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Itaperuna, Brasil

Available in: http://www.redalyc.org/articulo.oa?id=93012708012
ORIGINAL INVESTIGATION (ARTIGO ORIGINAL)

COMPARISON OF SEVERAL SEATING SOLUTIONS DESIGNED FOR PROLONGED SITTING AND CAR DRIVING WITH TRANSPORTATION-ORIENTED WHEELCHAIRS

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Submitted for publication: January 2009
Accepted for publication: April 2009

ABSTRACT
PAPAIOANNOU, G.; MITROGIANNIS, C.; FIEDLER, G.; HOSTENS, I.; SPAEPEN, A. Comparison of several seating solutions designed for prolonged sitting and car driving with transportation-oriented wheelchairs. Brazilian Journal Biomotricity, v. 3, n. 2, p. 194-207, 2009. The performance of a number of existing foam and air based wheelchair and car seats was compared to that of a new wheelchair air-filled seating system designed especially to minimize sitting discomfort during prolonged sitting and driving. Analysis of variance was used to test the effects of five different seats on pressure gradients and their performance in prolonged sitting and driving. Buttocks and back support pressure history were accessed with the Tekscan sensor pressure measurement system during prolonged sitting and driving. Differences on seat pressure effects on healthy subjects, between subject pressure effects and the performance of the new seat with respect to maximum and mean pressures were also investigated. In all tests regarding static and dynamic pressure distribution, prolonged sitting or prolonged driving, the new seating system performed significantly better than other foam or air based seats resulting in considerable reduction of the maximum pressure. The new modular air-cushion seat with its dynamic characteristics enhances wheelchair-and car driving related comfort.

Key Words: Pressure; Wheelchair-car driving; Seating comfort.
INTRODUCTION

Seating comfort is becoming increasingly important for the transportation industry and the development of a new, more comfortable seat is costly and time consuming. Seat comfort becomes more important when people with mobility problems (spinal cord injured persons, amputees, paraplegics etc.) are certified drivers, use their wheelchair for prolonged periods of time or use it as the driver’s seat during car driving. It is well established that repetitive or sustained external mechanical loads are among the primary causes of pressure sores (CRANE et al., 2007; FERGUSON-PELL et al., 1993; HERMAN et al., 1999; LINDER-GANZ et al., 2007). Managing those external loads in persons with mobility problems is a constant challenge in the clinic and in everyday life (BADER et al., 1988; BENNETT et al., 2004; BOUTEN et al., 1999; GUTIERREZ et al., 2004; MCNEES et al., 2007). Besides the load magnitude, other load characteristics like duration, direction, distribution, (3Ds), and loading rate should be considered in the discussion of soft tissue responses to external loads. Duration is critical, since there is an apparent inverse relationship between the pressure and its duration of application leading to the formation of pressure ulcers (AKBARZADEH, 1991; BADER et al., 1988; BROWN, 2003; LI et al., 2006; MEIJER et al., 1989).

A large body of research focuses in identifying tissue damage mechanisms (LINDER-GANZ et al., 2007; QUINTAVALLE et al., 2006; VERVER et al., 2004) and the dynamic elements of the human-seat interface in an effort to reduce whole-body vibration (WBV) and musculoskeletal disorders in automobile drivers (FUNAKOSHI et al., 2004; GÜNDÖĞDU, 2007; LIN et al., 2004; MAKHSOUS et al., 2005; WALTON, 2007) or wheelchair users (HOSTENS et al., 2001; HOSTENS et al., 2003; MOSHOU et al., 2005; RAMON et al., 2000). Studies of vibration related discomfort report poor performance when wheelchairs are used as car driver’s seats during the driving task (HOSTENS et al., 2003). The problems arise from the default upright position of the wheelchair seat resulting in a considerable difference in the driver’s posture as compared to that assumed in most recreational vehicle seats.

The classical methodology of pressure distribution benchmarking of different cushions and seats is most commonly used for performance comparisons (BARDSLEY, 1999). However, individual differences between users introduce challenges in matching cushion-seat with patient needs (VAN DER EERDEN et al., 1999). Custom made, appropriately contoured cushions and seats are the most commonly applied solutions with the drawback of the associated increased costs.

