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Original Article

Finding the Optimal Setting of Inflated Air Pressure for a Multi-cell Air Cushion for Wheelchair Patients with Spinal Cord Injury

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Pressure distribution patterns of the seating interface on the multi-cell air cushion (ROHO High Profile) of 36 adults with spinal cord injury (SCI) (Neurological level Th3 -L1) were measured at different air pressure levels by a pressure mat measurement system. Stress distribution relative to the inflated air pressure in the air cushion on the patients' wheelchairs was analyzed to determine the appropriate inflated air pressure of the cushion for patients. The maximum pressure points in all subjects were at the areas of the ischial tuberosities (82 to 347 mmHg). The optimal reduction in interface pressure at the ischial tuberosities was obtained just before bottoming out. The cushion air pressure at that point was between 17 and 42 mmHg, and correlated well to body weight ($r = 0.495$, $P = 0.0021$). In contrast, the maximum pressure levels did not correlate to body weight or the Body Mass Index (BMI). Pressure at the ischial area could be reduced, but not eliminated, by adjusting the air pressure. The maximum pressure levels seemed to be related to the shape of the buttocks, especially the amount of soft tissue, and exceeded the defined threshold for pressure ulcers (> 80 g/cm^2).

Key words: spinal cord injury, decubitus ulcer, cushion, pressure, wheelchair

When pressure ulcers develop in the seating surface of patients with spinal cord injury (SCI), the patients' quality of life may be reduced. Many factors affect the development of pressure ulcers in SCI: such as seating pressure, shearing-force, the temperature and moisture content of the skin, tissue viability, hygiene and nutritional status [1-6]. A number of methods of prevention have been reported [5, 7-10].

In active persons with SCI, the most prevalent site of pressure ulcers is the skin over the ischial tuberosities [4], because the patient's body weight concentrates to the ischial site in a seated position [11]. The emphasis on relieving the pressure around the ischial tuberosities in order to alleviate the high concentration of pressure has resulted in a variety of wheelchair cushion designs [12-14]. Among those cushions, a multi-cell type of air cushion was found to be more effective in relieving pressure at the seating surface than the other cushions available [11, 15-17]. Pressure of the seating surface varies according to inflation of the cushion. In 1986, Krouskop *et al.* [18] studied the effect of inflation pressure on performance in an air-filled cushion. However, the data (6 normal volunteers and 8 SCI patients) were combined in the analysis. From the clinical observations, muscle tones of SCI patients are different from normal volunteers and presumably pressure distribution

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are also differed. The purpose of the current study was to systematically determine the appropriate air pressure of the ROHO cushion for SCI patients. A reliable method for determining this would be of great clinical value.

Materials and Methods

Subjects (Table 1). Between 1999 and 2001, the subjects were 36 adults with SCI enrolled in the rehabilitation program at the Kibikogen Rehabilitation Center for Employment Injuries, all of who agreed to participate in this study. Written informed consent was obtained from all participants. All were paraplegic, and their neurological level ranged from Th3 to L1. All but one were classified as having complete paralysis (impairment scale A, based on the ASIA International Standard) [19]. One patient was classified as impairment scale B. In the study group, there were 30 patients with a history of decubitus ulcers, all with good balance.

The mean age of the 36 patients was 40.1 ± 15.9 years (18–71 years). There were 28 males and 8 females. The time between injury and examination was 81.5 ± 130.1

