A Novel Air-cell Mattress Based on Approximate Anthropometric Model for Preventing Pressure Ulcer

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Abstract: Air mattress is now used widely to prevent the pressure ulcer by reducing the localized pressure peaks. In this paper an air-cell mattress and its pressure control method based on an *approximate anthropometric model* are presented. The air-cell mattress has eighteen cylindrical air cells made of porous material allowing air leakage to contribute in reducing the development of pressure ulcer by lowering the pressure peak, temperature and humidity. To determine an optimal air-cell pressure appropriate for each user, we divide the parts of the body into four sections such as head, trunk, hip, and leg. Then, the pressure of each section is independently calculated from the weight of each part based on the individual body height and weight and the approximate anthropometric model. Air supply system for the air-cell mattress is implemented by using four electronic solenoid valves and an air compressor, and it is driven by a real-time micro-controller. The experimental results with seven subjects shows that the proposed air-cell mattress is effective for the prevention of the pressure ulcer.

Keywords: Pressure ulcer, air-cell mattress, approximate anthropometric model, pressure control

1. INTRODUCTION

Pressure ulcer is a lesion that develops as a result of unrelieved pressure to the area and results in damage to underlying tissue [1]. There are many factors that contribute to the development of pressure ulcers; external pressure, shear force, friction, temperature, humidity, posture, infection, nutrition and so on. In the factors, the external pressure is considered to be the primary cause. By the external pressure applied to a skin area, the normal flow of blood and oxygen to tissue in that area is reduced. Since the average blood pressure in capillaries is 32 [mmHg] in the arteriolar limb [2], the external pressure should not be exceeded the blood pressure in capillaries for preventing the pressure ulcer. The part of body that the pressure ulcer is open developed is the tissue over the bony prominences such as occipital, scapula, elbow, sacrum, heel, trochanters, ischial tuberosities, coccyx, and external malleoli [3]. Koisak [4] found out relationships between the external pressure and the time, that the pressure ulcer is developed in one hour by 600 [mmHg] external pressure, and in twelve hours by 150 [mmHg] external pressure, respectively.

To prevent the pressure ulcer it is important to reduce the external pressure below 32 [mmHg]. Therefore, air seat cushions or air mattresses [6] are open used for reducing the external pressure applied to the area. However, the mattress controlled by a uniform pressure is not adaptable to the changes of body pressure due to the difference of body weights and heights of individual users.

Another way to remove the localized pressure is to change seating posture. For instance, wheelchair users with limited mobility should separate the underlying body part from the seat during at least one minute at an interval of thirty minutes. A patient living on bed long-term needs a nursing aid to change his body posture every two hours for a relief of the external pressure. Even though the nursing aid services devotedly, the patient cannot feel comfort because the aid acts to a disturbance of a sound sleep. Recently an electric bed to change lying posture automatically was presented [5]. However its size was bulky, so it needed a wide space to install in general house.

In this paper we propose a novel air-cell mattress that consists of eighteen air-cells made of porous material allowing air leakage to contribute in reducing temperature and humidity, and also propose an air pressure control method for dispersing the external pressure. To determine the air pressure of the mattress appropriate for each user, we divide the parts of the body into four sections such as head, trunk, hip, and leg. Then, the pressure of each section is independently calculated from the weight of each part based on the individual body height and weight and an *approximate anthropometric model*. Air supply system for the air-cell mattress is implemented by using four electronic solenoid valves and an air compressor, and it is driven by a real-time micro-controller.

We perform experiments with seven subjects having various weights and heights individually to evaluate the pressure distribution performance. From the experimental results compared with two commercialized air mattresses, we show that the proposed air-cell mattress is effective for the prevention of the pressure ulcer.

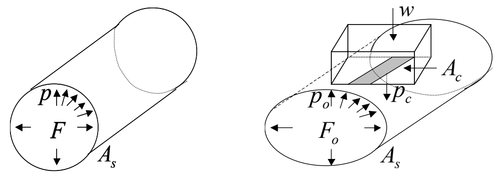
2. AIR-CELL MATTRESS FOR PREVENTING PRESSURE ULCER

2.1 Relationship of air-cell and body pressure

When a fluid in an airtight tube acts to a wall or a virtual plane with $A_s[m^2]$ area as the uniformly distributed compression force $F[N]$ as shown in Fig. 1(a), pressure $p[N/m^2]$ produced by the force is expressed as follows:

$$p = \frac{F}{A_s}, \tag{1}$$

It is known that gas is the compressibility fluid. But, if fluid velocity is slower than the acoustic velocity and the variation of its density by temperature changes is almost none, gas is regarded as the incompressibility fluid. Moreover, gas is also considered as the inviscid fluid if the viscosity of molecules in it is smaller as ignorable. In this study we assume the air in the air-cell is the ideal fluid with the incompressibility and the inviscid property. Therefore when a rigid body with weight $w[Kgf]$ is loaded on the air-cell as shown in Fig. 1(b), the pressure by the load acts all part in the air-cell with the same