The new seating system for pressure management is part of a novice electric wheelchair design. The new wheelchair is designed to allow easy mounting of different seating systems and can adapt to the requirements of use within all major transportation modes (PAPAIOANNOU et al., 1999). The patient can use the wheelchair in a standalone mode and to drive a car by assuming the drivers’ seat without help from escorting persons. This suggests increased hours of prolonged sitting without any transfer of the mobility challenged person out of the seat.

New tools have been developed to account for the transient properties of the car seat system as a pressure and vibration relief interface with respect to the continuing downsizing of cars and the new demands for comfort, convenience and safety (FUNAKOSHI et al., 2004; GIACOMIN et al., 2003; HOSTENS et al., 2001; LIN et al., 2004; RAMON et al., 2000). Although comparisons between foam and air-cushion based seating systems have been performed in the laboratory set-up (CARCONE et al., 2007; COGGRAVE et al., 2003; CRANE et al., 2007; WATANABE et al., 2007), it is necessary to compare the seats during actual driving with a car due to the differences in the particular
This study evaluates comfort and pressure distribution profiles associated with a number of commercially available seating systems and wheelchair seats as compared to a new wheelchair seat during prolonged sitting and prolonged driving of a car. It is part of a multidisciplinary effort to design a transportation wheelchair with high impact safety and advanced sensor comfort for people with mobility problems. The new wheelchair aims to solve the problem of use within all transportation modes (car, bus, train and aeroplane).

METHODS

Three wheelchair models were used in the tests (MEYRA Optimus (wh1) (MEYRA Vlotho, Germany) in figure 1a, MEYRA Sprint (wh2) in figure 1b and TRANSWHEEL II (wh3) in figure 2. Five existing wheelchair or car seating systems (see table 1 and seats S1 in figure 4b, S2 in figure 1c, W1 in figure 1a, W2 in figure 1b and A1 in figure 2) were mounted on the wheelchairs and were tested for back and buttocks pressure performance during prolonged sitting.

The new electric wheelchair-car seating system A1 (Fig. 2 and Fig. 4c,e) provides anthropometry based seat customization. A modified ROHO cushion (Roho, Inc., Belleville, IL, USA) with adjustable air-cells of different sizes and side rotating panels for width adaptations (Fig. 4a-e) was implemented. The system allows for dynamic sitting adaptation using manual and automatic programmable air-pump driven manipulation of internal air pressure of five air subcushions through a new system of valves, controller, pressure regulator, air-pump and user interface (Fig. 4c). The seat consists of two subcushions at the back, two at the buttocks area and one at the thighs (Fig. 4a). The operator can pre-programme the system to always keep the max pressure level constant at a predefined threshold. Each subcushion has its own pressure valve that can be set with independent pressure threshold. Scenarios of optimum pressure profiles for each patient can be also programmed after normalizing the initial proper subject immersion. The operating logic of the system is presented in figure 3. The seat (Fig. 4 b, c, d) can fully assume the driver’s seat position since the wheelchair lowers down to anchoring point for
correction of H-point. This is the point where a person's hip sits in a car seat or wheelchair. It is an important measurement as the H-point of a car is much lower than that of an electric wheelchair when tied down at the driver's seat, which has a bearing on how comfortable the driving task becomes and how easy it is to get in and out of a car (Fig. 2) (PAPAIOANNOU et al., 1999). All studies were repeated during actual prolonged car driving tests with a monovolume vehicle (FIAT Scudo, FIAT AUTO S.p.A, Torino, Italy).

