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Comparative study of pressure distribution at the user-cushion interface with different cushions in a population with spinal cord injury ☆

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ABSTRACT

Background: Few studies have offered comparative information on the mechanical characteristics of different wheelchair seat cushions. The objective of the present study was to compare the benefits of the wheelchair seat cushions most frequently used in a population of patients with spinal cord injury in terms of pressure distribution and contact surface at the user-cushion interface.
Methods: Each one of 48 patients with spinal cord injury was seated in his or her own wheelchair on the four models of cushions analyzed (low-profile air, high-profile air, dual-compartment air, and gel and firm foam), which were presented in randomized order. The pressure distribution readings and support surface area of the user-cushion interface were obtained with a matrix of piezocapacitive sensors.
Findings: The dual-compartment air cushion yielded lower readings for all pressure parameters analyzed (P_{max}, P_{mean}, P_{sd}, and P_{isch}) than the other three cushion models ($P < 0.05$). The best surface parameter results (S_{tot}, $S > 60$ and $\%S > 60$) also were obtained with the dual-compartment air cushion ($P < 0.05$).
Interpretation: In the sample analyzed, the dual-compartment air cushion was the cushion with the best pressure distribution and largest contact surface of the user-cushion interface compared to the other three cushions studied.

1. Introduction

Pressure ulcers (PU) are areas of injury to the skin and underlying tissue that apparently are caused by sustained pressure, rubbing, or friction (McInnes et al., 2008). These areas usually are located over bony prominences and their severity can be classified by the tissue damage produced (Bergstrom et al., 1992). The reported prevalence of PUs in patients with spinal cord injury (SCI) who have already passed the initial phase of hospitalization is 33% (Fuhrer et al., 1993; Vidal and Sarrias, 1991). Although the etiology of PUs is multifactorial (Krause et al., 2001), the pressure at the interface between the user and the surface of the seat is considered the main factor involved in the development of PUs (Ferrarin et al., 2000).

Despite the fact that PU is one of the most problematic complications and there is a confirmed relation between high contact pressures at the user-cushion interface and PU incidence (Brienza et al., 2001; Conine et al., 1994), few comparative studies have been published on the mechanical performance of different types of cushions in a sample of patients with SCI. However, other aspects have been studied, such as the effect of posture (Henderson et al., 1994; Koo et al., 1996), seat inclination (Maurer and Sprigle, 2004) and the influence of the inflation pressure of air cushions on the distribution of user-cushion interface pressures (Hamanami et al., 2004). The mechanical characteristics of different types of cushions have been compared by other teams, mainly in groups of older adults or people with a neurologic pathology different from SCI (Apatsidis et al., 2002; Brienza et al., 2001; Conine et al., 1994; Geyer et al., 2001; Lim and Sirett, 1998; Rusell et al., 2003; Stinson et al., 2008).

In active people with SCI, the area where PUs appear most often is the skin located over the ischial tuberosities (Bennett et al., 1984), where the patient's weight is concentrated (Tanimoto et al., 1998). For this reason, much effort has been dedicated to alleviating pressure under the ischial tuberosities, which has lead to the appearance of a wide variety of wheelchair cushion models on the market (Burns et al., 1999; Rosenthal et al., 1996). Wheelchair cushions can be classified according to their composition into water, foam, gel, air, and viscoelastic cushions. These materials also can be combined to offer different attributes. Each of them contributes in some way to improving aspects such as correct positioning, stability, PU prevention, comfort, or reduced friction.

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Interface pressure between the user and the seating surface, despite its limitations, is the parameter most commonly used to evaluate how surfaces distribute the pressure of the user's body. The usefulness of graphic and numeric interface pressure outputs has been confirmed (Stinson et al., 2003). Other methods for evaluating the performance of different cushions are based on tissue deformation capacity (Levine et al., 1990), seat contour analysis (Sprigle and Schuch, 1993), or the thermal properties of the cushion (Ferrarin and Ludwig, 2000). Consensus about the critical pressure values at which pressure ulcers develop is still lacking, but the general recommendation is that tissues should be subjected to the lowest possible pressure (Meffre et al., 2007). Similarly, there is no agreement about the most effective pressure-relieving surface. Different studies have indicated that the use of PU-preventing seats that are designed to conserve tissue integrity reduces the incidence of PUs induced by prolonged sitting (Hamanami et al., 2004). However, the most recent review by The Cochrane Collaboration states that there is not enough clinical evidence to draw conclusions regarding the differential performance of seating surfaces in terms of objective clinical effectiveness (McInnes et al., 2008).

