in living independent lives; furthermore, they are restricted in their activities of daily living, and they typically require the use of a manual or electric-powered wheelchair to move. Assisting the self reliant life of a person with spinal cord injury is expected to encourage their social participation. Calculation of the independence rates of patients of tetraplegia (complete lesions at level C4 to T1) in a previous study revealed high independence rates for eating and bed to wheelchair transfer but low independence rates for dressing and toileting [1]. Moreover, the increased time spent by persons with tetraplegia for toileting and dressing may be a reflection of their lower residual function, which results in a longer time being taken for completion of balance and coordination tasks [2]. Clothing acts as means to sustain the self-esteem of persons with spinal cord injury and camouflage their physical imperfections, clothing may also improve their social inclusion. Then, it becomes necessary to develop clothing in consideration of the shape and body function of a person with spinal cord injury [3]. Persons with spinal cord injury typically use wheelchairs and sit in the same position for lengthy periods. Therefore, they are at risk of developing pressure sores, which are injuries caused to the skin and the underlying tissue by prolonged pressure on the skin [4]. In some persons with spinal cord injury, clothing has been reported to cause or exacerbate pressure sores [3]. Moreover, some persons with tetraplegia take a long time to defecate, because of which they spend lengthy periods seated on the toilet seat. This puts them at risk of developing pressure sores.

Therefore, clothing and toilet seats should be designed to help persons with spinal cord injury live independently and prevent the occurrence of pressure sores.

In general, clothing is expected to be functional as well as fashionable. The European research project 'Fashionable' involved the development of integrated technologies to meet the requirements of people with physical disabilities and special needs [5]. The National Rehabilitation Center for Persons with Disabilities held a fashion show—the *KOKURIHA* fashion show—to arouse people's interest in fashionable and functional clothing. Fashionable and functional clothing is expected to promote social participation of persons with disabilities.

A new testing device is required in order to promote the development of clothing and toilet seats for persons with spinal cord injury. Therefore, the purpose of this study is to develop a robot device for testing such assistive products and technologies.

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2. Dummy humanoid robot with deformation mechanism

To evaluate the usability of clothing and assistive products and technologies, robot devices that can simulate the human body or motion are proposed.

2.1. Past research on dummy robot

Several robots simulating the human body and motion have been developed in the past. Dummy humanoid robots for simulating a patient have also been developed and used for medical education. A dental patient robot called 'Hanako2 Showa' was developed jointly by Showa University and TMSUK [6]. This robot has the appearance of a woman, and it has been programmed with certain behaviors that are used to objectively evaluate the clinical ability of medical students. Further, a humanoid robot for airway management training was developed by Waseda University [7]. This robot was equipped with force sensors that were used to score the airway management performance of learners in order for them to subsequently be able to observe their own efforts. A method for testing a power-assist device using the humanoid robot HRP-4C has also been proposed [8]. This humanoid robot wears 'Smart Suit Lite' and measures the waist joint torque. Several human body parameters whose direct estimation is difficult can be determined using robotic techniques. The shape of HRP-4C is similar to that of an average Japanese female. Therefore, the shape of the robot needs to be deformable to be able to simulate various human body types.

Some robots have been designed to focus on the shape of the human body. One of the important uses of such a robot is to function as a substitute for an actual human trying on clothing. To this end, a female shape-changing robotic mannequin was developed by Abels et al. [9]; this robot can change its shape and imitate different human body types. The mechanism of deformation is necessary for assessing the suitability of clothing or wearable devices for humans.

2.2. Dummy robot simulating person with spinal cord injury

The upper body of a dummy humanoid robot simulating a person with spinal cord injury was developed by our research group as shown in Figure 1. This dummy robot has an exterior deformation mechanism of the shoulder and chest and a superior-limb mechanism to realize a variety of body shapes and upper limb motions.