Figure 2 - The TRANSWHEEL II wheelchair with specially designed frame consisting of crossed beams that allow for the seat height adjustment. This is necessary for the multipurpose use of the wheelchair: (a) indoors as autonomous mobility support (normal height position of seat: 833 mm), and (b) as vehicle seat at the driver’s or passenger’s location within a car (lowest height position of seat: 380 mm). This option allows the wheelchair seat to comply with the ergonomic and biomechanical requirements of the driving task. Note the difference in H-point location for the two positions and the more reclined pose and additional support for the lower extremity at position (b).
Figure 3 - The A1 wheelchair seat controller schematic. The air-pump is acting through the pressure regulator as central pressure positive input system and is connected to the main central system pressure sensor valve-S6. The pressure regulator is part of the controlling system (see figure 3e) and interacts with the controller accepting commands from the joystick and LCD screen. Notice how each valve/sensor (valve-S1 to S5) is also attached to the modified ROHO air subcushions and the controller. Feedback from the individual sensors of each subcushion and the total system pressure sensor valve-S6 enter the controller. There pressure thresholds and circulation of air between the subcushions can be pre-programmed. The schematic shows how a lower level threshold can affect the global decision in the control network of the system and finally viewed in the display. An additional output is provided for air release when total system pressure exceeds the threshold imposed by sensor valve-S6.
Figure 4 - The components of the new A1 seating system. a) five BASE UNITS (BU): Each BU is a modified ROHO subcushion connected to a valve shown in (d), b) seat system S1 with addition of modified ROHO. This is intermediate prototype of the iterative process that eventually results in seat A1. c) Final seat A1 on Wh3 (cover is removed to reveal the cushions), d) Control Unit (CU) for the programming of air traffic between the pump and the subcushions. The controller can retain a steady state flow between the different BUs or selectively inflate or deflate them. e) the A1 seat assembled at Wheelchair Wh3.

Table 1 - Modularity and material characteristics of the seating systems used in the study.

<table>
<thead>
<tr>
<th>SEATING SYSTEM TESTED</th>
<th>MODULARITY CHARACTERISTICS</th>
<th>MAIN MATERIAL AND PARTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car seating system 1: LANCIA KAPPA Fiat Scudo car seat: S1 (Fig. 4b)</td>
<td>Car seating system with no modularity in design and no adjustments for anthropometry-first iteration prototype that was tested and led to the design of wheelchair seat W2</td>
<td>FOAM, high-density (HD) poly-urethane foam</td>
</tr>
<tr>
<td>Car seating system 2: RECARO Orthoped seat: S2 (Fig. 1c)</td>
<td>Advanced car seating system with high modularity and several adjustments for tilt-turn functions and anthropometric adaptations according to the user size and needs</td>
<td>FOAM (HD) poly-urethane foam, modular back and buttocks support</td>
</tr>
<tr>
<td>Wheelchair seating system 1: MEYRA SPRINT basic seat: W1 (Fig. 1a)</td>
<td>Normal seating system with no adjustments and plain design of the contour of the back and buttocks support surfaces</td>
<td>FOAM (HD) poly-urethane foam</td>
</tr>
<tr>
<td>Wheelchair seating system 2: MEYRA OPTIMUS advanced seat: W2 (Fig. 1b)</td>
<td>Advanced seating system with modular parts and possibility of tilting and turning to match patient needs.</td>
<td>FOAM (HD) poly-urethane foam, modular back and buttocks support</td>
</tr>
<tr>
<td>Seating system based on Air-cushion subcushions: TRANSWHEEL seat A1 (Fig. 2)</td>
<td>A new dynamic seating system specially designed for wheelchair users.</td>
<td>AIR-CELLS subcushions-air-pump controller-pressure regulator valves/sensors and modular back buttocks support</td>
</tr>
</tbody>
</table>
The interface pressures that occur between the subject and the wheelchair seat were assessed with the Tekscan sensor mat™ in all the tests (Tekscan Inc., South Boston, MA, USA. Calibration and equilibration methods of the sensors are presented elsewhere (PAPAIOANNOU et al., 2008; PAPAIOANNOU et al., 2005). Fourteen wheelchair users (spinal cord injured persons with driver’s license; Males; Age: 23.3, SD=4.1 years, Weight: 81.7, SD=12.2 kg, Height: 1.79, SD=0.073 m) volunteered for the following testing protocols.