(a) Inner pressure of air-cell (b) Contact pressure by external load

Fig. 1 Pressure change of the air-cell by external load.

force. It is expressed as the following equation based on the Pascal's theorem.

$$p_c = \frac{w}{A_c} = \frac{F_o}{A_s} = p_o \qquad (2)$$

Here p_c and A_c denote contract pressure and contact area, and F_o and p_o are the total pressure and inner pressure in the air-cell, respectively. From Eq. (2), we can see that the contact press p_c is measurable indirectly by measuring the inner pressure p_o, and it is controllable by changing p_o.

The objective of this study is to minimize the body pressure caused by the body weight using the air-cell mattress. Accordingly, when the weight and contact area of each part of body are given, an optimal *reference air pressure* p_{ref} to minimize the body pressure for individual user can be obtained as follows:

$$p_{c\_i} = \frac{w_i}{A_i} = p_{ref\_i} \qquad (3)$$

where w_i and A_i are weight and contact area corresponding to each part of body. In this study we divide whole body into four parts as head, trunk, hip, and leg, because these parts are easily divided based on the body shape. Therefore *i* in Eq. (3) denotes $i = head, trunk, hip, leg$, and w_i and A_i are calculated by using individual anthropometric data and the approximate anthropometric model proposed in the next chapter. As a result, the body pressure p_{c_i} corresponding to the part *i* is minimized by the maximum contact area, A_i.

2.2 Air-cell mattress

To prevent development of the pressure ulcer, it is necessary to preserve an appreciate temperature and humidity at the skin area [1]. For this purpose we developed an air-cell made of porous material allowing air leakage. The type A as shown in Fig. 2(a) is an air-cell with high leakage, but the type B is made of a fabric with low leakage property. The type C is a hybrid-type air-cell using the fabrics used for the type A and the type B. All air-cells are cylindroid shape, and the size of all air-cells is 110x850x180 [mm] (WxDxH). In this study the type B and type C air-cells were used for the proposed air-cell mattress with considerations of control and prevention effectiveness. And each air-cell is configured at proper positions such that the type B is applied to light parts like legs instead of the type C.

The proposed air-cell mattress is composed of the type B air-cell except for some parts to be easily developed the pressure ulcer as shown in Fig. 3, and totally eighteen air-cells are used for the mattress. For the control effectiveness, we control the pressure of mattress for each section divided into four sections that are composed of 3, 4, 5, and 6 air-cells, respectively. And each section is corresponding to four body parts: head, trunk, hip, and leg. The mattress size is 2000x850x180 [mm] (WxDxH).

(a) type A (b) type B (c) type C

Fig. 2 Three types of air-cell.

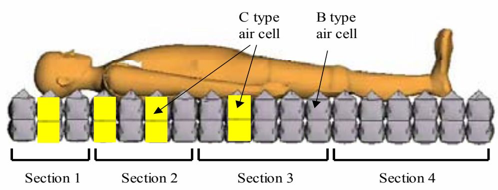


Fig. 3 Air-cell mattress composed of eighteen air-cells.

3. CONTROL SYSTEM OF AIR-CELL MATTRESS

3.1 Approximate anthropometric model

There were studies that generalize body segments from anthropometric data. Based on a standard anthropometric model presented by [7], we propose an *approximate anthropometric model* to calculate the reference pressure of each segment of mattress.