Table 1 Detail of subjects

Number	Age (yr)	Sex	Level	Body weight (kg)	BMI	Inflation pressure at PMP (mmHg)	Maximum pressure at PMP (g/cm²)	Area of high concentration at PMP (cm²)
1	23	f	Th3	41.6	18.2	17	87.3	8
2	26	m	Th4	52.0	18.4	28	206.0	52
3	27	f	Th4	51.0	21.0	21	100.2	10
4	48	m	Th4	57.0	18.8	19	184.5	33
5	56	m	Th4	79.0	26.4	42	88.3	11
6	22	f	Th4	60.1	23.8	24	130.4	38
7	62	m	Th4	61.0	22.4	27	159.1	71
8	35	m	Th4	57.0	21.7	22	88.2	4
9	28	f	Th5	56.7	21.1	29	94.7	12
10	24	m	Th5	50.4	18.5	26	125.7	27
11	29	m	Th6	41.1	11.8	25	346.5	51
12	37	m	Th6	66.3	23.5	25	100.6	14
13	23	m	Th6	67.0	21.9	29	344.1	68*
14	25	m	Th6	53.0	18.3	22	99.7	16
15	24	m	Th7	56.8	20.4	25	95.9	13
16	18	m	Th7	67.5	21.1	27	150.8	53
17	66	m	Th9	50.6	21.1	26	145.4	51*
18	30	m	Th9	60.0	21.3	26	114.3	84
19	29	f	Th9	59.3	23.8	20	92.8	9
20	71	m	Th10	51.0	17.6	23	96.4	25
21	59	f	Th10	47.5	21.1	17	134.4	28
22	57	m	Th10	64.5	24.6	33	153.2	199*
23	59	m	Th10	67.7	24.6	31	170.8	124*
24	52	m	Th11	60.5	22.8	26	90.6	11
25	34	m	Thl2	42.0	14.9	30	124.4	29*
26	47	m	Thl2	53.5	19.7	22	229.4	24
27	49	m	Thl2	71.0	22.9	27	280.9	64
28	40	m	Thl2	75.0	24.2	28	213.0	115*
29	21	f	Thl2	60.0	22.3	17	261.9	61*
30	21	m	Thl2	47.3	17.2	29	167.1	21
31	51	f	Thl2	41.1	18.7	25	193.5	60
32	33	m	Thl2	49.0	15.3	20	138.5	50*
33	51	m	Thl2	61.5	23.4	19	98.0	32*
34	64	m	Th12B	39.0	14.3	25	138.6	19
35	42	m	Li	81.8	26.7	32	117.6	60
36	61	m	Li	68.0	28.3	28	203.1	49*

B, Impairment scale B based on the ASIA International Standard. f, Female; L, Lumbar spine; m, Male; Th, Thoracic spine;
*, Area of high concentration (> 80 g/cm²) was not smallest at PMP.

months (6–495 months). The mean body weight was 57.4 ± 10.7 kg (39.0–81.8 kg), mean height 166.0 ± 8.5 cm (150.0–187.0 cm) and mean Body Mass Index (BMI) 20.9 ± 3.6 kg/m^2 (11.8–28.3 kg/m^2). All 36 lived independently, and were using the same cushion used in the current study (ROHO High Profile type, ROHO Co. Inc., IL, USA). This air cushion is made of 64 rubber cells, and is popular among patients with SCI at the rehabilitation center.

In the current study, the patients' wheelchairs (Models: MX, Integral, GWX, VWX, by OX Engineering Co. Ltd., Chiba, Japan) were used without altering the height of the footrests. The seat dimensions varied according to the leg length and hip width of the patients: lengths; 350, 380, and 420 mm, and widths; 340, 360, 380, 400, and 420 mm. The seats were 70 mm higher at the front than at the back, which made seat angles of 9.5 degrees, 10.4 degrees, and 11.3 degrees, respective to the seat length.

Equipment (Fig. 1). Pressures were recorded by the Tekscan pressure measurement system (Big-Mat 2000, a flexible sensor mat with a 2064 cell (43 × 48) matrix, Nitta Co., Osaka, Japan). Each matrix unit (1 cm^2) measured the pressure in one area. The measuring error was estimated to be from ± 7 to ± 10% [11, 16, 20]. The sensor seat was connected to a personal computer (NEC PC 9821NE) through an interface board. A digital manometer (HEM-711 Fuzzy, Omron Co., Kyoto, Japan), which was modified by an engineer from the Kibikougen Rehabilitation Center for Employment Injuries, was connected to the inflation valve of the cushion in order to measure the air pressure.

Fig. 1 Measurement system.

Procedures. All measurement took place while the subjects sat on their prescribed wheelchairs at rest in a neutral (or comfortable) position. The subjects placed their trunk against the backrest, and hands in their lap as usual. The patients wore casual clothes. The sensor mat was placed between the patient and the ROHO cushion for the pressure distribution measurement.