- Test protocol 1 investigated the result of prolonged sitting on the buttocks and back support pressures of fourteen subjects. The test included twelve sets of measurements for every subject. During each measurement two minutes of continuous pressure data from the buttocks and back support was acquired (200Hz) with wheelchair W2 and seat S2. Each set was performed every 10 minutes so that the total duration of the test was two hours. Each subject was asked to find the most comfortable position in which she/he sat for two hours with no (or minimum) movement. The protocol was repeated for seats S1 and W2.

- Test protocol 2 was identical to test 1 but was performed inside a mono-volume car with car driver’s seats S1 and S2 (n=14). The test was carried out during actual driving conditions in a variety of road surfaces. Details of this protocol that has also been used as part of investigating vibration related comfort can be found elsewhere (HOSTENS et al., 2003). The effects of prolonged (two hours) driving on pressure profiles were evaluated.

- Test protocol 3 was a repetition of test 2 but with the new seating system A1 mounted on wheelchair Wh2. The study investigated the ability of seat A1 to automatically adjust the pressure profiles during prolonged driving with the wheelchair assuming the driver’s seat. The system aimed at keeping the max pressure level constant and equal to the patient specific optimum profiles. Feedback for the pressure optimum was constantly provided from the computer screen of the software and the A1 controller display.

RESULTS

The effects of prolonged sitting on pressure distribution for wheelchair seats S1, S2, W2 (i.e. further modified S2 with unmodified ROHO) and A1 (unmodified and modified ROHO versions) were analysed. In Test 1 the response variable was the maximum pressure over all the pressure values at the buttocks and back support of each subject. The question of whether there is an increase in maximum pressure over time was tested with a repeated measures analysis. The repeated measures analysis refers to the 12 measurements of maximum pressure collected in a sequence of equally spaced points in time (total of two hours static sitting). Therefore, the time effect is also called the within subject effect. In the statistical analysis, the interest centres on how the maximum pressure means change over time. The method that is used is based on the mixed model with special parametric structure on the covariance matrices. This type of repeated measures analysis is modelling the correlation structure of the repeated measures, which itself is not of primary interest but is essential so that inferences about the means are valid. The MIXED procedure of the SAS software with a repeated statement and an auto-regressive covariance structure of order one is used to produce the analysis results.

Although for seat S2 there is an increase in the plot of the means, the procedure did not really find a significant main time effect giving a p-value of 0.0891 for the F-test based on the subject means with auto-regressive covariance specified. For seats S1 and W2 however, the analysis indicated a significant main time effect with a p value of 0.005. In addition to investigating maximum pressures, the different pressure magnitude levels were
also studied. Therefore, equally spaced intervals of pressure expressed in mmHg are constructed starting from interval 0-19 mmHg, to 19-38 mmHg and up to interval 175-maximum-220 mmHg. In this new design, there are two factors of interest: time and pressure-interval. The evident increase in sub-maximal pressure over time for all subjects (within subject effect) suggests that this growth depends on the magnitude of the intervals of pressure. The main time-effect hypothesis is now enhanced by the interval-and-time interaction characteristic influences. Visualisation of the data (Fig. 5) suggests that the intervals above middle (>77-97 mmHg) seem to have the most influence and these are only included in the model. Performing the MIXED model for this design and for seat S2 yields a significant time effect (p = 0.052) and also a significant difference in pressure interval (p = 0.0001). Similarly the same analysis for seats S1 and W2 indicated significant time effect (with p values of 0.072 and 0.0067 respectively) and also a significant difference in pressure interval.

![Figure 5](image)

**Figure 5** - The increasing trends of the sub-maximal interval 5 in (a) and the maximal interval 10 in (b) expressed as number of occurrences (%) during the prolonged seating tests performed with the five seats (14 subjects). The Data from modified and unmodified ROHO (no pre-programmed controller based modifications) are shown. In all cases the modified ROHO (new seat A1) performed better (particularly for max pressure interval 10) than all other seating systems. Seats S2 and W2 perform similarly and the poorest results refer to seat S1.
Significant probabilities for the t-tests for the parameters were found for seat S2. The linear coefficient for interval 5, which corresponds with values in (77-97 mmHg) interval is significant (p=0.0246). So, a significant linear time trend is found for the pressure area within the (77-97 mmHg) interval with a positive estimator for the parameter. Also the proportion of pressure values lying in interval 6, (97-116 mmHg), is significantly increasing over time, p = 0.0185. The linear coefficients for intervals 7 up to 10 are not significant, so there is no linear time trend. These differences in results from the t-tests for the linear coefficients indicate interaction between time and interval, though the statistical test for the interaction term was not significant. This contradiction is resolved by observing that the linear coefficients are nearly equal; they differ from each other by less than two of their standard errors.

