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Comparative biomechanical evaluation of different wheelchair seat cushions

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Abstract—The aim of the present study was to perform a comparative biomechanical analysis of four antidecubitus wheelchair cushions. Thirty wheelchair users were considered divided into three groups: paraplegic subjects (with no cutaneous sensation), neurologic subjects (with intact cutaneous sensation), and elderly subjects. The biomechanical evaluation was performed using a piezoresistive sensor matrix system to quantify parameters referred to pressure distribution, seating surface and posture. Dedicated software was developed for the automatic elaboration of the raw data and the computation of the parameters of interest. Differences among cushion types and subject groups were analyzed. An analysis of time-transient behaviors was also performed. Results showed that no significant differences in pressure peak reduction were found among the four cushions. Moreover, no time-transient behavior was shown by any cushions. However, both the location of pressure peaks and posture were dependent on cushion types. Comparison of the three subject groups showed that elderly subjects had the highest mean pressure and the lowest contact surface, while paraplegics presented the highest pressure peaks. This procedure appears indicated for individualizing the prescription of a wheelchair cushion and even for customizing a cushion to induce a specific posture.

Key Words: *decubitus ulcers, posture, pressure distribution, pressure sores, wheelchair cushion.*

INTRODUCTION

One of the most pervasive and persistent complications affecting people with restricted mobility is decubitus ulcers (otherwise known as pressure sores) induced, by lying or sitting in one position for too long. The main factors involved in the formation of decubitus ulcers are: insufficient vascularization in the tissues subjected to high pressure (mainly under bony prominences) due to the occlusion of blood and lymphatic vessels (1,2); the stagnation of sweat on the skin as a result of inadequate air replacement (3); the presence of local areas of high temperature (1,4); and shear stresses on the skin (5). However, the findings of several experimental studies encourage the view that interface pressure between the body and the sitting (or lying) surface is the principal factor involved in

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the formation of pressure sores. This explains the large body of research and commercially available devices devoted to skin pressure relief. Although there are no conclusive data as to the critical levels of pressure capable of causing the onset of pressure sores, the general recommendation that the least possible pressure be placed on the tissues is widely accepted (1,6–8).

Pressure measurement under the subject's sitting surface using a sensor matrix is the most commonly used quantitative method of analyzing the antidecubitus properties of wheelchair cushions. Other evaluation methods reported in the literature have been based on tissue shape and deformation (9), seat contour (10,11), and thermal properties of cushions (3,12). However, the clinical applicability of these approaches has been limited by technical shortcomings, high costs, and the lack of standardization (9); therefore, most authors still favor sitting pressure measurement.

The aim of this study was twofold: 1) to develop an evaluation and elaboration procedure which, starting from the distribution of interface pressure between the buttocks and the cushion, would provide not only peak pressure values, but also information on the contact surface and the postures associated with specific cushions; and 2) to apply this procedure in three selected groups of wheelchair users: spinal cord injured (SCI) subjects, elderly subjects with motor impairment, and subjects with multiple sclerosis (MS), in order to compare four different antidecubitus cushions, two of which present innovative design solutions.

Increasingly, devices able to analyze pressure distributions are being used in clinical environments (13,14). The technical characteristics of these devices (accuracy, linearity, hysteresis, temperature drift, sampling frequency, and so forth) depend on the kind of sensors used—piezoresistive, capacitive, or pneumatic (15). However, all provide the distribution of pressure on the contact surface between cushion and buttocks. The most widely used parameters computed from pressure distribution are maximum peaks of sitting pressure and their location on the buttocks, with particular reference to specific bony prominences, such as ischial tuberosities or sacral bone (7,14,16,17).

It appeared to us that other interesting parameters could be obtained from the pressure map. Accordingly, the first goal was to exploit the information content of the pressure distribution by means of dedicated elaboration of the acquired data and computation of innovative parameters.

Regarding the use of this procedure to evaluate different cushions and subject groups, we sought to verify whether any common features could be found among subject groups or cushion types, in order to establish general guidelines for cushion prescription.

The thermal properties of the four cushions considered in this paper were analyzed in a previous study using an infrared thermographic system (12).

METHODS

Experiments were performed on four types of antidecubitus cushions, using a biomechanical method to quantify parameters related to the distribution of interface pressure between the buttocks and cushion in a static posture (18).