Although the sensors that detect the pressures at the user-cushion interface have been used in clinical experiments, it would be interesting to use these systems as a prescription aid for selecting the cushion with the most appropriate mechanical behavior for patients with SCI and reducing the risk of PUs. Our work hypothesis was that a user-cushion interface pressure-recording system could be used to assess the mechanical characteristics of different types of cushions in a population of patients with SCI. Having more information available on wheelchair cushion properties should help to optimize prescriptions.

For this reason, the objective that we set in this study was the following:

- Characterize the clinical utility of the user-cushion interface pressure-recording system by comparing the distribution of pressures and contact surface at the user-cushion interface of four cushions commonly prescribed to patients with SCI in our hospital center.

2. Methods

2.1. Patients

The inclusion criteria were the following:

- Age: 18–65 years.
- Patients with complete cervical or thoracic spinal cord injury ASIA A.
- Absence of PU in the last month.
- Absence of history of surgical resection of any part of the pelvis or femur.
- Range of passive hip flexion of at least 90°.

The sample selected with these criteria was 48 patients whose demographic characteristics, including risk of PU (Bergstrom et al., 1987), are listed in Table 1. All the patients signed the respective informed consent form before enrollment in the study, which adhered to the ethics guidelines of the declaration of Helsinki. The protocol was approved by the local ethics committee.

Table 1
Demographic characteristics of the sample analyzed ($n = 48$).

Variable	Result
Sex (men)[b]	38 (79)
Age (years)[a]	42 (17.0)
Weight (kg)[a]	67.6 (18.6)
BMI[a]	23.3 (6.0)
Cervical (C4–C8)[b]	13 (27)
Thoracic (D1–D12)[b]	35 (73)
Time from injury (months)[a]	104.6 (99.7)
Braden scale[a]	13.0 (2.4)

[a] Data are means (SD) for continuous variables.
[b] Data are expressed as number (%) for categorical variables.

2.2. Cushion models

The aim of this study was to characterize the clinical utility of the user-cushion interface pressure-recording system with a simple application of wheelchair cushions commonly prescribed at our center, a hospital specialized in SCI with more than 30 years of clinical experience (Fig. 1). We were not trying to exhaustively study wheelchair cushions, just the utility of the user-cushion interface pressure-recording system for selecting them. At other centers, the cushions used may yield better results than the following cushions used in this study:

- *Cushion 1*. Single-compartment, low-profile air cushion. Kineris low-profile model, Askle Santé Winncare (Askle Santé Winncare Group, Nimes, France).
- *Cushion 2*. Single-compartment, high-profile air cushion. Kineris high-profile model, Askle Santé Winncare (Askle Santé Winncare Group, Nimes, France).
- *Cushion 3*. Dual-compartment air cushion divided into two chambers that simulate an ergonomic seating base. Roho Enhancer Model, The Roho Group (Roho, Inc., Belleville, IL, USA).
- *Cushion 4*. Gel and firm foam cushion. Medical Sunrise Jay-2 Model (Jay Medical, Ltd., Boulder, CO, USA).

In every case, the cushions were covered with their own cover and a protective cover consisting of a nonskid, flameproof inner layer and a breathable, elastic outer layer so that the patient did not know which cushion he or she was using. Several sizes were available for each cushion model and the most appropriate model for the user's dimensions was used in each case.

The user-cushion interface pressure-recording system used was Xsensor model X2 imaging equipment (Xsensor Technology Corporation, Calgary, Canada). Each adjacent transducer has a sensing area of 1.6 cm^2 that registers a pressure image. The digital signal is transmitted to the PC via a high-speed USB port at a sampling frequency of 10 Hz.