The body shape of a person with higher degrees of injury undergoes greater changes, owing to the abdominal muscles becoming flaccid [3]. Then, such a person would be keen to conceal or camouflage the stomach shape, and he/she would select larger sized, ill-fitting clothing; however, in doing so, the person would be at risk of developing pressure sores. A comparison between the abdominal circumference of Japanese persons with spinal cord injury [10] and that of healthy Japanese males [11] revealed that the difference in the averages of these two sets of abdominal circumferences was about 100 mm. From the comparison results, it was found that the body shape of a person changes upon incurring spinal cord injury. Therefore, it is important to simulate the abdominal shape of a person with spinal cord injury. Persons with spinal cord injury using a wheelchair are at risk of developing pressure sores from being seated for lengthy periods. The areas of incidence of pressure sores in Japanese persons with spinal cord injury have been found to be the ischial tuberosities, sacrum, coccyx, and greater trochanters [12]. Furthermore, the pressure force on the seat differs depending on the body posture and seat cushions [13]. Then, an adjustment mechanism of the trunk posture for the dummy robot is necessary in order to evaluate pressure sores depending on the seated posture.

One of the important tasks in the present study is to evaluate pressure sores around the hip. The area of the pressure sores changes depending on the seated posture. Thus, in order to enable the dummy robot to realize several seated postures, it is necessary to implement one degree of freedom (DOF) of the trunk along the pitch axis in the robot.

Further, to enable verification of assistive products and technologies, it is necessary to implement a deformation mechanism of the abdominal area and the DOF of the trunk in the dummy robot simulating a person with spinal cord injury. This study reports on the development of the trunk joint mechanism and abdominal mechanism, as well as a tactile sensor system aimed at measuring clothing pressure on the abdominal area and evaluating the comfort level of clothing.

3. Mechanism of trunk joint

Some persons with paraplegia or tetraplegia take a long time to be seated, and their hip pose may change from that supported by the ischial tuberosity to that supported by the sacral bone owing to the forward sliding of the hip. To simulate these seated postures, it is necessary to implement the DOF of the trunk along the sagittal-plane robot for the dummy robot. Therefore, the joint of the pitch axis is implemented at the position corresponding to between the thoracic spine and the lumbar spine of human. An outline of this robotic mechanism is shown in Figure 2.

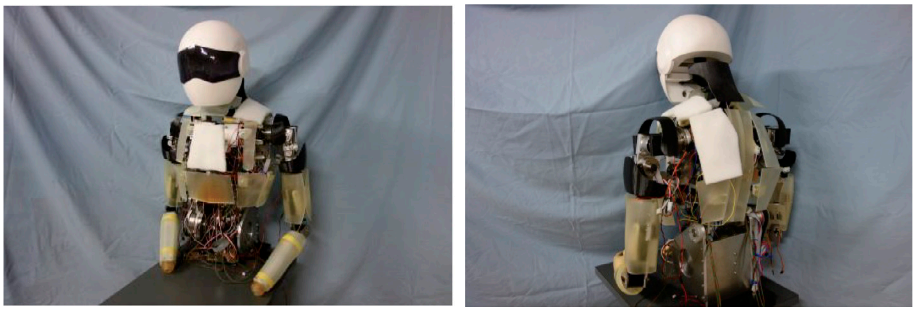


Figure 1. Developed upper body of dummy humanoid robot simulating persons with spinal cord injury. This robot can have the upper limb mechanism and the deformation exterior of chest, shoulder, and blade bone.