The cushion was prepared on a hard examination table by over-inflation of all cells, and then the valve was opened for a few min until the internal cushion pressure and external air pressures equalized. The valve was then closed. The measurement cycle began approximately 8 min from the first setting or passive deflation. The patients was lifted to the flat examination table, and seated on the mat, which was on the cushion on the table. After 1 min, the sensor mat was calibrated. Then the sensor mat was removed, and allowed the recommended 3 min for recovery [15]. During recovery, the cushion and patients were returned to the wheelchair. At the end of the recovery period, the patients pushed themselves up using their arms, to allow the mat to be placed on the cushion. After 1 min of sitting, the pressure distribution and cushion pressure were recorded. The patients then pushed up in the chair as the mat was withdrawn. The patients lowered their body onto the cushion while the air pressure was released through the air valve of the cushion. After the cushion pressure stabilized and the sensor mat recovered (3 min), the next round of calibration and recording was begun. The measurement process in the wheelchair was repeated. The cycle was: pressure valve adjustment during sensor mat recovery, 3 min; calibration, 1 min; sensor mat recovery, 3 min; pressure distribution recording, 1 min. Data were collected for each subject at 4 or 5 different inflation air pressures from approximately 40 mmHg to 15 mmHg. Measurement ceased after the patients' buttocks reached to the bottom of the cushion. Seventeen patients reached the bottom on the fourth measurement.

The computer monitor displayed the distribution of areas of pressure concentration beneath the contact surface of the buttocks as a monochrome gradation (Fig. 2). The total seating surface area (cm^2) was defined as areas of pressure greater than 10 g/cm^2. The maximum pressure value (g/cm^2) and areas of high concentration (defined as > 80 g/cm^2) were measured.

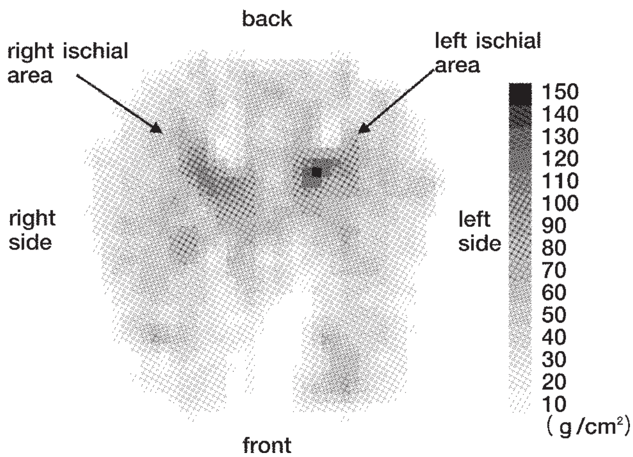

Fig. 2 The computer monitor displayed the distribution of areas of pressure concentration beneath the contact surface of the buttock as a monochrome gradation. This example is the pressure distribution of subject No.17 at an inflated pressure of 26 mmHg.

Results

The highest pressure points in all subjects were at the ischial areas. The seating surface area changed from 672 to 1630 cm^2 (1136.6 ± 190.1 cm^2) (Fig. 3). The maximum pressure changed from 87.3 to 439.2 g/cm^2 (196.6 ± 85.2 g/cm^2) (Fig. 4). The areas of high concentration (> 80 g/cm^2) changed from 4 to 220 cm^2 (62.3 ± 41.4 cm^2) (Fig. 5).

From these findings, we observed that there is a definite point at which the cushion pressure provided the lowest amount of concentrated pressure on the contact area (point of minimum pressure: PMP) (Fig. 6). Fig. 6 indicates the relationship between the cushion pressure and the maximum pressure on the contact surface. At the PMP, the inflated air pressure was 25.3 ± 25.6 mmHg (17–42 mmHg), seating surface was 1158.3 ± 190.3 cm^2 (672–1517 cm^2), maximum pressure was 154.6 ± 69.1 g/cm^2 (87.3–346.6 g/cm^2), and area of high concentration (> 80 g/cm^2) was 44.3 ± 39.3 cm^2 (4–199 cm^2). The areas of high concentration (> 80 g/cm^2) were smallest at PMP (26 subjects) or near PMP (10 subjects; the