Prior to each trial, the sensor was calibrated according to the manufacturer's specifications to 10–210 mmHg

2.3. Data collection protocol

Every patient was seated on each of the cushions analyzed in randomized order. The randomization code was developed using a computer random number generator to select random permuted blocks. Block lengths were four.

The wheelchair setup was normalized so that all the patients were positioned with their arms resting on thighs and feet on footrests, and with the hips, knees and ankles flexed 90°. The seat was positioned parallel to the ground and the back was perpendicular, although a tilt of up to 10° was allowed to ensure the comfort of patients, according to previously designed protocols (Fergusson-Pell, 1990).

The inflation pressure of the air cushions was determined individually, following the manufacturer's recommendations. The explorer slipped a hand between the cushion surface and the

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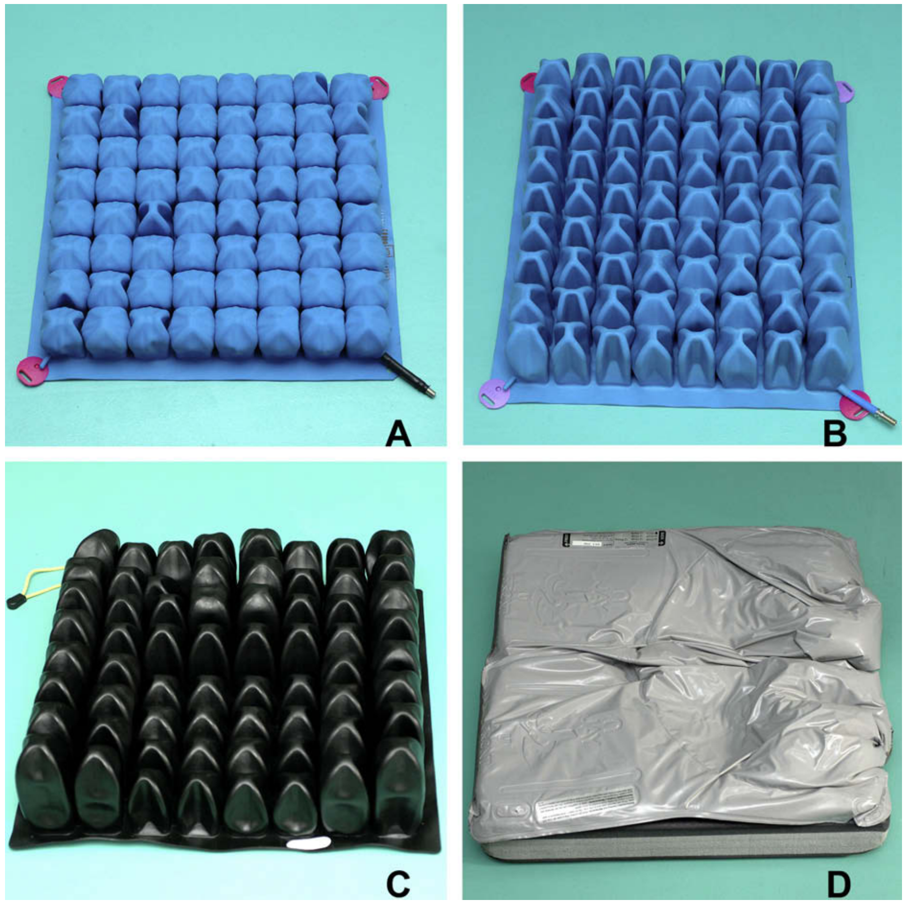

Fig. 1. Cushions analyzed in the present study. A: cushion 1, upper left (low-profile air); B: cushion 2, upper right (high-profile air); C: cushion 3, lower left (dual-compartment air) and D: cushion 4, lower right (gel and firm foam).

person's bottom to locate the ischial tuberosity. The valve was turned counter clockwise to gradually release air, without the explorer removing his or her hand from under the person's sitting bones. The cushion was deflated until the explorer could barely move the fingertips. Finally, the explorer wiggled his or her fingers to make sure there was no more than 1 in. and no less than 1/2 in. between the subject's bottom and the seat.