We divide the body into four sections as the mattress segmentation such as head, trunk, hip and leg. The length of each section is obtained by a relative length to the body height, h, as shown in Fig. 4. Here the shapes of each part are the sphere for head, the cylinder for leg, and the hexahedron for trunk and hip, respectively. Assuming that the maximum contact areas of each part are the surface of a half of the sphere and the cylinder for the head and leg, and the bottom area of hexahedron for trunk and hip, we can calculate the maximum contact areas as the following equations.

$$A_{head} = 2\pi \cdot (0.065h)^2 \qquad (4)$$

$$A_{trunk} = 0.240h \cdot 0.174h \qquad (5)$$

$$A_{hip} = 0.253h \cdot 0.191h \qquad (6)$$

$$A_{leg} = 2\pi \cdot 0.0275h \cdot 0.377h \qquad (7)$$

In above equations, A_{head}, A_{trunk}, A_{hip}, and A_{leg} are the maximum contact areas of each parts. As the same manner,

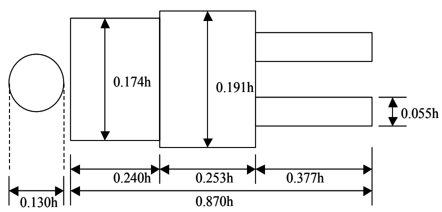


Fig. 4 The proposed approximate anthropometric model.

Table 1 Approximate weights of each part of body.

Part of body	Head	Trunk	Hip	Leg
Weight	0.081*w*	0.355 *w*	0.342 *w*	0.222 *w*

the weights of each part are also approximated as Table 1 [7]. From the estimated maximum contact area and the part weight, the reference pressure of each section is obtained by Eq. (3).

3.2 Pressure control system

The pressure control system for the air-cell mattress is composed of real-time controller, pressure sensor, solenoid valve, and compressor. We utilize a microprocessor (ATMega -128, ATMel Co.) embedded ADC, serial I/F, PWM output, and other input-output ports for the real-time controller. Since the mattress is composed of four sections, four pairs of pressure sensor and solenoid valve are set up for each section, respectively. GUI system to input user's information such as body height and weight is made of LCD and key switches. The control software is performed on a preemptive real-time kernel, uCOS-II [8], and it is composed of six tasks totally. Four tasks for pressure control of each section are executed with 20 [msec] cycle, and key processing and ADC tasks are executed with 100 [msec] and 50 [msec] cycle, respectively. The solenoid valve is driven by PWM of which duty rate is proportional to the difference from the reference pressure. If the sensed pressure is higher than the reference pressure, the valve is closed until air pressure is the same as the reference pressure by air leakage, because the control system has no outlet valve. In Fig. 5, the implemented air-pressure control system is shown.

4. EXPERIMENTAL RESUTLS

We performed a comparison experiments with two commercialized mattresses. In the experiments, we selected body pressure distribution and body posture as the evaluation items. The body pressure is measured by a contact-type pressure sensor array (FSA Bed system, VISTA medical Co.) that has 10% error tolerance. Fig. 5 shows a body pressure distribution of a user lying on a generic mattress without any air-cell. The user's height and weight was 169 [cm] and 61 [Kg]. In the generic mattress, higher pressure more than 100 [mmHg] is forced to occipital, scapula, elbow, sacrum, and heel as shown in Fig. 6.

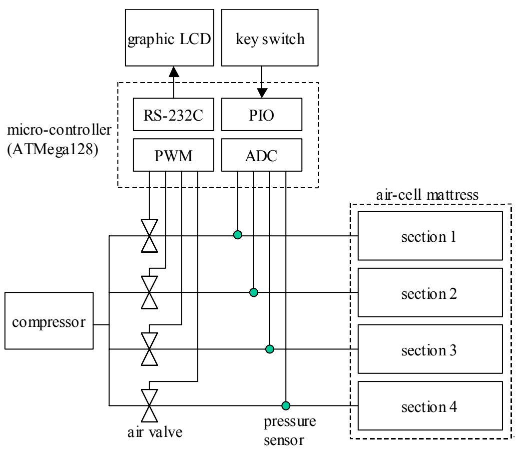


Fig. 5 Pressure control system for the air-cell mattress.

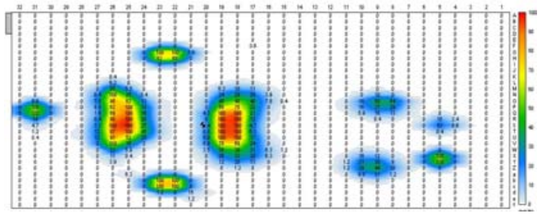


Fig. 6 Body pressure on generic mattress.

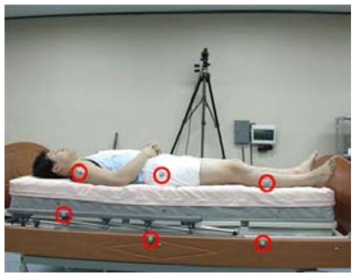


Fig. 7 Attached reflective markers on body and bed for measuring body posture.