The measuring system consisted of a matrix of piezoresistive pressure sensors (Tekscan Inc., Boston MA). The resistance of each sensor was a function of the perpendicular force exerted on it. The matrix used in the present study measured 49 × 53 cm and was approximately 0.1 mm thick. There were 42 rows and 48 columns of sensors, giving a total of 2,016 sensors. The area of each sensor was 7 × 7 mm=49 mm^2. The intersensor distance was 3 mm. The acquisition frequency was set at 20 Hz. The stated working range was 0–255 mmHg, with a resolution of 1 mmHg. In our application, a magnitude threshold was set at 3 mmHg for noise reduction. A customized A/D converter connected the sensing pad to a PC that supported data recording, processing, and graphic presentation application software.

The system required equilibration before use, in order to compensate for any inevitable heterogeneity due to construction and usage problems. Equilibration was performed by applying an even pressure to the whole surface of the sensing pad through an inflatable rubber diaphragm (placed between the sensor and a weight), and calculating the weight factor to be attributed to each sensor in order to obtain a homogeneous pressure distribution.

The system was also calibrated to assign absolute pressure values to the digital output, from the A/D converter connected to the sensing pad. This was done by applying a pressure distribution as similar to the actual test conditions as possible, with a known total load value. For this purpose, we used a wooden mannequin replicating the shape of the buttocks and the thighs, to which lead

disks, simulating different body weights, were applied. The results of both operations were saved on file for use during the actual tests.

The acquisition protocol was designed to evaluate the cushions under normal conditions, with several fixed parameters to assure test reproducibility. During each trial, the cushion was placed on the seat of subject's own wheelchair. The subject was then seated comfortably with arms folded and feet on the footrests, which were regulated to keep the joints flexed at 90º. The pelvis was placed as far back on the seat as possible with the thighs in a level position. The seat surface was horizontal and the backrest was tilted backwards by no more than 10º depending on the subject's comfort. This posture, which was controlled with an anatomical goniometer, was defined in accordance with the previous studies of Ferguson-Pell et al. (15) and Hobson (17).

Data acquisition was performed after 1, 5, 10, and 15 min from the moment the user sat down on the cushion. Each acquisition lasted 1 s, during which time the subject was asked not to move. This repetition allowed us to elucidate any differences in temporal, transient behavior among the cushions. Tests with control subjects and with the calibration mannequin were carried out in a preliminary phase to check the stability and accuracy of the measuring system. A dedicated program to elaborate pressure data obtained by the acquisition instrument was developed in Matlab® software (The MathWorks Inc., Natick, MA). Specifically, it performed the following functions:

- artifacts rejection (due, for example, to folds on the sensor edges)
- time averaging on different acquisition frames
- data spatial filtering (using a 3×3 square moving average)
- data interpolation (by means of cubic splines) when some sensors were not working or artifacts were present inside the contact surface
- data presentation in terms of isobar graphs, colored code pressure maps, and three dimensional (3-D) graphs, and
- the computation of three classes of parameters: pressure, postural, and surface.

Pressure parameters were: maximum pressure peak value (p_{max}), peak values in critical anatomical areas (p_{it}–ischial tuberosities, p_s–sacrum, p_{gt}–great trochanters), total mean pressure value (p_m) and standard deviation (p_{SD}) of the pressure value distribution on the entire contact surface—defined as the area where the pressure value was ≥3 mmHg. In particular, p_{it} and p_{gt} were computed as the average of the left and right peak values under the respective bony prominence, to avoid the influence due to incorrect lateral pelvic obliquity (since the asymmetry was taken into account by the parameter p_{diff} (see later) and absolute peak value by parameter p_{max}).

The following formulas were used to compute the parameter p_m and p_{SD}:

$$p_m=\frac{1}{N}\sum_{x=1}^{Nr}\sum_{y=1}^{Nc}p(x,y) \qquad [1]$$

$$p_{SD}=\sqrt{\frac{1}{N}\sum_{x=1}^{Nr}\sum_{y=1}^{Nc}(p(x,y)-p_m)^2} \qquad [2]$$

Where:
p(x,y)=Pressure value measured by sensor x, y of the matrix (only where p ≥3 mmHg)
N_r=Number of rows of the sensor matrix (42 in our case)
N_c=Number of columns of the sensor matrix (48 in our case)
N=Number of sensors which measured a pressure value ≥3 mmHg

The p_{SD} parameter indicated pressure dispersion around the mean value. Therefore, a small p_{SD} value signified a fairly uniform pressure distribution (a perfectly flat distribution would present a p_{SD}=0) while a high p_{SD} value indicated an uneven distribution with sharp pressure peaks. The anatomical points corresponding to the ischial tuberosities, the sacrum and the great trochanters were identified through the isobars plot in which these regions can be detected from the presence of pressure peaks. The position of the ischial tuberosities could be detected in all subjects in the study, regardless of the sitting modalities (see below). In some cases, the position of sacrum and great trochanters could not be recognized due to the absence of clear pressure peaks present under them.