Significant linear time trend is found also for intervals 5 and 6 for seats S1 and W2. Graphically, the linear time trends for the intervals 5 (77-97 mmHg) and 10 (175-220 mmHg) for all seats tested can be seen in figures 5a and 5b: The figures suggest that modified ROHO seat A1 performed better with regards to pressure increases in the prolonged sitting study than seats S1, S2 W2 and unmodified ROHO A1. This best performance seat A1 helped keep the max pressure to below 100mmHg for all subjects.

Seats S1 (first iteration prototype) and S2 were used for buttocks and backpressure measurements during driving a car for one hour to report on the effects of the initial design. The repeated measures analysis used here referred to the 6 measurements of maximum pressure collected in a sequence of equally spaced points in time (total of one hour driving). An increase in the plot of the means for seat S1 and S2, and the MIXED procedure (SAS) indicated a significant main time effect giving a p-value of 0.0001 and 0.0005 respectively for the F-test based on the subject means with auto-regressive covariance specified (Fig. 6).

![Figure 6 - Comparison of the behaviour of the buttock pressure for the two different seats (first iteration seat S1 and seat S2). The greater differences occur at the submaximal levels of pressure.](image)

Test 3 was a repetition of test 1 for each subject (n=14) with the new modified ROHO seat A1. The pressure level at the buttocks and back was continuously monitored while changing the subject’s immersion to the air cushions. Control of the air pump from the joystick and feedback from the software allowed the subject to stabilise the pressure distribution to a steady state for more than two hours. However, to further validate the
results, the question of whether there is an increase in maximum pressure over time was tested with a repeated measures analysis. The MIXED procedure with a repeated statement and an auto-regressive covariance structure of order one was used to produce the analysis results. The procedure did not find a significant main time effect giving a p-value of 0.0841 for the F-test based on the subject means with auto-regressive covariance specified.

The new seat design A1 mounted on the new wheelchair wh3 was tested while assuming the driver’s position. The back and buttocks pressure profiles were assessed for an hour of continuous driving. Air was shifted between the different subcushions or by changing the subject immersion to the air-cushions following pre-programmed instructions from the controller for keeping the max pressure within predefined values. The hypothesis of the increase in maximum pressure over time was tested with a repeated measures analysis. The procedure did not find a significant main time effect giving a p-value of 0.07 for the F-test based on the subject means with auto-regressive covariance specified.

A two factorial ANOVA is performed to test whether there is a difference in maximum pressure between seat S2 and seat W1 and whether this difference is evident between the different subjects. The interaction between subject and seat is therefore included in the model. The seat pressure means differ for the different subjects. Performing the analysis of variance for balanced designs, we find for the usual F-test: 1) a significant effect of the seat, \( p = 0.0001 \), 2) a significant effect of the subject, \( p = 0.0001 \) and indeed a significant interaction between seat and subject with \( p = 0.0001 \). Because the interaction is present, the seat pressure “means” for each subject are compared separately. For subjects 1, 3, 6, 7, 8, and 9 seat W1 shows a significantly poor performance comparing to that of seat S2. The subjects 4 and 5 show the opposite results, also with a very low p-value of 0.0001. Only for the subject 2 and 10, no significant difference among the seat means was observed \( p = 0.0641 \) and \( p=0.0732 \) respectively (Fig. 7).

![Figure 7 - Buttock pressure differences between seat S2 and seat W1. The issue of subject variability and its interaction with the two different seats suggests that the same seat can be the pressure relief solution to one and the pressure problem generator to another individual.]