The body posture is measured by hip flexion angle obtained by a motion analysis system with six infrared CCD cameras (Vicon 370, Oxford Metrics Co.). For measuring the body posture, the infrared makers were attached on the gleno-humeral joint, hip joint, shank link, and both hip sides as shown in Fig. 7. The subject's posture for the measurement is the dorsal decubitus with which the limbs are relaxed.

For the data reliability, we only use a data set measured in the steady state. The subjects are five men and two women under 30 years old. The average height and weight were 171.8 ± 12.7 [cm] and 70.8 ± 16.6 [Kg]. As the commercialized mattresses, we use a mattress controlled by a static pressure value, which is called *Y_mat*.

Another is a mattress of which the pressure reference is controlled by user's weight only [6]. We call this mattress as *C_mat*. Two mattresses commonly have a function to control pressures alternatively between odd and even rows, but the air pressure of all air-cells is controlled by a uniform pressure value.

4.1 Comparison of body pressure distribution

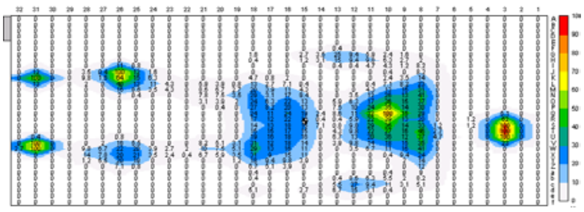
We compared the average and the maximum pressure of the proposed mattress called *KOREC_mat* to the distribution of *Y_mat* and *C_mat*.

Fig. 8 shows the body pressure distribution of three types of air mattress for a standard subject with 169 [cm] and 61 [Kg]. *Y_mat* had the highest body pressure than others, because its main control target is to reduce the contact time only by alternating air-cells. *C_mat* controls the air pressure considering user's weight, so it showed good pressure distribution than *Y_mat*. However, the maximum pressures at some parts were higher than 32 [mmHg]. This means that it has a possibility to develop the pressure ulcer. The *KOREC_mat* showed lower pressure distribution not only the average pressure but also the maximum pressure.

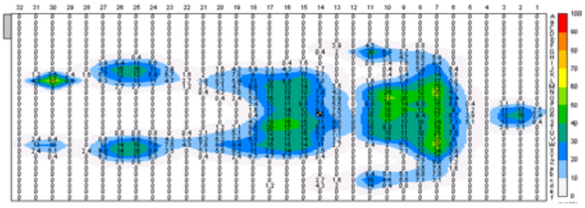
Table 2 shows the experimental results for six subjects. The experiments were performed three times, and the average and the maximum value are the mean of the three measures. The result shows that the average pressure of all mattresses satisfies the limit pressure, 32 [mmHg], but the maximum pressures are higher than the limit pressure except the *KOREC_mat*.

Table 2 Body pressures of six subjects according to three air-cell mattresses.