Postural parameters were used to elucidate the possible influence of the cushion on the posture of the user.

These were: the position of the center of pressure (x_{CP}, y_{CP}) in an anatomic system of Cartesian axes, taking the line between the ischial tuberosities and its median axis as a reference (**Figure 1**); the difference between the peak pressure values in the right and left side (p_{diff}), and the sitting modality (SM). Sitting modality was defined on the basis of the location of the highest pressure peak—"sacral" when the highest peak was located on the central posterior part of the contact surface (**Figure 2**), "trochanteral" when it was on the lateral side of the contact surface (**Figure 3**), and "ischial" when it was under one of the ischial tuberosities (**Figure 4**).

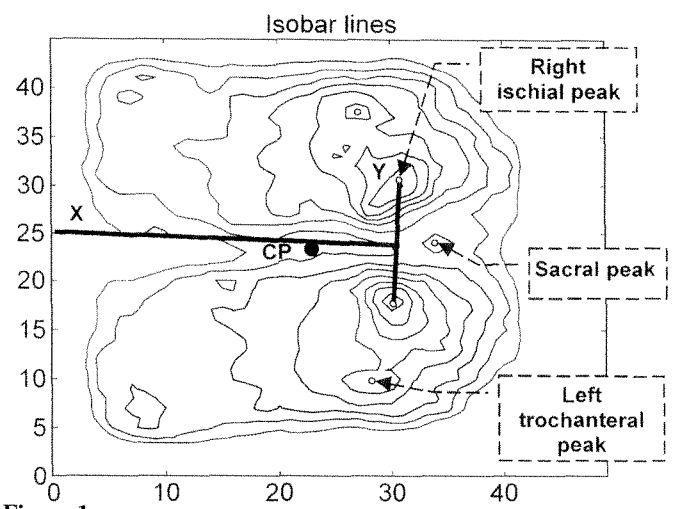

Figure 1.
Pressure map with isobars lines and the anatomical reference system (X=longitudinal axis, Y=transversal axis) defined on the basis of the position of ischial tuberosities. Center of Pressure (CP) is displayed as well as sacral, trochanteral and ischial pressure peaks. Note that X and Y are not parallel to matrix rows and columns: it depends on the orientation of the sensing pad in relation to the pelvis.

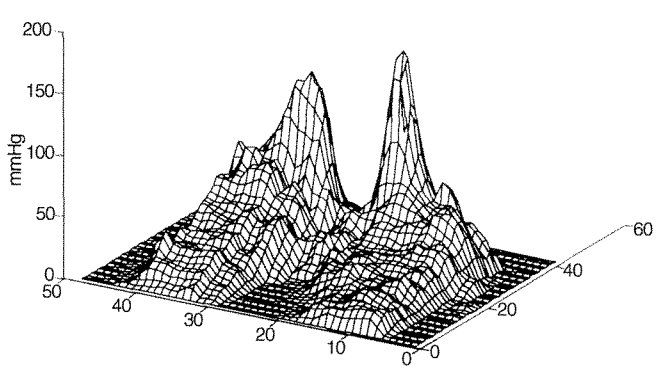

Figure 2.
Example of a 3-D representation of pressure distribution of the sacral sitting modality.

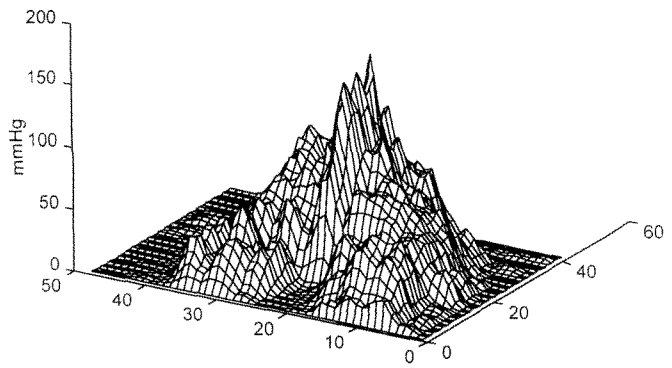

Figure 3.
Example of 3-D representation of pressure distribution of the trochanteral sitting modality.