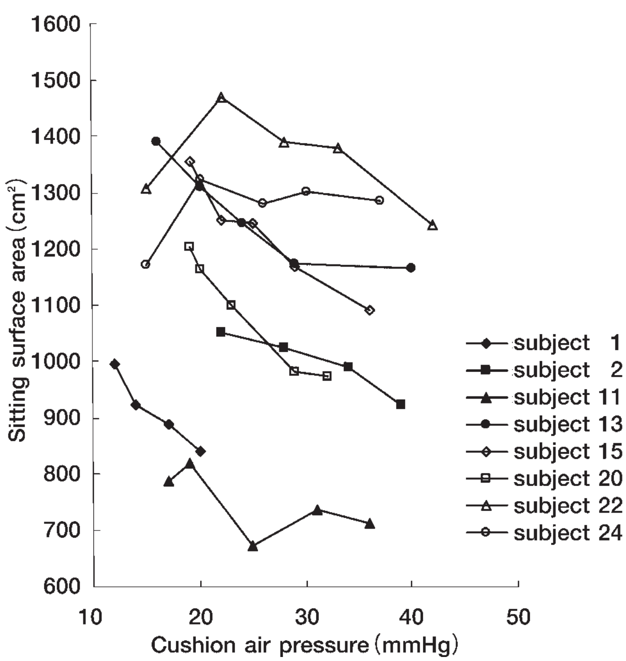

Fig. 3 Changes in cushion air pressure (mmHg) and the seating surface area (cm^2) in 8 representative subjects.

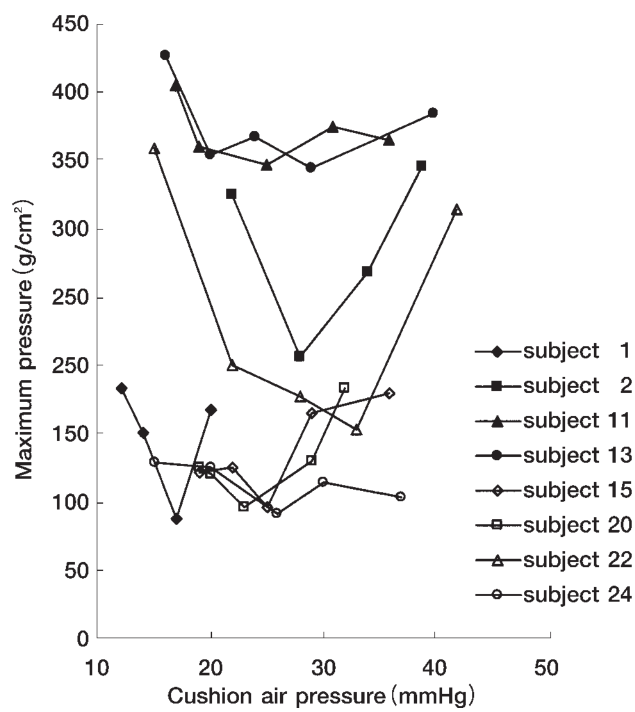

Fig. 4 Relationship between the maximum pressure within the sitting surface (g/cm^2) and the cushion air pressure (mmHg) of 8 representative subjects.

difference of the air pressure to PMP were 5.9 ± 3.2 mmHg (1–12 mmHg)) (Table 1).

There was no significant correlation between the cushion air pressure at PMP and the maximum interface pressure (r = 0.048, P = 0.7810) (Fig. 6). There was no correlation between the maximum interface pressure at PMP and body weight (r = 0.039, P = 0.8206) or BMI (r = 0.147, P = 0.3908). However, the correlation coefficient between the cushion air pressure at PMP and the subjects' body weight was r = 0.495 (P = 0.0021) (Fig. 7).

Discussion

Active persons with SCI spend many hours sitting in their wheelchairs, and a great deal of attention has been focused on maintaining healthy skin in the contact areas. Numerous studies on the relationship between the intensity and duration of pressure on the skin and pressure ulcers have been published [1, 2, 6, 21]. The pressure-time relationship is a parabolic curve, indicating that skin breakdown occurs at low pressure for long periods as well as at high pressures for short periods. Higher interface pressures have been associated with a higher incidence of pressure ulcers [22, 23]. The current study used the findings of Henderson *et al.* [21, 24], which set the safety range below 60 mmHg (81.7 g/cm²) to define the areas recording a pressure of > 80 g/cm² as areas of high-pressure concentration exceeding the pressure ulcer threshold.