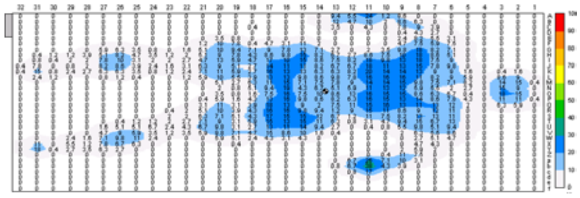
Subjects		*Y_mat* [mmHg]				*C_mat* [mmHg]				*KOREC_mat* [mmHg]			
		Head	Trunk	Hip	Leg	Head	Trunk	Hip	Leg	Head	Trunk	Hip	Leg
Subject 1 (189cm, 79Kg)	Avg.	23.7 ±2.8	14.0 ±1.7	12.0 ±2.5	11.3 ±0.9	19.9 ±7.1	9.5 ±1.1	8.5 ±0.3	8.7 ±0.5	9.2 ±1.8	7.1 ±0.3	7.6 ±0.4	4.2 ±0.2
	Max	94.7 ±9.2	87.6 ±21.4	75.6 ±30.8	72.0 ±30.2	75.6 ±26.1	50.6 ±20.0	39.6 ±15.0	52.6 ±16.2	25.0 ±4.5	23.0 ±1	21.6 ±2.9	11.6 ±4.6
Subject 2 (175cm, 67Kg)	Avg.	31.5 ±30.8	13.4 ±1.3	10.2 ±1.3	13.2 ±3.1	11.0 ±3.8	9.9 ±1.0	8.5 ±0.7	7.5 ±0.2	9.2 ±0.6	8.4 ±0.2	7.6 ±0.4	4.3 ±0.2
	Max	72.0 ±48.5	100 ±0	61.6 ±34.5	87.6 ±21.4	19.3 ±3.2	32.3 ±6.1	27.0 ±7.0	50.0 ±13.9	24.33 ±7.7	25.6 ±6.4	20.0 ±1.7	19 ±1.7
Subject 3 (180cm, 82Kg)	Avg.	16.9 ±13.2	11.9 ±2.4	10.8 ±1.1	10.1 ±1.2	15.6 ±80.	8.6 ±0.8	9.7 ±1.1	9.7 ±0.9	8.9 ±1.1	8.1 ±0.4	9.0 ±0.9	5.4 ±2.5
	Max	47 ±45.9	78 ±27.1	55.0 ±15.1	69.0 ±26.7	50.0 ±43.6	39.3 ±7.5	30.3 ±6.7	45.3 ±11.1	24.3 ±5.0	25.6 ±6.4	20.0 ±3.0	19.0 ±0.6
Subject 4 (179cm, 97Kg)	Avg.	18.0 ±11.1	14.3 ±1.2	14.0 ±2.1	13.2 ±5.5	13.7 ±11.3	10.4 ±2.1	9.9 ±1.1	8.9 ±2.7	9.2 ±0.3	10.0 ±4.4	9.5 ±0.3	5.0 ±0.4
	Max	63.0 ±47.5	72.0 ±14.9	75.5 ±10.0	84.0 ±46.9	22.0 ±42.1	35.0 ±44.4	39.5 ±17.0	44.5 ±48.2	34.0 ±1.2	27.0 ±4.9	39.3 ±8.0	13.6 ±1.0
Subject 5 (154cm, 64Kg)	Avg.	41.7 ±6.1	17.0 ±0.1	12.3 ±0.7	9.9 ±1.5	15.6 ±3.7	13.0 ±1.4	9.6 ±1.4	8.0 ±2.0	6.5 ±3.2	8.9 ±2.0	9.7 ±0.1	5.7 ±2.3
	Max	100 ±0	100 ±0	77.5 ±31.8	72.0 ±39.6	43.0 ±12.4	36.5 ±36.8	28.5 ±15.1	48.5 ±42.6	22.3 ±25.7	48.6 ±21.7	26.0 ±8.7	24.6 ±11.5
Subject 6 (157cm, 46Kg)	Avg.	12.6 ±6.2	9.7 ±0.3	11.5 ±1.3	9.2 ±5.0	7.8 ±0.2	6.3 ±0.4	7.87 ±0.1	6.07 ±0.1	5.9 ±0.2	5.4 ±0.14	5.0 ±0.1	3.7 ±0.1
	Max	100 ±0	83.0 ±24	49.5 ±20.5	56.0 ±62.2	24.0 ±0.7	18.5 ±0.7	22.0 ±1.4	18.0 ±0	17.5 ±0.7	14.5 ±0.7	13.0 ±0	14.0 ±0



(a) Pressure distribution of *Y_mat*



(b) Pressure distribution of *C_mat*



(c) Pressure distribution of *KOREC_mat*

Fig. 8 Body pressure distributions of the dorsal decubitus for a standard subject with 169[cm] height and 61[Kg] weight.

4.2 Comparison of body posture

For a sound sleep, it is important to preserve appreciate the COG position and the hip flexion angle. The COG is measured by the pressure sensor array. Fig. 8 shows the COG position according to three mattresses. In this study the COG position means the distance from the top of head to the COG. In Fig. 9, *Y_mat* and *C_mat* have large variations because air-cells of them were controlled alternatively between odd and even rows. But the *KOREC_mat* well preserved a uniform COG position.

We also compared the hip flexion angle, because the heavy weight causes that the hip falls into the mattress and that

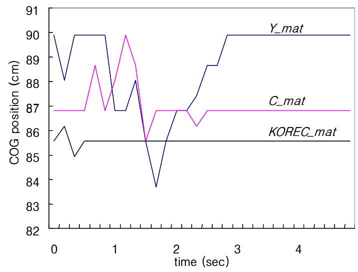


Fig. 9 Variation of COG by three types of air-mattress for the standard subject.

