Prevalence of Sensor Saturation in Wheelchair Seat Interface Pressure Mapping

Michael Wininger & Barbara A. Crane

To cite this article: Michael Wininger & Barbara A. Crane (2015) Prevalence of Sensor Saturation in Wheelchair Seat Interface Pressure Mapping, Assistive Technology, 27:2, 69-75, DOI: 10.1080/10400435.2014.976800

To link to this article: https://doi.org/10.1080/10400435.2014.976800

Accepted author version posted online: 22 Oct 2014.
Published online: 22 Oct 2014.

Submit your article to this journal

Article views: 226

View Crossmark data

Citing articles: 2

View citing articles
Prevalence of Sensor Saturation in Wheelchair Seat Interface Pressure Mapping

MICHAEL WININGER, PhD1,2 and BARBARA A. CRANE, PhD, PT, ATP/SMS1*

1 University of Hartford, Department of Rehabilitation Sciences, West Hartford, Connecticut
2 Veterans Affairs Cooperative Studies Program, VA Connecticut Healthcare System, West Haven, Connecticut

Pressure mapping is a frequently used tool with great power to provide information about the forces between a patient and a wheelchair seat. One widely recognized limitation to this paradigm is the possibility of data loss due to sensor saturation. In this study, we seek to quantify and describe the saturation observed in the measurement of interface pressures of wheelchair users. We recorded approximately two minutes of interface pressure data from 22 elderly wheelchair users (11M/11F, 80 ± 10 years) and found that 4.7% of data frames had 1 saturated sensor, and 9.0% had more than one saturated sensor, for a total of 13.7% of all frames of data. Data from three of the 22 subjects (13.6%) were substantially affected by the persistent presence of saturated sensors. We conclude that for this population of elderly wheelchair users, sensor saturation may be a concern and should be factored properly into study design a priori.

Keywords: pressure mapping, pressure, pressure ulcer

Introduction

Pressure mapping is a common measurement tool used in both clinical and research activities that provides real-time imaging of the forces at key anatomical points of contact. This is critically important for maximizing comfort and minimizing risk of pressure ulceration (Bar, 1991; Brienza, Karg, Geyer, Kelsey, & Treffer, 2001). Indeed, evaluation of interface pressure data in sitting has been recommended for guiding clinical decision-making for 30 years (Swain, 2005; Yaqun, 2010). There are several technologies used in interface pressure mapping, and although outside the scope of this report, we refer the reader to two very comprehensive reviews on pressure mapping technologies and the types of sensors used in pressure mapping (Ferguson-Pell & Cardi, 1993; Gyi, Porter, & Robertson, 1998) for additional information about the technologies themselves.

Despite the increasing use of pressure mapping in both clinical practice and rehabilitation research, pressure mapping technology is not a perfected science. Concerns about reliability and validity of pressure mapping data have been investigated (Sprigle, Dunlop, & Press, 2003); however, there are potential technical difficulties involved in these data that are under-represented in the literature. In particular, sensor saturation—the placement of immeasurably high load on one or more sensors—is a potentially significant problem that has not been adequately measured and may be under-reported.

It is difficult to estimate the number of studies affected by the issue of sensor saturation, as understandably—occurrences are likely to go unreported. However, for those investigators that have reported the issue, the responses to sensor saturation include use of a special seat cushion to avoid saturation (Lacoste et al., 2006), exclusion of data collected using certain cushion types (Akins, Karg, & Brienza, 2011), removal of an entire participant’s data set from the analysis stream (Bar, 1991; Tam, Mak, Lam, Evans, & Chow, 2003), wholesale changes in study design (i.e., different outcome measures chosen for fear of saturation; Aissaoui, Lacoste, & Dansereau, 2001; Kim, Kim, & Oh, 2012); and reports of saturation as an issue or potential issue, but with no remediation described or being described as successfully avoided (Burns & Betz, 1999; Rithalia, 2005). We note that the Akins et al. (2011) study incorporated a “Molten” sensor, which differs from that used here, but is an illustrative example of a response to sensor saturation nonetheless.