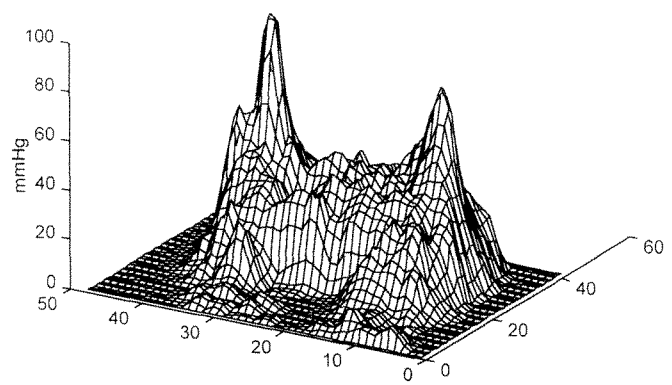

Figure 4.
Example of 3-D representation of pressure distribution of the ischial sitting modality.

The surface parameters were: the total contact surface (S_{tot}), the surface of areas with low (S_{lp}), medium (S_{mp}), and high pressure levels (S_{hp}) (defined, respectively, in the ranges <50 g/cm^2, 50–100 g/cm^2, and >100 g/cm^2), and their percentage value with respect to the total contact surface (%S_{lp}, %S_{mp}, %S_{hp}). These values, corresponding, respectively, to 37 and 74 mmHg, were defined based on ranges presented in literature (1,2,16,19).

The types of wheelchair seat cushions tested are:

• Cushion 1 (Dynamic, Royal Medica S.r.l., Italy): polyuretanic gel-filled (levagel®) bubbles under the buttocks and foam-filled bubbles under the thighs, with a foam base (**Figure 5,** bottom right);

• Cushion 2 (Dynamic Plus, Royal Medica S.r.l., Italy): polyuretanic gel-filled (levagel®) bubbles, with a foam base (**Figure 5,** bottom left);

• Cushion 3 (Roho Low Profile, Roho Inc. , Illinois, USA): rows of communicating air-filled rubber cells on a flat rubber base (**Figure 5,** top right);

• Cushion 4 (Jay2, Sunrise Medical, Colorado, USA): a contoured, firm foam base, covered in the ischial area by a silicon gel pad (flolite®) (**Figure 5,** top left).

Cushions 1 and 2 are innovative products, where the combination of gel and bubble-shaped surface is considered in order to combine the advantages of both these components (high heat capacity, good pressure relief from bony prominence and air circulation).

All cushions were analyzed with the covers provided by the manufacturers, which have non-slip, plastic material underneath and stretchable tissue on the top. The size of the cushions was chosen individually, in relation to the anthropometric parameters of each subject. The air pressure in cushion 4 was set individually, following the recommendations of the manufacturer.

Figure 5.
The cushions analyzed in the present study : cushion 1 (bottom, right), cushion 2 (bottom, left), cushion 3 (top, right) and cushion 4 (top, left).

Thirty subjects took part in the study (see **Table 1**):

• Group A: ten paraplegic subjects with complete spinal cord injury at the thoracic level and no sensitivity in the buttocks or thighs; A grade of ASIA Impairment Scale (20).

• Group B: ten subjects with pathologies of the nervous system (mainly multiple sclerosis) with normal sensitivity.

• Group C: ten elderly people with motor impairments and normal sensitivity.

Cutaneous sensitivity was evaluated by a clinician con-

Table 1.
Main characteristics of subjects.

Subj	Age	Sex	Pathology	Weight	Height
			GroupA		
1	28	m	SCI(T3/T4)	66	180
2	28	m	SCI(T10)	65	180
3	44	m	SCI(T3/T4)	57	172
4	32	m	SCI(T3/T4)	82	182
5	28	m	SCI(T11/T12)	82	175
6	22	f	SCI(T11/T12)	56	165
7	32	m	SCI(T12)	62	164
8	29	m	SCI(T1)	62	182
9	32	m	SCI(T9)	65	172
10	33	f	SCI(T1)	72	174
			Group B		
11	65	m	My Ra Neu	73	175
12	44	m	MS	80	175
13	43	m	Polio	31	130
14	32	f	MS	42	160
15	68	m	Hemi-L	63	170
16	24	m	MS	85	180
17	55	m	MS	85	171
18	55	m	MS	65	165
19	41	m	MS	88	172
20	35	f	MS	52	170
			Group C		
21	82	m	Hemi-L	75	175
22	68	m	MS	67	168
23	69	m	Hemi-L	72	168
24	72	f	Mot Imp	80	175
25	74	f	Hemi-L	75	165
26	85	f	Mot Imp	34	152
27	83	f	Hemi-L	40	165
28	56	f	Mot Imp	85	170
29	87	m	Hemi-L	74	172
30	64	m	BLA	55	173
Mean 50.3±20.9				66.3±15.4	169.9±10

Subj=subject; age in years; weight in kg; height in cm; SCI=spinal cord injury (with lesion level); Polio=poliomyelitis; MS=multiple sclerosis; BLA=bilateral leg amputation; Hemi=hemiplegia on Left or Right side; Mot Imp=motor impairment; My Ra Neu=myeloradiculoneuritis; Mean=Mean±SD.

sidering both pin prick and light touch, according to the standard neurological classification of spinal cord injury (20).