**DISCUSSION**

Treatment and prevention of pressure sores focuses on limiting the duration of peak pressures applied to the skin surface.
Although tests involving benchmarking and pressure comparisons of wheelchair seats have been performed in the past it is still necessary to evaluate more seats during actual prolonged sitting and car driving. This is due to the specific sitting and posture biomechanics involved in the task of driving a car. The present study compared and evaluated existing solutions of foam based wheelchair systems, car seating systems and the new wheelchair seating system designed especially to minimize sitting discomfort during prolonged sitting and driving.

Foam seat S1 performed considerably poorer than foam seat S2 with respect to maximum pressures during sitting pressure tests for all subjects. Wheelchair seat W2 was better than S1 but indicated peak pressure differences with seat S2. Notable differences between the seats occur at the submaximal and maximal pressure intervals where in all cases seat S1 demonstrates 1.5 to 2.5 greater peak pressures than seat S2. Seat S2 revealed better performance than wheelchair seat W1 in six of ten healthy subjects and similar results for two subjects. The ANOVA indicated a significant interaction between seat and subject. The analysis leads to suggestive rather that conclusive results since seating system S2 performs better with most of the subjects (without however demonstrating perfect pressure relief characteristics) but still remains the pressure problem generator to a few individuals.

The different seating systems (S1, S2, and modified/unmodified A1) demonstrated very different results in prolonged sitting. Prolonged sitting on seat S2 (total of two hours) for all subjects (n=14) did not alter significantly the maximum pressures at the buttocks and back support. However, a significant increase in the sub-maximal pressure over time was evident, especially for the pressure intervals above the fifth interval (77-97 mmHg). It is shown from our tests that seats S2 and W2 performed equally whereas S1 gave the poorest results due to its oversimplified padding structure and flat contouring characteristics.

Seats S2 and W2 provide adequate support and considerably good buttock pressure results due to their advance padding and ergonomic design. Seating system S1, being a first iteration seat design was also evaluated for pressure gradients during one hour driving yielding a significant main time effect on maximum pressure. These results provided a useful input towards the design of the final seat A1. The modified ROHO seat A1 by allowing continuous automatic optimization of individual pressure profile performs considerably better in prolonged driving than its unmodified ROHO seat A1 version and the rest of the seating systems collectively. Continuous monitoring of the back support and buttocks pressures lead to optimal pressure results by sustaining a pressure steady state for one hour of car driving. It was apparent that patient specific preprogrammed air circulation between the different air-subcushions results in a continuous redistribution of the localized, weight-bearing, pressure sensitive areas of support.

Seat A1 helped keep the maximum back and buttocks pressures lower than 100 mmHg during prolonged sitting or prolonged driving/passenger status in all tested subjects. This max pressure optimization is required to prevent capillary occlusion and prevent the onset of pressure sores.

CONCLUSIONS

When wheelchairs are compared to modern office equipment or car seats they indicate poor sitting comfort and quality. This fact is particularly bad for wheelchair users since they have to sit more hours a day and complain about sitting discomfort and posture problems. These risks are more profound for wheelchairs that are used in public
transportation means or assume the car driver’s seat. The price for autonomy of the person with mobility problems while using the transportation infrastructure is additional discomfort from excessive sitting during the day without transfer from the wheelchair.

Our benchmarking suggested that our new design seat A1 with modified ROHO cushions is an important investment in contrast to the future cost of the patient entailed by an inferior sitting quality. Air based systems have been proven superior to foam based systems. Such dynamic wheelchair and car seating systems can lead to more radical solutions to the problems associated with prolonged sitting since they offer: a) Frequent changes of the maximum pressure, b) decrease and better distribution of the dynamic load at the back and buttocks by dynamic modification of pressure between several air subcushions, c) patient specific anatomically shaped cushion subsection for seat and back.

ACKNOWLEDGEMENT

The work was supported by the European Union’s DE/TAP programme (project TRANSWHEEL DE 3013). Hardware support came from SAFE S.S.F. Safe Smart Fabric Adaptable Surface Ltd Cyprus.

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