Given the potential frequency with which sensor saturation may be encountered, and the non-trivial efforts involved in mitigating this circumstance, it is incumbent to ask: How common is sensor saturation in a representative seating interface pressure data set? This question is important for two reasons: (1) publishing estimates of saturation frequency allows for future studies to be designed with enough statistical power to accommodate anticipated data loss, and (2) opening a discourse over the rate of sensor saturation will allow researchers in this and related fields to make a data-driven decision on whether it is of broad interest to pursue a solution to this problem, creating a pathway to more efficient study design. The purpose of this study was to (1) quantify and describe the occurrence of sensor saturation in pressure mapping data, and (2) assess the impact of sensor saturation on commonly reported pressure mapping measures, on data collected from a sample of subjects for whom pressure measurement is commonly used for clinical decision-making and/or for research purposes.

*Address correspondence to: Barbara A. Crane, PhD, PT, ATP/SMS, University of Hartford, Dana 410C, 200 Bloomfield Avenue, West Hartford, CT 06117. Email: bcrane@hartford.edu
Methods

Participants

We intentionally set out to recruit a diverse cohort of wheelchair users for this study. Accordingly, the entrance criteria were intentionally broad: Participants were not excluded based on type of wheelchair or seat cushion type; participants were also allowed to use a variety of other positioning supports (e.g., wedges, blankets, and towels). Additionally, participants needed to be capable of sitting in a wheelchair comfortably for the observation period (between 15 and 20 minutes) and able to follow basic instructions of the researchers. Participants were only excluded if they had a current pressure ulcer at the time of data collection (a history of pressure ulcers was acceptable, so long as there were not ulcerations at the time of the study).

A convenience sample of 22 subjects was drawn from the local community and from six participating long-term care centers. Twenty-one of the participants were current wheelchair users, utilizing either manual or powered wheelchairs, and one participant had recently transitioned from wheelchair use to supervised ambulation in his facility. Participant demographics are reported in Table 1. All participants were oriented to the study, its team members, and provided informed, written consent prior to data collection. Methods for this study were approved by the University of Hartford Human Subjects Committee prior to subject recruitment.

Data Collection Protocol

The pressure mapping system used during this research project was the Force Sensitive Applications (FSA) system (Vista Medical, Winnipeg, Manitoba, Canada). This system uses a flexible mat with a 430 mm x 430 mm sensing area with an array of 16 x 16 resistive force sensors, each measuring 23.8 mm x 23.8 mm with a gap between sensors of 3.1 mm x 3.1 mm. The overall dimension of the mat was 533 mm x 533 mm. The mat materials are designed to minimize the risk of hammocking on contoured surfaces (Ferguson-Pell & Cardi, 1993).

The FSA mat was calibrated to the standard 200 mmHg maximum, according to the manufacturer’s instructions, and using the manufacturer’s auto-calibration system. Participants were transferred out of their wheelchairs by facility-employed therapists. The pressure mat was placed as close to the subject’s buttocks as possible (i.e., above any blankets or other extraneous materials), so that contact was directly with the participant. The pressure mat was contained in a thin isolation bag to protect it from exposure to urine or infections materials. Participants were tested wearing their normal clothing, including incontinence protection garments as needed. Participants were positioned in their wheelchairs using their existing foot supports, arm supports, and any other postural support materials typically used for each individual. All were positioned with as much pelvic symmetry as possible and their feet were supported to achieve approximately 90 degrees of hip and knee flexion, if they had the available range of motion to accommodate this position.