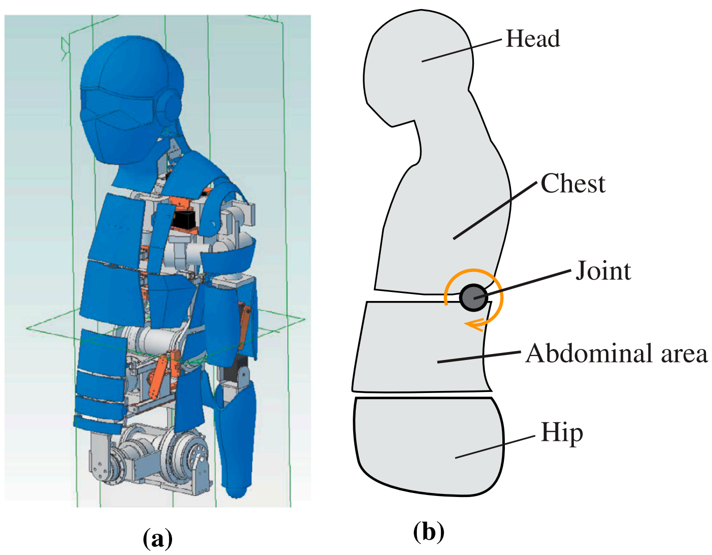


Figure 2. Outline of developed dummy robot with abdominal mechanism. (a) 3D CAD data of upper body, abdominal, and hip mechanisms. (b) Trunk joint mechanism.

Moreover, two types of seated postures—seated on the ischial tuberosity and seated on the sacral bone (20° rotation of the trunk joint)—are simulated; these postures are shown in Figure 3.

In Figure 3, the part in red indicates the simulated sitting bones, and the part in green indicates the simulated tailbones. It is expected that the contact condition on the seating face will change depending on the seated posture. Simulation of different seated postures will be useful for evaluating the risk of developing pressure sores.

4. Abdominal mechanism

The body shape of a person with spinal cord injury may differ depending on the degree of disability and his/her lifestyle. This study focused on the abdominal area and developed a deformation mechanism and tactile sensor system for it.

4.1. Exterior deformation mechanism

The average and maximum abdominal circumferences of a healthy male are 770 and 906 mm, respectively [11]. Maruyama et al. measured the abdominal circumference of 44 persons with spinal cord injury, and found the average and standard deviation (SD) to be 881 mm and 121 mm, respectively. Then, in the present study, the maximum abdominal circumference was assumed as 1123 mm by taking a sum of the average and two times the SD. Therefore, the abdominal mechanism of the dummy robot needs to adhere to this maximum abdominal circumference.

Two types of deformation mechanisms—one where the abdominal area projects forward and the other in which it extends on both the lateral sides—were developed. When some amount of fat of the back was incorporated in the dummy robot, the change in the body shape could not be observed; therefore, the deformation mechanism of the back was not developed. This forward

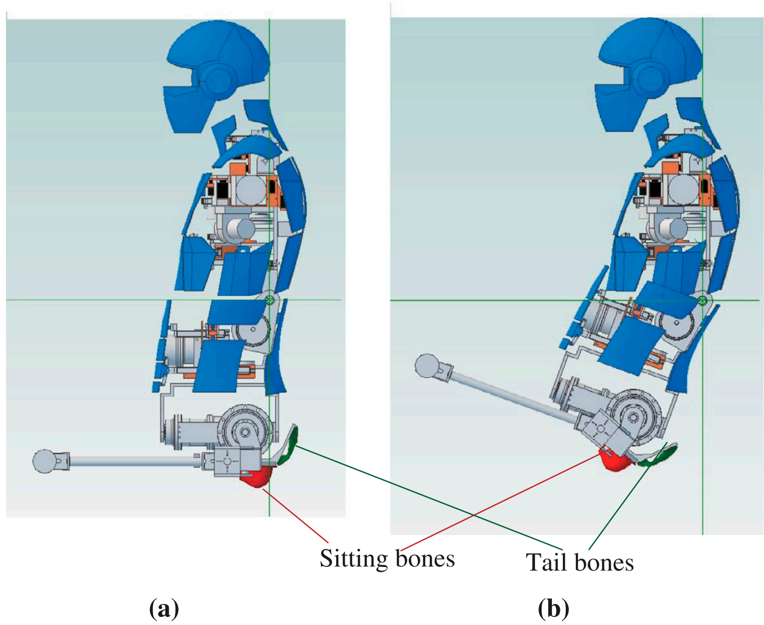


Figure 3. Simulation of seated postures of dummy robot; (a) sitting on sitting bone and (b) sitting on tailbone.