When a patient is seated on the air cushion on the wheelchair, most of their weight is distributed on the seating surface, with some divided between the footrest

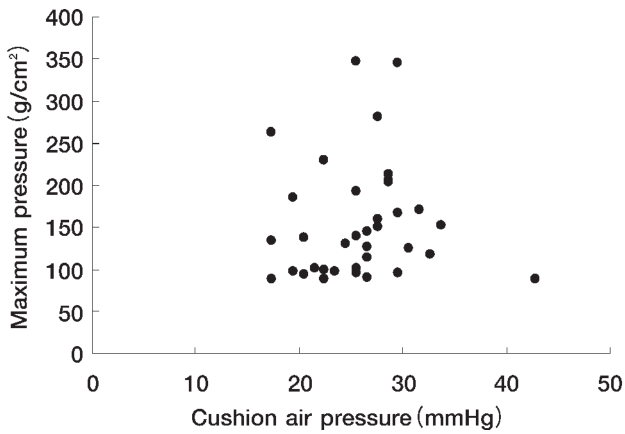

Fig. 6 Cushion air pressure and the maximum pressure in the areas of high-pressure concentration at PMP (the point of minimum pressure) (r = 0.048, P = 0.7810). PMP indicated the level of cushion air pressure at which the surface contact pressure was lowest in the areas of high-pressure concentration.

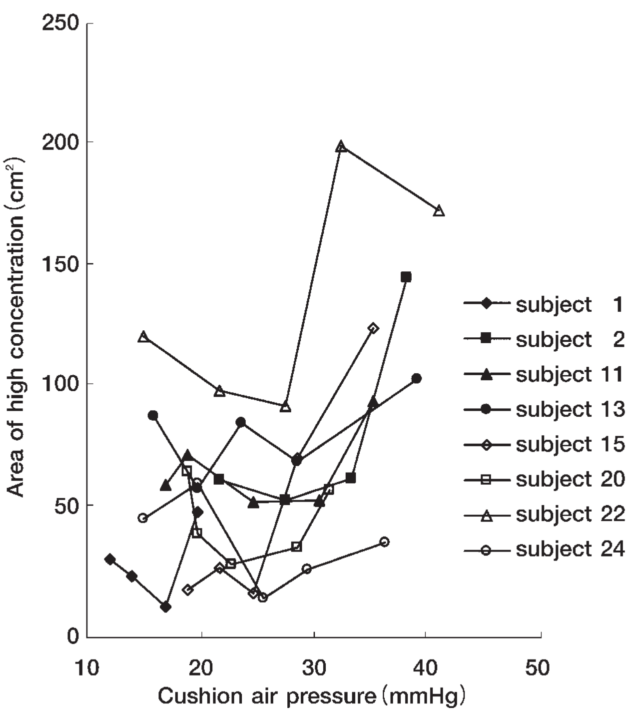

Fig. 5 Changes in the areas of high-pressure concentration > 80 g/cm² (cm²) and inflated air pressure (mmHg) of 8 representative subjects.

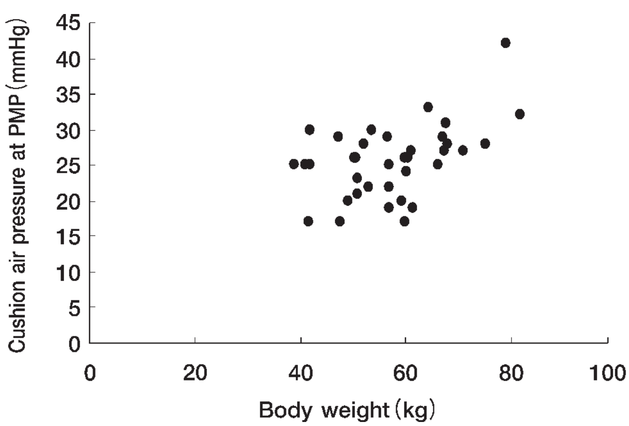

Fig. 7 Cushion air pressure at PMP and the body weight (r = 0.495, P = 0.0021). Patients with a higher body weight had higher-pressure levels in the cushion at PMP.