Once positioned in the wheelchair, participants were instructed to sit as still as possible for six minutes to allow for appropriate settling time, and to minimize the impact of sensor creep on the final data collected (Crawford, Stinson, Walsh, & Porter-Armstrong, 2005; Giesbrecht, Ethans, & Staley, 2011). Interface pressure data were recorded at 1 Hz for approximately two minutes, yielding approximately of 120 samples per participant and subjects were reminded to sit as still as possible during the data collection period. We chose two minutes to provide a robust sample of 120 frames for review, with adequate power to identify weight shift (Maurer & Sprigle, 2004; Reenalda et al., 2009).

Data Analysis

Data were extracted directly from the files exported from the FSA software, and analyzed in the Matlab numerical programming environment (Mathworks, Natick, MA). Sensor data were processed only for noise cancellation: Sensors reporting <5 mmHg for all time points were assumed as reading noise only (i.e., no load), and were overwritten as zero. For each participant, and for each frame, the number of saturated sensors (sensors reading 200 mmHg) were counted.

Recognizing that pressure may change rapidly during weight shifts or postural adjustments of the subjects, we employed a filter to detect movement of center of mass. For any frame in which the center of mass moved by a distance of more than 1 sensor distance (23.8 mm) in any direction relative to the previous frame, that frame was excluded from analysis. The center of mass was computed as the centroid of all active (non-zero) sensors, weighted according to pressure value. For those data frames containing multiple saturated sensors, an effort was made to determine whether the saturated sensors were co-located or distant from one another. For our purposes, co-located sensors (“islands”) were defined as sensors that were adjacent to each other, according to a binary image-counting routine available through the Matlab Image Processing Toolbox (bwlabel function).

Feature Extraction

Clinical studies incorporating pressure mapping often report on parameters calculated based on the matrix of pressure data. In order to estimate the impact of sensor saturation on pressure

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Average ± Standard Deviation; N = 22, unless indicated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>80 ± 10 years</td>
</tr>
<tr>
<td>Height</td>
<td>1.65 ± 0.127 m</td>
</tr>
<tr>
<td>Weight</td>
<td>74.84 ± 20 kg (N = 19)*</td>
</tr>
<tr>
<td>Height</td>
<td>28 ± 5.8 kg/m² (N = 19)*</td>
</tr>
<tr>
<td>Sex</td>
<td>11M/11F</td>
</tr>
<tr>
<td>Wheelchair type</td>
<td>Standard manual or hemi-height manual: N = 15</td>
</tr>
<tr>
<td>Cushion type</td>
<td>Custom manual tilt or power wheelchairs, N = 7</td>
</tr>
</tbody>
</table>

Note: *Missing weight data for three of the subjects.
array feature extraction, we calculated three commonly reported measures: peak pressure, average pressure, and the pressure gradient (Brienza et al., 2001; Sprigle et al., 2003; Sprigle & Sonenblum, 2011; Swain, 2005). Because it is not feasible to estimate the impact of sensor saturation by using frames with saturated sensors (that the sensor is already saturated eliminates the ability to compare to a “Ground Truth” [GT]), we analyzed only those frames with no saturation.

All files containing saturated sensors were removed from the analysis stream, and for any subject with at least one frame without saturation, an ensemble average pressure profile was created by averaging sensor data across all samples, yielding a single representative pressure map per subject. The single sensor with the maximum local pressure value was then censored by replacing its value with the average of pressure values recorded for its neighboring sensors using a k-Nearest Neighbor (kNN) imputation method (k = 4), a commonly used routine for restoring missing data (Chen & Shao, 2001; Kim, Golub, & Park, 2005). The three descriptors were then calculated from both the raw dataset (containing the GT sensor), and from the censored data. Comparison between raw and censored data was performed within-subjects with a Wilcoxon rank-sum significance test to determine departure from null impact; we chose the rank-sum in favor of the paired t-test, as we anticipated that at least one of the parameters would not withstand the assumption of normality (Wininger & Crane, in press).