abdominal deformation mechanism was implemented using linear actuators (Miniature Linear Actuators, Firgelli Technologies, Inc.) to realize expansion in the case of a large deformation. The maximum actuator stroke of the upper part of the abdominal mechanism is 50 mm, and that of lower part is 100 mm. Two rotation motors—one each to deform each side of the abdominal mechanism—were implemented.

The abdominal mechanism of the dummy robot is shown in Figure 4. Specifically, Figure 4(a) shows the abdominal mechanism before deformation, and Figure 4(b) shows the maximum expansion shape of this mechanism after deformation. Figure 4(c) shows connection parts among abdominal covers and linear actuators. These joints between each connection part have the joint friction. These joints don't have actuators. That is, these exteriors are moved by hand in this paper. Moreover, the maximum flexion angle of the trunk joint of Figure 4(a) is 30 °, the one of Figure 4(b) is 23 °.

From Figure 4, the abdominal mechanism deforms considerably, and therefore, several degrees of deformation of the abdominal area can be simulated using this mechanism. The abdominal circumference before deformation is 860 mm; this value is similar to the average abdominal circumstance of a person with spinal cord injury (881 mm). Moreover, the abdominal circumference after deformation is 1140 mm, which is larger than the maximum abdominal circumference of a person with spinal cord injury (1123 mm). Here, the gap between forward and side exterior is approximated as a linear distance between the front and side edge points.

Therefore, the abdominal mechanism of the dummy robot is capable of simulating different body shapes of persons with spinal cord injury. However, the gap between forward and side exterior is large, and it may affect the clothing pressure. A new abdominal mechanism having a small gap between exteriors will be explored in future work.

4.2. Tactile sensor system

Some robots equipped with tactile sensors on the entire body have been developed for communication with humans and generation of the several motions. For example, Maggiali et al. developed an artificial skin system that is based on a conformable mesh of interconnected sensors with a triangular shape in order to form a networked structure [14]. These sensors simulate the human skin in order to monitor the pressure of the entire body. Ohmura developed tactile sensors and implemented them in a humanoid robot in order to realize the roll-and-rise motion and lift-up motion using tactile feedback control [15,16]. This tactile sensor sheet, which is in the form of a flexible printed circuit (FPC) board, can be implemented on a curved surface. The robot named 'macra' can monitor the deformation of the full-body soft cover using three-axis force sensors and sense several contact states during communication with humans [17].

The goal in the present study is to measure and quantify the body load depending on the body shape. Then, it becomes necessary to implement a tactile sensor system in the abdominal mechanism of the dummy robot. The

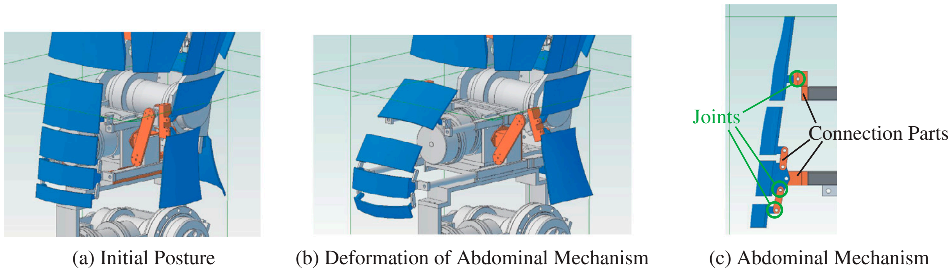


Figure 4. Outline and 3D CAD simulation data of abdominal deformation mechanism.