Statistical analyses were performed using ANOVA and the Student's t-test (with Bonferroni correction) with a confidence level of 0.05. Significance levels of differences among cushion types, sitting times and subject groups were evaluated for each of the previously defined parameters. Differences among cushion types and sitting times were tested using repeated measures and paired data set techniques.

RESULTS AND DISCUSSION

Temporal Transient Behaviors

Considering the whole population (30 subjects), data analyses performed on each cushion type did not reveal any significant differences among the 1-, 5-, 10-, and 15-min sitting times. This indicates that none of the cushions showed significant temporal, transient behaviors, at least within the first 15 min of sitting. For example, **Figure 6** shows the comparison of mean pressure (p_m), averaged on all subjects, for all cushions and sitting times. A small (and not significant) increase of p_m was shown by all cushions. This was

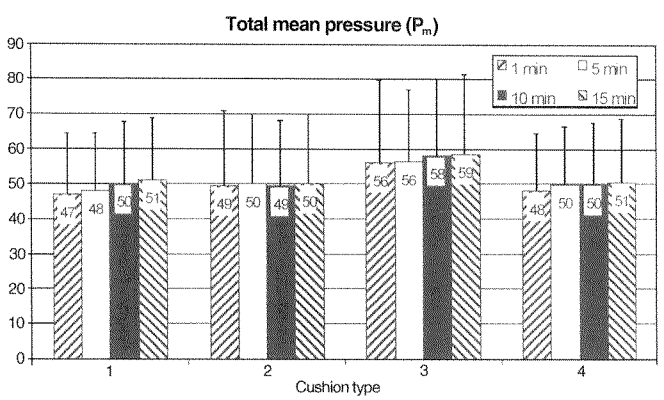

Figure 6.
Mean pressure (p_m) on the contact surface, averaged for all subjects. The values at different sitting times are reported for each cushion. An insignificant increase in pressure with time is shown. The outer bars mark the inter-subject variability, in terms of standard deviation.

probably due to sensor instability, since the maximal increment registered after 10 min (e.g., 6.4 percent, cushion 1). This is within the creep range of the Tekscan system, reported for the same loading time by Ferguson-Pell and Cardi (15)— an estimate up to 26 percent, but largely dependent on the applied pressure value. Therefore, even if cushion 2 presented the least increment over time, the differences in temporal, transient behaviors among the four cushions were not significant. For this reason, data referring to 1-min sitting time will be considered, later. This time was chosen in order to minimize the influence of the instability of the sensor.

Differences Among subject Groups

The main parameters (mean±SD) computed for each subject group and cushion type are reported in **Tables 2 and 3,** namely, pressure parameters, and surface and postural parameters, respectively. Also presented are the results of ANOVA performed among the three subject groups.

Parameter p_m was significantly higher for all cushions used with group C subjects than group B subjects. Since mean weight was similar in the three subject groups, this finding may reflect the smaller contact surface presented by the elderly group (see **Table 3**). Parameter p_{max} was higher in group A than in group B subjects only for cushion 3, and p_{it} was higher in group A than in group B subjects only for cushion 4. Parameter p_{SD} was higher (even if not significantly so) in the paraplegic group (group A) than in the other two groups. The contact surface at medium (percent S_{mp}) and high (percent S_{hp}) pressure levels was significantly larger in the elderly (group C) than in the others for almost all cushions (**Table 3**).

Even if both mean pressure and contact surface at high pressure were greater in the elderly subjects, compared to the other subjects, the paraplegic subjects presented the highest pressure peak values (more than 250 mmHg in one case) with all cushions. These findings are consistent with those of a previous study (19), and highlight the importance of careful routine skin assessment in subjects with spinal cord lesion. Moreover, the greatest variability in pressure parameters (see SD values of all parameters in **Table 2**) was shown by the paraplegic subjects. This reflects the considerable differences among subjects within this category, probably related to the different degree of muscle atrophy. This finding highlights the importance of single subject analysis.

Differences Among Cushion Types

The differences among cushion types are discussed for the whole population (see last four rows of **Tables 2 and 3**) unless specified otherwise.

As for the pressure parameters, pressure on the ischial tuberosities was significantly lower for cushion 4 compared to the other cushions (p_{it}, as shown in **Figure 7**). This reduction may be explained by the sitting modality.