A continuous measurement then was made during 1.5 min in order to observe the temporal behavior of the cushion in terms of the pressure at the cushion–subject interface. We ruled out making measurements during more prolonged periods of time in light of previous experiences in which no significant variations were appreciated when measuring 15 min (Ferrarin et al., 2000).

2.4. Data analysis

Following the above recommendations, it was assumed that the peak pressure areas on the body–support interface during static erect sitting coincided with the ischial tuberosities (Tam et al., 2003). As recordings were not made during wheelchair propulsion, it was not considered necessary to design a mathematical model of the pelvis to identify the points corresponding to the ischial tuberosities. In any case, the location of these zones of interest on the pressure map was confirmed by palpation using a hand introduced between the subject and the pressure-recording system. When the ischial tuberosities were palpated, the explorer pressed the dorsal hand against the pressure-recording system without changing hand position. The area of increased pressure produced by the explorer's fingers against the pressure-recording system marked the ischial tuberosity area. An algorithm was developed in Matlab (The MathWorks, Natick, MA, USA) for processing the data for the following functions:

- Identification of lost sensor data or artifacts. These data were interpolated by third-order spline functions.
- Selection of the areas corresponding to the ischial tuberosities.
- Filtering by means of a mobile medium using a 3×3 matrix consisting of averaging the values recorded in the cells adjacent to the cell analyzed (Ferrarin et al., 2000).
- Obtain the mean pressure map of an analysis by averaging the data from 90 s of recording.

2.5. Variables analyzed

The variables analyzed were grouped as follows:

(a) Variables related to user-cushion interface pressure distribution.

The variables recorded for every user with each type of cushion were peak maximum pressure of the entire pressure map (P_{max}) and peak pressure in the area of the ischial tuberosities (P_{isch}). P_{isch} was the maximum reading in the cells of the ischial tuberosity area. The side on which the highest readings were obtained was the only side considered. The mean and standard deviation of the entire pressure map in each recording (P_{mean} and P_{sd}). The P_{sd} parameter informed us about the degree of dispersion of the

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pressure map recorded by the sensor. A small P_{sd} indicates a uniform pressure distribution, whereas a large P_{sd} reflects an irregular distribution, with areas of high peak pressures (Ferrarin et al., 2000).

(a) Variables related to the user-cushion contact surface.

The variables related to the contact surface were total contact surface (S_{tot}), the contact surface with pressure readings over 60 mmHg ($S > 60$), and the percentage of the total contact surface with pressure readings over 60 mmHg ($\%S > 60$). The 60-mmHg value is the cut-off point at which the risk of developing a PU is thought to increase (Conine et al., 1994).

2.6. Statistical analysis

The goodness of the fit of quantitative variables to a normal distribution for each variable was determined using the Kolmogorov–Smirnov test. A descriptive analysis was made of the clinical and functional variables by calculating the mean and standard deviation of the variables with a normal distribution. The median and interquartile range were calculated for the variables that did not have a normal distribution. Frequencies and percentages were used to describe the qualitative variables.

Due to the completely randomized block design, the differences in the pressure and surface variables between the four types of cushions were compared using repeated-measure analysis of variance (ANOVA) for the variables that had a normal distribution. The Friedman test was performed on the variables that did not have a normal distribution.

When the analysis of variance or the Friedman test indicated significant differences, either the Bonferroni test or the Wilcoxon test with the Bonferroni correction, respectively, was used to compare pairs of cushions.

A probability (P) of <0.05 was considered significant for all comparisons. Data were analyzed statistically using the SPSS 12.0 (SPSS Inc., Chicago, IL, USA) statistical package.