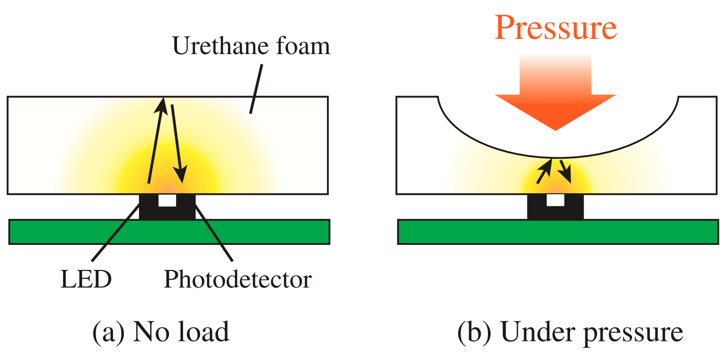


Figure 5. Mechanism of tactile sensor system consisting of LED, photodetector and urethane foam.

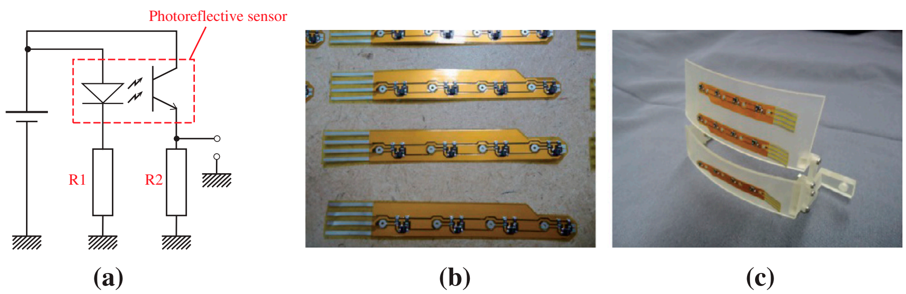


Figure 6. Outline of developed sensor sheets. (a) Circuit diagram of sensor. (b) Sensor sheets. (c) Sensor sheets implemented on exterior body of abdominal mechanism.

exterior of dummy robot has a curved surface shape and the tactile sensor sheet has a flexible structure and several measurement points. The comfort level of clothing can be verified from the clothing pressure. Comfortable pressures of clothing range from 19.6 to 39.2 hPa, where uncomfortable pressures range from 58.8 to 98.0 hPa [18]. In this study, a tactile sensor system was developed to distinguish between contact states (no pressure, comfortable pressure, and uncomfortable pressure) based on the mechanism of the sensor in reference [15]. This photoreflective sensor consists of a light-emitting diode (LED) and a photodetector. The scattered ray generated from the LED changes through the deformation of the urethane foam, and this change is measured by the photodetector. The sensing mechanism is shown in Figure 5.

The abdominal area of the dummy robot is curved surface shape (Figure 5). Therefore, the developed tactile sensor system was implemented on an FPC board. The circuit diagram of the sensor is shown in Figure 6(a), and the developed sensor sheet consisting of four sensor elements is shown in Figure 6(b).

The photoreflective sensor used is NJL5901AR-1 (New Japan Radio Co. Ltd.), and its size is 1.6 mm × 1.3 mm. Here, R1 and R2 of the sensor are 470 Ω and 3.9 kΩ, respectively. The distance between sensors is 10 mm, and the size of the sensor sheet is about 70 mm × 9 mm. The thickness of the urethane foam is 10 mm. Figure 6(c) shows the outline of implementation of the sensor sheets on the exterior body of the abdominal mechanism.

The pressure voltage characteristics of the sensor were measured. The force was measured with a 6-axis force sensor (PFS055YA251U6, Leptrino Co. Ltd). The pressure was calculated by dividing the measured force value by the area of the force sensor. The measurement results are shown in Figure 7. The blue and green circles represent the increasing pressure force and decreasing pressure force, respectively.