Table 2.
Main pressure parameters at 1 min sitting time for each subject group and for the total study population.

	Type	p_m	p_{SD}	p_{max}	p_{it}	p_{gt}	p_s
Group A	1	48±18	26±10	142±61	119±59		
	2	51±24	30±17	169±128	143±107		
	3	62±31	29±14	**140±78 *B**	112±74		
	4	49±19	25±11	121±59	**94±46 *B**	128±77	
Group B	1	**34±11 *C**	20±8	88±46	73±31		
	2	**32±8 *C**	19±6	87±35	73±25		
	3	**40±14*C**	21±6	**77±24 *A**	70±22		
	4	**26±4 *C**	19±5	79±23	**47±15 *A**	76±19	
Group C	1	**62±11 *B**	20±5	117±32	110±31		122±0
	2	**67±14 *B**	19±5	133±56	119±48		138±13
	3	**69±16 *B**	19±6	110±33	96±18		67±8
	4	**55±9 *B**	18±4	114±49	75±29	96±33	79±0
Total	1	47±18	22±8	116±52	101±46		
	2	49±22	22±12	130±88	112±74		
	3	56±24	23±10	109±56	93±48		
	4	48±16	21±8	103±48	**71±37 ** **	91±36	

Type=cushion type; all pressures in mmHg, mean±SD; *significant difference (ANOVA $p<0.05$) found among subject groups with a specific cushion (the letter indicates the group showing the significant difference); **indicates a significant difference found in a given parameter among the four cusions; Total=total study population.

Table 3.
Main surface and postural parameters at 1 min sitting time for each subject group and for the total study population.

	Total	S_{tot}	$\%S_{lp}$	$\%S_{mp}$	$\%S_{hp}$	%ISM	%TSM	%SSM
Group A	1	1017±119	**71±18 *C**	**21±11 *C**	8±8	90	10	0
	2	**1066±138 *C**	**69±20 *C**	**22±12 *C**	9±10	80	20	0
	3	931±133	58±23	**27±11 *C**	15±18	80	20	0
	4	1079±182	61±23	28±14	11±11	67	33	0
Group B	1	1017±247	**79±14 *C**	**17±11 *C**	**4±3 *C**	100	0	0
	2	**1049±260 *C**	**82±10 *C**	**15±8 *C**	**3±2 *C**	100	0	0
	3	912±206	**71±17 *C**	**24±13 *C**	5±4	100	0	0
	4	1065±245	81±11	**16±9 *C**	3±3	30	70	0
Group C	1	873±223	**52±15 *A,B**	**35±10 *A,B**	**13±8 *B**	80	10	10
	2	**810±180 *A,B**	**46±15 *A,B**	**37±10 *A,B**	**18±7 *B**	80	0	20
	3	795±162	**39±16 *B**	**43±8 *A,B**	18±11	65	5	30
	4	1013±158	63±16	**31±14 *B**	6±4	25	63	12
Total	1	972±207	68±19	24±13	8±8	90	7	3
	2	981±225	66±21	24±13	10±9	86	7	7
	3	**882±174 ** **	**57±23 ** **	**31±13 ** **	**12±13 ** **	82	8	10
	4	**1053±195 ** **	69±19	25±14	6±7	41	56	3

Type=cusion type; S_{tot}=total contact surface, in cm^2, mean±SD; $\%S_{lp}$=percentage of low pressure area, mean±SD; $\%S_{mp}$=percentage of medium pressure area, mean±SD; $\%S_{hp}$=percentage of high pressure area, mean±SD; %ISM=percentage of ischial sitting modality; %TSM=percentage of trochanteral sitting modality; %SSM=percentage of sacral sitting modality; *significant difference (ANOVA $p<0.05$) found among subject groups with a specific cushion (the letter indicates the group showing the significant difference); **indicates a significant difference found in a given parameter among the four cushions; Total=total study population.

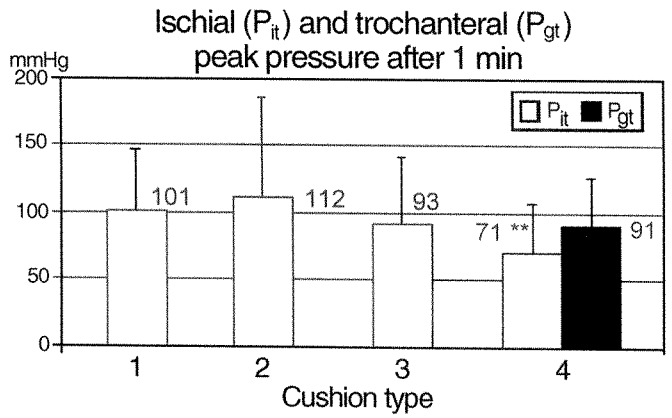

Figure 7.
Ischial (p_{it}) and trochanteral (p_{gt}) mean pressure peaks for all subjects. For each subject, right and left side pressure peaks were averaged. Data show a statistically significant pressure reduction on ischial tuberosities for cushion 4, compared to the others.