and backrest [25]. This weight loading on the seating surface is almost in proportion to their body weight (r = 0.819, $P < 0.0001$) (Fig. 8). Theoretically, the interface pressure reflects this weight, and the pressure is in inverse proportion to the contact area between the buttocks and cushion (Pascal's law). However, the detailed pressure distribution of the seating surface has an uneven pattern. The pressure applied by the hard and prominent areas is higher than that of the surrounding softer tissues. Reduction of the interface pressure widens the contact area, and supports the weight more evenly.

In the current study, the areas of highest-pressure concentration were always under the ischial tuberosities [26]. Pressure was reduced at these points by adjusting the inflated air pressure in the air cushion so as to widen the contact area.

The pressure between the buttocks and seat cushion was influenced by many factors. The factors for the cushion are physical consistency, size, air capacity, shape, material, and air pressure [8, 11, 15, 27]. The human factors that influence pressure distribution are body weight, size and shape of the buttocks, build, the level and nature of paralysis, sitting balance, spinal scoliosis, *etc* [9, 15, 28, 29]. An adjustable wheelchair design also effects the distribution of the body weight [9, 21, 25, 30, 31]. The angle of the backrest (reclining position was excluded) did not significantly affect the maximum pressure [32].

The current study could have been improved by measuring the volume of air removed during deflation as

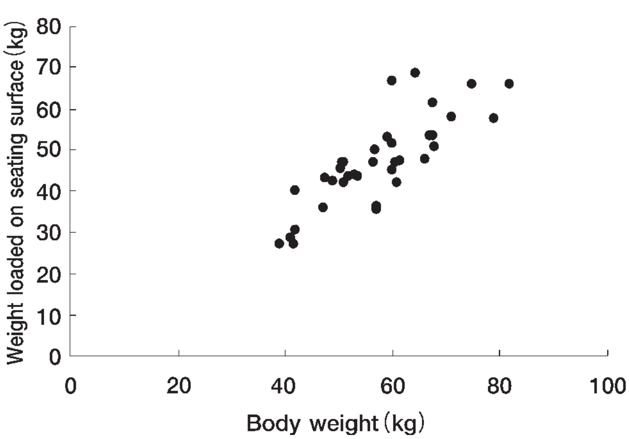

Fig. 8 The amount of weight loaded on the sitting surface was almost in proportion to the subjects' body weight (r = 0.819, $P <$ 0.0001).

well as the air pressure. Adjusting the air pressure is difficult for patients, their caregivers, and their physical therapists. The authors found that by adjusting the air pressure alone, it was difficult to replicate the exact adjustment of the air pressure for each subjects, because it needed a few minuets until the internal cushion air equalized.

Despite numerous publications on the differentiation or effectiveness of pressure relief for wheelchair cushions, few reports have focused on the inflation pressure and interface pressure of the ROHO wheelchair cushion [18]. The determination of optimal air cushion pressure is one means of mediating the complex interrelationship of variables. Individual optimal cushion inflation pressure could be determined relative to the widest pressure distribution on the sensor mat by changing the cushion inflation pressure. The inflated air pressure at PMP was correlated to the subjects' body weight (r = 0.495, $P =$ 0.0021) (Fig. 7), so persons who are heavy require a higher inflated air pressure (Table 1) [18]. It is important to recognize that PMP is obtained just before bottoming out, and that the pressure value remained higher than the level considered safe. In a clinical setting, the inflated air pressure should be kept slightly higher than the pressure at PMP to create space between the buttocks and the wheelchair seat, in order to compensate for body movement and vibration. The manufacturer recommends a degree of inflation that maintains space between the individual's deepest prominence and the cushion base. This prevents bottoming out during movement.