3. Results

The demographic characteristics of the 48 patients studied are summarized in Table 1. The results obtained for the pressure distribution variables at the user-cushion interface appear in Table 2. Analyses *a posteriori* in repeated comparisons showed that the dual-compartment air cushion (cushion 3) had the lowest P_{max}, P_{isch}, P_{mean}, and P_{sd} values and that the differences were highly significant. The gel and firm foam cushion (cushion 4) had the highest P_{mean} values ($P < 0.05$ vs. cushion 1, cushion 2 and cushion 3), but significantly lower P_{isch} values than cushion 1 ($P < 0.05$). There were no significant differences in any variable between cushions 1 and 2.

The surface variable measurements (Table 3) revealed that the cushion that performed best was again the dual-compartment air cushion (cushion 3), which had the largest total contact surface (S_{tot}) ($P < 0.05$ vs. the other three cushions), lowest $\%S > 60$ values ($P < 0.05$ vs. cushion 1 and cushion 2 and cushion 4) and lowest $S > 60$ ($P < 0.05$ vs. cushion 2 and cushion 4, with the exception of cushion 1, $P = 0.11$).

The cushion with the least favorable mean S_{tot} value was the single-compartment, low-profile air cushion (cushion 1) ($P < 0.05$ vs. cushion 2, cushion 3 and cushion 4), but the cushion with the largest surface area above the risk threshold measured by $S > 60$ and $\%S > 60$ was the gel and firm foam cushion (cushion 4) ($S > 60$: $P < 0.05$ vs. cushion 1, cushion 2 and cushion 3; $\%S > 60$: $P < 0.05$ vs. cushion 1, cushion 2, and cushion 3).

4. Discussion

The user-cushion interface pressure-recording system was very useful for assessing the mechanical characteristics of different types of cushions. In the sample analyzed in this study, the dual-compartment air cushion exhibited the best mechanical performance with regard to the distribution of pressures and contact surface at the user-cushion interface compared to the other three cushions studied (low-profile air, high-profile air and gel and firm foam) in a sample of people with SCI.

Wheelchair cushions for people with SCI are used to redistribute pressures in the support area more homogeneously and reduce the risk of developing PUs (Gutiérrez et al., 2004). The occurrence of the first skin lesions has been used as a measurement of results in comparative studies of cushions (Conine et al., 1994), but such studies require large patient samples and close follow-up of skin condition during months. Studies similar to the one reported here

Table 2
Results of the variables related with pressure distribution.

	Cushion 1, low-profile air	Cushion 2, high-profile air	Cushion 3, dual-compartment air	Cushion 4, gel and firm foam
P_{max}[2] (mmHg)	207.5 (59.0)^{a}	199.5 (64.8)^{b}	105.5 (83.3)^{a,b,c}	180.5 (75.8)^{c}
P_{isch}[2] (mmHg)	207.5 (70.0)^{a,d}	195.5 (82.0)^{b}	102.0 (83.5)^{a,b,c}	159.5 (105.5)^{c,d}
P_{mean}[1] (mmHg)	39.2 (7.1)^{a,d}	38.5 (6.8)^{b,e}	34.9 (6.1)^{a,b,c}	41.9 (8.7)^{c,d,e}
P_{sd}[1] (mmHg)	25.1 (7.5)^{a}	23.1 (6.4)^{b}	17.9 (5.9)^{a,b,c}	26.0 (9.6)^{c}

Same letters indicate significant difference (ANOVA GLM and Bonferroni correction for normal variables and Friedman and Wilcoxon with Bonferroni correction for non-normal variables; $P < 0.05$).
[1] Data are means (SD).
[2] Data are medians (interquartile range as the measurement of data clustering).

Table 3
Results of the variables related with surface distribution.

	Cushion 1, low-profile air	Cushion 2, high-profile air	Cushion 3, dual-compartment air	Cushion 4, gel and firm foam
S_{tot}[1] cm^2	1081.3 (200.6)^{a,d,e}	1154.6 (235.3)^{b,d}	1376.0 (255.7)^{a,b,c}	1153.3 (245.0)^{c,e}
$S > 60$[2] cm^2	112.9 (139.1)^{d}	112.1 (151.7)^{a,c}	76.6 (164.9)^{a,b}	174.2 (264.5)^{b,c,d}
$\%S > 60$[2]	10.6 (12.1)^{a,d}	10.4 (11.4)^{b,e}	5.1 (10.7)^{a,b,c}	16.6 (23.2)^{c,d,e}

Same letters indicate significant difference (ANOVA GLM and Bonferroni correction for normal variables and Friedman and Wilcoxon with Bonferroni correction for non-normal variables; $P < 0.05$).
[1] Data are means (SD).
[2] Data are medians (interquartile range as the measurement of data clustering).