In fact, this cushion induced a trochanteral sitting modality (TSM) in 56 percent of the subjects (see **Table 3**). This was particularly evident in the subjects with pathologies of the neuromotor system (group B, TSM=70 percent) and in the elderly subjects (group C, TSM=63 percent).

Moreover, when we compared the trochanteral pressure peaks (p_{gt}) in cushion 4 with the ischial pressure peaks (g_{it}) in the other cushions (see **Figure 7**), statistical analysis failed to reveal any differences among the cushions. Further support for this observation came from the analysis of the absolute maximum peak of pressure (p_{max}), where no significant differences in this parameter were found among the cushions, regardless of where the maximum pressure peak was exerted. The pressure reduction on the ischial tuberosities, observed in cushion 4, was counterbalanced by a higher pressure distribution under the great trochanters, a fact that introduces two further critical points at risk of sores. Therefore, this cushion is indicated for subjects at risk of ulcers on the ischial areas and in whom the area of the great trochanters is intact. In the present study, subjects with a history of femur fracture or arthritis at the hip joint referred pain within minutes of sitting down on this cushion. It is likely that the biomechanical action of the cushion on the pelvis and the legs induced an uncomfortable intra-rotation of the legs at the hip joints. Thus, as a general rule in evaluating pressure peaks in specific anatomical areas induced by a given wheelchair cushion, it is important to keep in mind both pressure distribution and the particular pathologic condition of the subject.

There were no significant differences among cushion types in the mean pressure (p_m) and standard deviation parameter (p_{SD}) calculated over the whole contact area. The latter parameter proved to be more useful for the analysis of individual subjects than for performing group comparison. Whether a different definition—for example, only within a defined critical sub-area (e.g., the S_{hp})—would be more significant will need to be investigated in a future study.

As for postural parameters, the analysis of the position of the center of pressure with respect to the anatomical reference axes revealed no differences among the four cushions. Unsurprisingly, asymmetries were found between right and left sides of subjects with a monolateral pathology such as hemiplegia. However, these asymmetries were not correlated with the affected side and varied among cushions and subjects. It may be argued that no cushion is capable of correcting a subject's posture alone. Only by introducing such specific devices for postural adjustment as modular wedges of different shapes, dimensions, and functions (not considered at the present stage of our study), can this goal be achieved. In this regard, analyzing the location of the center of pressure may be helpful in adapting cushions to individual needs.

As mentioned before, cushion 4 induced the trochanteral sitting modality in 56 percent of the subjects, particularly in those who were not autonomous in wheelchair propulsion. The sacral sitting modality was observed in only a small number of elderly subjects (Group C) and mainly with cushion 3. In this subject group, pressure peaks on the sacral area (p_s) were higher with cushions 1 and 2 than with the other two cushions (see **Table 2**); however, this difference did not reach a significance level, due to the low number of cases.

As for the surface parameters, the smallest total contact surface was shown by cushion 3, the largest by cushion 4, with cushions 1 and 2 in between (**Figure 8**). These findings were confirmed by the surface of areas at different pressure classes: cushion 3 presented the larger high-pressure areas and the lowest low-pressure areas, both for absolute (**Figure 8**) and percentage values (**Figure 9**). This finding is almost certainly related to the non-anatomical design of the cushion. Improvements could be made in two ways: 1) by reaching a compromise between inflation pressure and the height of the cells (in this case, high profile cells with low air pressure would better mold to the body shape),

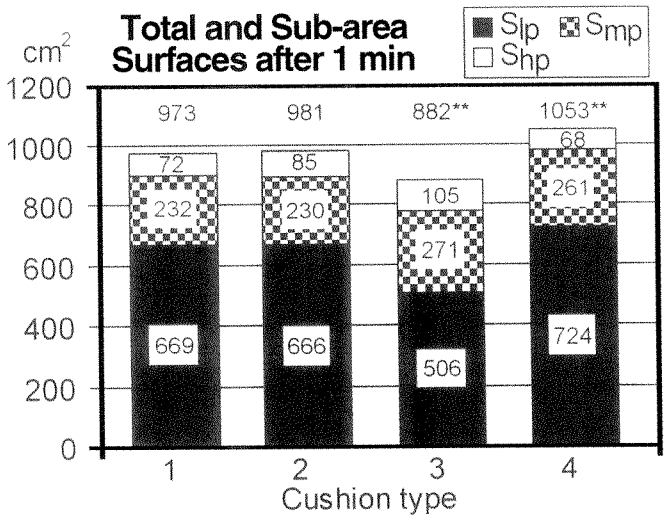

Figure 8.
Total contact surface and sub-areas, divided into pressure classes (S_{lp}, S_{mp}, and S_{hp}). Cushions 3 and 4 are statistically different from the others.