Krouskop *et al.* [18, 33] stated that there were greater peak seat-interface pressures under the bony prominence of the subjects classified as thin than under subjects who were classified as obese. In the current study, as Brienza *et al.* [8] has reported, the maximum pressure at PMP did not correlate with the subjects' body weight (r = 0.039) or with the BMI (r = 0.147). We considered that the range of maximum pressure in the area of high concentration appeared to be determined by the consistency of the tissue around the ischial tuberosities. The bulk of muscles, distribution of subcutaneous fat, thickness of the skin, and grade of bony protrusion were the factors that contributed to the pressure beneath the ischial tuberosity. A standardized grading system for these factors did not exist at the time of the current study, which was a limitation of the study. However, during manuscript preparation, Aissoui *et al.* [26] published a possible solution. The authors of the current study suggest that the engineering solution proposed by Aissoui *et al.* might be able to represent these factors, in a reduced fashion, by the ratio of the area of high concentration (> 80 g/cm^2) to the seating surface area. This reflects the concentration of the pressure between the buttocks and the cushion [26]. In the current study, the maximum pressure at PMP correlated with the ratio of the area of high concentration to the seating surface area at PMP (r = 0.466, P = 0.0042) (Fig. 9). This high ratio indicates that the ischial tuberosities protruded strongly, and that the weight on the seating surface was mainly concentrated around the ischial tuberosities. This pattern was marked by wide areas of very high-pressure concentration (> 80 g/cm^2) (dark bands in Fig. 2) which corresponded to the ischial tuberosities. Conversely, when this ratio is low, the weight was dispersed widely around the ischial tuberosities, and the areas of high-pressure concentration were small. These patterns differ from those reported in able-bodied individuals, where the pressure was distributed more evenly [26]. A person with SCI and a high ratio may be a candidate for the development of pressure ulcers at the ischial tuberosities.

We can demonstrate that the interface pressure between the buttocks and the air cushion was relieved by the modification of the inflated air pressure of the air cushion. The cushion pressure at PMP varied widely (17 mmHg to 42 mmHg) among the subjects, and correlated to body weight at PMP (r = 0.495, P = 0.0021) (Fig. 7).

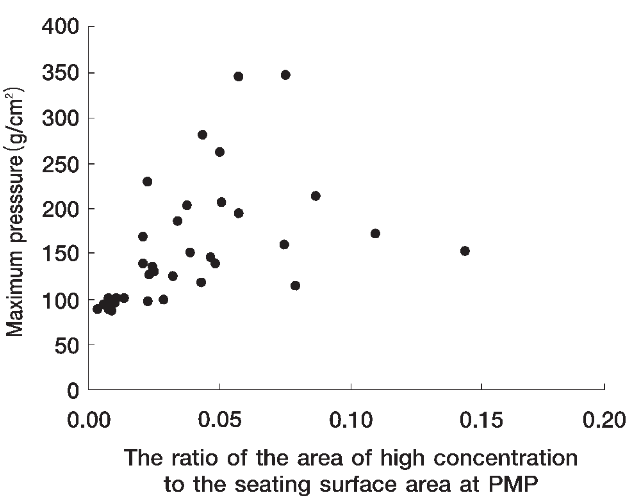

Fig. 9 The maximum surface pressure correlated to the ratio of areas of high concentration to the seating surface area at PMP (r = 0.466, P = 0.0042).

However, the maximum surface pressure at PMP and the body weight did not correlate. The maximum surface pressure at PMP and BMI did not correlate. The maximum pressure at PMP seemed to relate to the shape of the buttocks, especially the amount of soft tissue around the ischial tuberosities. A valid classification system for the human buttocks at a seated position, as well as a new wheelchair cushion made of new material adjusted to the buttocks, would reduce pressure at the ischial tuberosities.

It is necessary to recognize that the lowest pressures at the ischial tuberosities remained higher than the levels considered safe. By changing the cushion inflation pressure, we were not able to bring the interface pressures under the ischial tuberosities below the threshold levels for pressure ulcers. Routine preventive measures, including performing periodical push-ups from the cushion, observation of the skin at the prevalent sites of the pressure ulcers and other methods presented in self-care education during rehabilitation are essential. The clinical usefulness of systematic adjustment of the cushion air pressure to prevent pressure ulcers remains to be determined by subsequent studies.

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