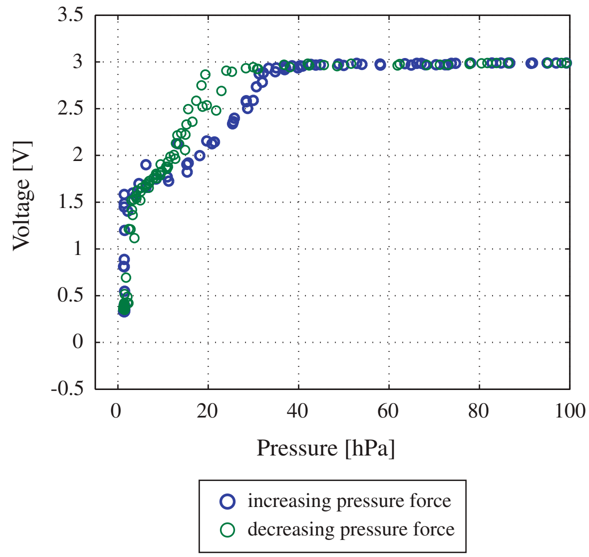


Figure 7. Response of developed sensor in terms output voltage-input pressure relationship.

From Figure 7, it can be seen that the voltage of the sensor increases linearly with the increase in pressure force from 0 to 40 hPa. The range of this linear increase includes the range of comfortable pressure values. However, this range of comfortable pressure exhibits hysteresis characteristics; that is, decreasing pressure force is larger than the increasing pressure force. Moreover, the voltage of the sensor saturates above a pressure force of 50 hPa, and so, the range of uncomfortable pressure values is included in the saturation range of this sensor.

Therefore, although the developed sensor system can judge whether the clothing pressure is comfortable or uncomfortable, it cannot verify the degree of discomfort.

5. Actual dummy robot

The abdominal mechanism and trunk joint mechanism of the dummy robot were developed, and change in posture and the deformation of the abdominal mechanism were confirmed. The full body of the dummy robot with the abdominal mechanism is shown in Figure 8. The dummy robot is made of aluminum. The actuator of the trunk joint mechanism consists of an electronically commutated(EC) motor (Maxon Motor AG) and a harmonic drive (Harmonic Drive Systems Inc.). The specifications of actuator are as follows: The nominal voltage is 24 V. The nominal torque is 289 mNm. The nominal speed is 3740 rpm. The planetary gear-head with a reduction ratio is 1/4.3. The reduction in the harmonic drive is 1/100. The exterior body of the dummy robot was fabricated using 3D printer.

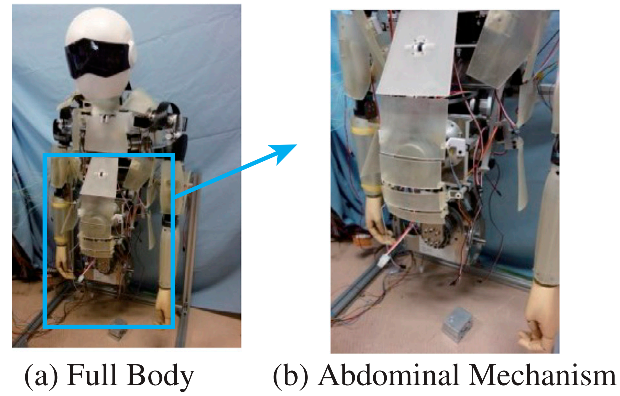


Figure 8. Overview of actual developed dummy humanoid robot with abdominal mechanism.