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have been published on the mechanical performance of different types of cushions in patients with SCI. One study is a case report on one patient, which was interesting in terms of analytical methodology but has no statistical significance (Yuen and Garret, 2000). In another study, the performance of a cushion that was custom-contoured for the patient was compared to a foam cushion. However, only 4 of the 10 patients who initiated the study had complete measurements (Sprigle et al., 1990). The two studies most comparable to our current study are those of Burns et al. (1999) and Ferrarin et al. (2000), although Tekscan piezoresistive sensors were used in both studies as the measurement device. Ferrarin et al. (2000) made a comparative biomechanical analysis of four types of cushions in a heterogeneous sample consisting of three types of patients with different pathologies, in which a group of 10 patients with SCI, all with an injury between T1 and T12, was identified. Burns et al. (1999) examined the performance of three types of cushions in 16 patients with SCI, all at the cervical level. Individuals categorized as ASIA A were included only because they are the patients at greatest risk of developing PUs because of the loss of sensitivity. ASIA B patients, who lack mobility but still have their sensitivity preserved below the level of the lesion, have a somewhat lower risk.

Another element that makes it difficult to compare the results of different studies is the instrument used to measure user-cushion interface pressures. The device used in this study has a spatial resolution of 1.6 cm^2. Although some devices have a greater resolution, the results obtained are considered valid because we focused on identifying areas of risk for developing PUs rather than specific value at each point. In addition, the measurements were consistent because the sensor was checked before each test according to the manufacturer's specifications. Each device has characteristics that result in a differentiated performance and specific indications depending on the surface to be measured (Nicholson et al., 2001). Consequently, notable differences are found in the pressure readings of a given patient on a specific cushion obtained by different measurement devices. Differences were found between sensors within subjects and probably resulted from factors influencing the reading obtained with individual sensors. These include the effects of hammocking, hysteresis or the potential for mat creasing or folding under the subject (Fergusson-Pell and Cardi, 1993). However, we think that the results presented here are sufficiently valid because all the cushions were compared using the same measurement system, so the absolute values obtained were less important that the comparative values between cushions. This means that we probably would obtain the same comparative results but different absolute results using another sensor. Nonetheless, it might be worthwhile to compare sensor systems to confirm this point. Finally, another question that has to be debated is the algorithm used to analyze the variables, particularly when analyzing pressure maps in real time (Bogie et al., 2008).

Studies have been published on the possible relation between BMI and pressure readings and surface values (Kernozek et al., 2002; Stinson and Porter-Armstrong, 2003; Stinson et al., 2003), but we recorded BMI data in the present study only to characterize the sample. No correlation analysis was made because this was not the aim of the experiment.

The posture of the patient during the study was defined by Fergusson-Pell (1990). Our definitions of the recording variables coincided to a great extent with those of Ferrarin et al. (2000). Although studies have been made using a standardized wheelchair for all the subjects (Hobson, 1992; Koo et al., 1996), we preferred to use each patient's usual wheelchair in order to size the setup to the patient's dimensions.

We found that the dual-compartment air cushion had the most satisfactory performance in terms of pressure parameters and contact surface. Of the pressure parameters, the lowest P_{max}, P_{mean}, and P_{isch} values were obtained and the low P_{sd} indicated that the pressure was distributed more homogeneously. When designing a cushion, it is important to maximize the contact surface to reduce pressure. The dual-compartment air cushion not only had the largest S_{tot} values, but it also had the smallest $S > 60$ and $\%S > 60$ values, meaning that the surface exposed to high pressures was smaller. This is probably because the dual-compartment air cushion combines the known advantages of air cushions in relieving pressure with the postural advantages of the anatomically correct seat contour that gel and firm foam cushions provide. It is interesting that the low-profile air cushion had the least favorable S_{tot} values and that P_{isch} values were high compared to the gel and firm foam cushion. This finding can probably be attributed to cushion shape, as has been discussed in other studies (Ferrarin et al., 2000).