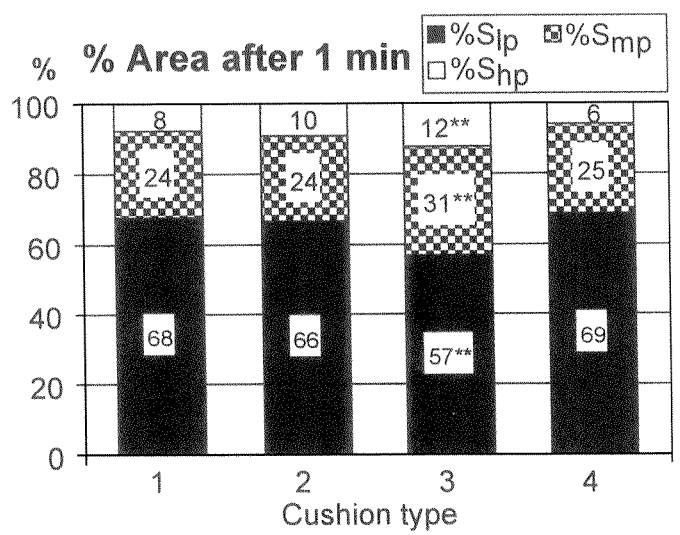

Figure 9.
Relative values of sub-areas, computed as percentages of total contact surface. Cushion 3 presents significantly higher $\%S_{hp}$ and $\%S_{mp}$ values and smaller $\%S_{lp}$ values compared to the other cushions.

and 2) by redesigning the cushion with cells of different heights, to adjust to the anatomical shape of the buttocks, as recently proposed (Enancher cushion, Roho Inc., Illinois, USA). That being said, since the sitting modality induced by air-filled cushions depends on their inflation pressure, they should be adjusted based on individual postural requirements.

CONCLUSION

In the present study, we developed a protocol for the analysis of pressure peaks, contact surfaces and sitting modalities. Based on that, a comparative evaluation of four different antidecubitus cushions was performed on a sample of thirty subjects. The applicability and reliability of the proposed protocol was successfully tested.

Overall, the two innovative cushions (cushions 1 and 2) proved to be comparable with the others in terms of quality and did not present any macroscopic differences, either in maximal pressure peak reduction or in temporal, transient behaviors. Nonetheless, the four tested cushions revealed interesting differences in pressure peak location and postural parameters.

Data analysis showed that pressure peaks were almost always on the ischial tuberosities for cushions 1, 2 and 3, and on the great trochanters for cushion 4; the latter made more than half of the subjects assume the trochanteral sitting modality. Pressure peaks on the sacral areas were recorded only in a few elderly subjects and mainly with cushion 3. Thus, it would appear that cushion 4 could be of benefit to subjects needing to minimize pressure peaks on the ischial tuberosities, while its use in subjects with trochanteral skin fragility and hip or femur problems should be considered with caution. For the same reason, careful attention must be given to subjects at risk of developing pressure sores in the sacral region who rely on cushion 3. In this regard, recommendations may include proper regulation of inflation pressure based on individual requirements, and on-line visualization of the pressure map.

As for the innovative parameters proposed in this study, the percentage value of areas at different pressure classes (percent S_{lp}, percent S_{mp}, percent S_{hp}) appeared to be correlated with the matching of the cushion surface shape to the anatomical contour of the buttocks. Therefore, when used in conjunction with the commonly computed peak pressure, they can help in the analysis of cushion adaptation to a specific subject. Moreover, it was argued that the proposed parameters related to the position of the center of pressure with respect to the anatomical reference axes (x_{CP}, y_{CP})provide useful information concerning postural adjustment.

Our results, like those of previous studies (1,7,19), indicate that it is not possible to identify a single cushion type that is effective in all subjects or in a specific category of subjects. From the point of view of pressure peak relief in vulnerable areas, the alternating use of two cush-

ions, each of which induces a different sitting modality, may be of benefit.

On the other hand, the instrumental and data processing procedures used in the present study appear to provide a useful tool for individualizing the prescription of a wheelchair cushion and for adapting its modular components.

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