5.1. Posture adjustment and deformation of abdominal mechanism

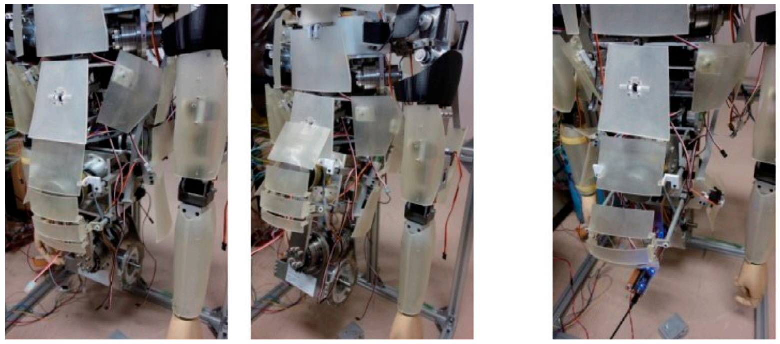
The bent trunk posture shown in Figure 3(b) is implemented using the actual dummy robot as shown in Figure 9(b), and the deformation of the abdominal mechanism shown in Figure 4(b) is implemented as shown in Figure 9(c). The posture shown in Figure 9(a) is the initial posture, and that in Figure 9(b) is the posture where the dummy robot is bent by about 10 ° at the trunk.

5.2. Measurement tactile sensor patterns with deforming abdominal mechanism

The tactile sensor patterns were obtained, when abdominal part of dummy robot was deformed by the linear actuators. The five sensor sheets implemented four sensor elements were mounted on the abdominal parts. The value of each sensor element was set to zero when the dummy robot wore the clothing (shirt). The change of clothing pressure was measured. The upper part of the abdominal mechanism was translated by 40mm, and the lower part of one was translated by 70 mm.

The experimental results are shown in Figure 10. In practice, the abdominal parts and tactile sensors were covered urethane foam and this shirt.

Pressure value of 3 and 5 sensor sheets increased, the pressure value of 4 sensor sheet showed slight change. The pressure value of 1 and 2 sensor sheets decreased. The lower part of the abdominal mechanism was translated larger than the upper part of one, and the sensors mounted on the lower part were changed higher than the ones of the upper part. Moreover, I think that the sensors of the upper part were separated from the clothing, and the pressure values decreased to negative value.



(a) Initial Pose (b) Bent Trunk (c) Deformation of Abdominal

Figure 9. Simulation results of actual dummy robot. (b) Posture with bent trunk achieved using developed trunk joint mechanism. (c) Deformation of abdominal mechanism using linear actuators.

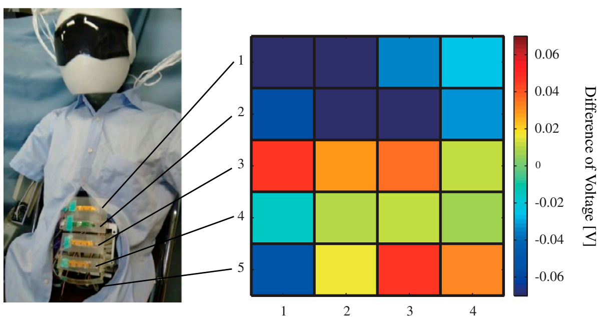


Figure 10. Change of tactile sensor patterns when abdominal mechanism of the dummy robot was deformed.

6. Conclusion

In this study, a dummy robot was developed for evaluating the comfort level of clothing. Specifically, the posture and abdominal shape of persons with spinal cord injury were focused on and a trunk joint mechanism and abdominal mechanism that can realize various trunk postures and various deformations of the abdominal area were developed. The trunk joint mechanism was implemented with the aim of realizing seated postures of persons with spinal cord injury. Further, to simulate abdominal obesity of persons with spinal cord injury, a deformation mechanism was developed by employing linear actuators and rotating servo motors. A tactile sensor system was also developed for measuring clothing pressure in the abdominal area. In future work, the clothing pressure induced in the abdominal area for various body shapes of real humans will be measured with the aim of comparison of the obtained results with the data obtained using the dummy robot, and based on the comparison results, the efficiency of the proposed evaluation method implemented in the dummy robot will be discussed. Moreover, the abdominal segments have passive joints, and we will discuss a new mechanism in which the position and attitude repeatability is good. The surface friction condition of the exterior body segments is important. Therefore, the 3-axis force sensors will be implemented on the exterior to estimate the friction condition.

Disclosure statement

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