Despite the good results obtained in our sample with the dual-compartment air cushion, the prescription of a cushion to a new patient must be individualized because this cushion may not necessarily be the most suitable for a specific patient.

The results reported for four cushions in the study by Ferrarin et al. (2000) coincided with our results for only two cushions (low-profile air cushion and gel and firm foam cushion). In a comparison of their group of 10 paraplegic patients vs. our 48 patients with SCI, Ferrarin et al. (2000) obtained somewhat lower P_{max} and S_{tot} values than we did, whereas the P_{mean} was slightly higher.

In the comparisons of different types of cushions, both studies coincide in finding that P_{max} was higher in the low-profile air cushion than in the gel and firm foam cushion. Both studies also found that S_{tot} values were higher with the gel and firm foam cushion. However, we obtained somewhat lower P_{mean} and P_{sd} values with the low-profile air cushion in our sample. The data of the high-profile air cushion and dual-compartment air cushion could not be compared because these cushions were not examined in the Ferrarin et al. study (2000).

In the study by Burns et al. (1999), the high-profile air cushion, gel and firm foam cushion, and a dynamic cushion not considered in our study were compared. The overall P_{max} readings obtained by Burns et al. were lower than in our study. It is worth noting that in the Burns study, the high-profile air cushion yielded lower P_{max} values than the gel and firm foam cushion, in contrast with the findings in our series (Burns et al., 1999). The Burns study differed methodologically from our study in the measurement devices used and the fact that readings were made at certain times in a 6-min interval. In the clinical case presented by Yuen and Garret (2000), the air cushion offers better results than the gel and firm foam cushion (Sprigle et al., 2003). Although few conclusions can be drawn from a single case, the findings of this case report coincided with those of Takechi, who obtained better results with air cushions than with a gel and firm foam cushion and a foam cushion (Takechi and Tokuhiro, 1998). It is difficult to establish comparisons with the results of Henderson et al. (1994) because they measure the pressure distribution in 10 people with paraplegia, focusing on the effect of trunk angle on those pressures; the type of cushion was not considered. Kernozeck and Lewin (1998) evaluate the differences in user-cushion interface values under static conditions and during wheelchair propulsion. They found lower values under static conditions than those reported here in 15 patients with thoracic SCI who used a gel and firm foam cushion.

Other studies have compared pressure-relieving surfaces in populations that do not have SCI, generally older adults or people with different neurologic disorders. It is interesting that Geyer et al. (2001), in a study of 40 patients of advanced age, obtained a P_{max} of 101.1 mm Hg and a P_{sd} of 41.2 mm Hg with foam cushions. Although these experiences may be valid for comparing data capture and analysis protocols, the results are not comparable because it has been demonstrated that pressure readings at the user-cushion interface are higher in people with SCI than in healthy subjects (Brienza and Karg, 1998; Hobson, 1992).

The present study only compared the performance of four cushions in terms of the distribution of user-cushion interface pressures. None of the other points of interest in cushion selection was evaluated. In some cases, features such as stability, ease of transfer, moisture control, or maintenance needs may be more important than small differences in support pressures when selecting a wheelchair cushion (Burns et al., 1999).

5. Conclusion

The data collected allow us to affirm that the dual-compartment air cushion exhibited the best mechanical performance with regard to the distribution of pressures and contact surface at the user-cushion interface in a sample of people with SCI compared to the other three cushions studied (low-profile air, high-profile air and gel and firm foam). However, all wheelchair cushions must be evaluated in studies that follow-up skin condition to complete the clinical evaluation.

Conflict of interest statement

The authors of this article state that they do not have any conflicts of interest. This study was not financed by any public or private organization.

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