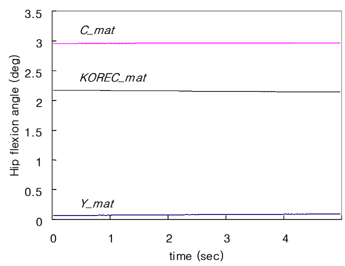
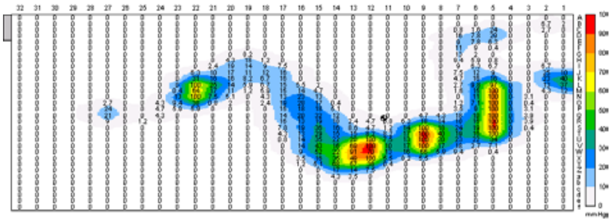


Fig. 10 Variation of hip angle by three types of air-mattress for the standard subject.

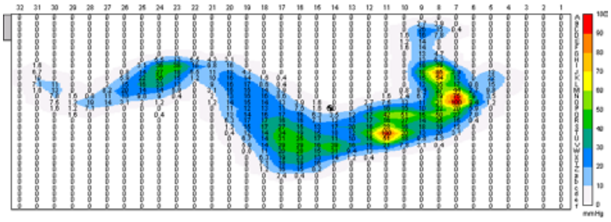
disturbs a sound sleep. As a result, *Y_mat* had less flexion angles since it controlled the pressure of the air-cell with high pressure (see Fig. 10). This caused high body pressure. But the hip flexion angle of *C_mat* was about 2.9 [deg]. This was higher than *KOREC_mat*, 2.0 [deg], because it did not consider the difference of weight according to the part of body.

4.3 Comparison of body pressure distribution of the lateral decubitus

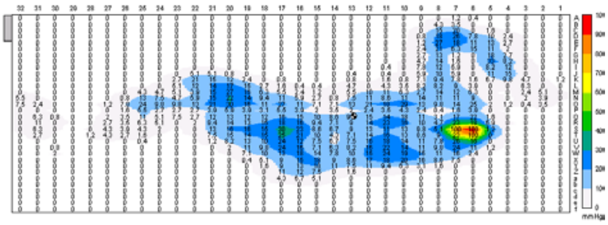
We experimented the body pressure distribution of the lateral decubitus posture. The experiments were performed to the standard subject with 169[cm] height and 61[kg] weight, and the target pressure of the air-mattress was set to the same pressures as the experiments for the dorsal decubitus.



(a) Pressure distribution of *Y_mat*



(b) Pressure distribution of *C_mat*



(c) Pressure distribution of *KOREC_mat*

Fig. 11 Body pressure distribution of the lateral decubitus for a standard subject with 169[cm] height and 61[Kg] weight.

Fig. 11 shows the distributions of body pressure of the lateral decubitus, and the pressure values at each part of body are shown in Table 3. The *KOREC_mat* also has excellent pressure distribution properties. But, a high pressure was shown in the shoulder part, which was caused by high loads on the narrow contact area on the lateral shoulder (see Fig. 11(c)).

Table 3 Body pressures of the lateral decubitus for the standard subject.

Part of body	*Y_mat* [mmHg]		*C_mat* [mmHg]		*KOREC_mat* [mmHg]	
	Avg.	Max	Avg.	Max	Avg.	Max
Head	10.4 ±0.6	34.6 ±2.3	10.1 ±0.9	21.6 ±3.2	4.6 ±3.3	10.5 ±8.3
Trunk	13.5 ±0.2	100 ±0	19.5 ±2.9	100 ±0	9.1 ±3.0	72.0 ±48.5
Hip	20.9 ±0.1	100 ±0	12.3 ±0.4	40.3 ±7.0	8.9 ±1.8	25.3 ±8.1
Leg	14.8 ±0.1	100 ±0	10.4 ±0.3	41.6 ±3.1	5.8 ±1.3	24.0 ±4.5

5. CONCLUSION

In this paper we proposed a novel air-cell mattress for preventing pressure ulcer often developed to the disabled and the elderly persons [9]. Since the external pressure is the primary cause to develop the pressure ulcer, we proposed a method to distribute the external pressure based on the approximate anthropometric model. The proposed air-cell mattress composed of eighteen cylindrical air-cells was made of porous material allowing air leakage to contribute in reducing the development of pressure ulcer by dispersing the pressure peak, temperature and humidity. To determine an optimal air-cell pressure appropriate for each user, the body was divided into four sections such as head, trunk, hip, and leg. Then, the pressure of each section was independently calculated from each weight of parts based on the individual body height and weight and the approximate anthropometric model.

From the comparison experiments with seven subjects, we showed that the proposed air-cell mattress was effective for the prevention of the pressure ulcer.

As a future work, we will test a medical feasibility by measuring the flow and pressure of blood.

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