Results

Prevalence of Sensor Saturation

For the 22 study participants, 2,643 total frames of data were collected (119–121 frames per subject). When accounting for possible artefact due to shifting of weight, we eliminated 28 frames (1.1% of data set) as having a supra-threshold change in center of mass. We found that 359 of 2,615 remaining frames (13.7%) contained one or more saturated sensors, and noted that some saturation was seen in 4 of the 22 subjects. Please refer to the flow diagram in Figure 1 for a detailed description.

Distribution of Saturated Sensors

Among the 235 frames with multiple saturated sensors, 111 (47.2%) contained one “island,” meaning all saturated sensors were adjacent to one another; and for 124 of the frames, there were two “islands”—or two regions in which saturated sensors were co-located (see Figure 2). For two of the three subjects with saturated sensors, visual inspection revealed that the saturation occurred in the region of the sacrum/coccyx; in the third subject, the saturation occurred beneath the ischial tuberosities (see Figure 3).

Impact on Feature Extraction

After discarding frames with saturated sensors, 20 subjects contained at least one frame of non-saturated data from which we were able to estimate the impact of sensor saturation on features commonly extracted from pressure array data. We found that parameters extracted from censored data were lesser than those extracted from GT datasets on all three features, however the effect sizes varied: maximum pressure decreased by 8.7 ± 7.1% (p < .0001), average pressure decreased by 1.0 ± 0.05% (p < .0001), and the pressure gradient decreased by 4.0 ± 3.0% (p < .0001).

We determined that as the GT value increased, imputation error increased reliably and substantially (ρ = 0.66; correlation of imputation error against GT value, where imputation is
Fig. 3. Illustration of the location or distribution of saturated sensels for subjects 1, 17, and 20. Demonstrates saturated sensels located in ischial tuberosity and sacral regions for all three of these subjects.

given as the difference between estimated value and GT). Our GT values ranged from 61.4 mmHg to 189.5 mmHg, with imputation error ranging from 15 mmHg to 95.1 mmHg; all imputations were under-estimates.

Discussion

Study Design

Here, we sought to quantify the occurrence of saturation in pressure sensor data collected at the seating interface among elderly wheelchair users. Pursuant to a maximally generalizable study, we designed a broad set of inclusion criteria and minimal exclusion criteria; our data conditioning methods were minimal, consisting of only two steps: thresholding minimal activity at 5 mmHg, and withholding frames indicative of a weight shift. We used a standard commercially available pressure mat for data collection, and operated in strict accordance with manufacturer’s recommendations in terms of calibration, placement, and maintenance. The design of this study was intentionally simplistic, to maximize clarity and reproducibility.

Sensor Failure

It is reasonable to ask whether the saturation observed in this report relates to a defective sensor. We report that all sensors are fully functional, and none appeared to be defective or damaged. To illustrate, Table 2 shows that 1, 6, and 4 sensors were saturated by the three subjects with saturated frames. From Figure 3, it is evident that the sensors so saturated were 11 different sensors in different regions of the mat, and that in data collected from other subjects, there is no saturation. While it is certainly possible that some saturations reported elsewhere could be due to a defective sensor, we believe that this is not the case here.

Following the findings of others, where peak seat interface pressure was observed in elderly individuals with low Body Mass Index (BMI), we sought to determine whether there were any identifiable factors which distinguished the three subjects with saturated data. The weight of one of these subjects (ID 17) was unknown, however, subject 1 weighed 81.5 kg (BMI of 26.5 kg/m²), and subject number 10 weighed 67.4 kg (25.5 kg/m² BMI). Subjects 1 and 17 were seated on mildly contoured foam seat cushions (as were the majority of subjects enrolled), and subject 20 was seated on a foam and gel combination cushion. As indicated in Table 1, the average weight for our subjects was 74.8 kg (SD 20 kg) and the average BMI was 28 kg/m² (SD 5.8 kg/m²). None of these conditions appeared to be “outliers” in the sample. This compares with a study performed by Reenalda et al. (2009) who also found no relationship between BMI and interface pressures in seating.

Feature Extraction

Clearly, it is impossible to know the impact of sensor saturation on features extracted from pressure array data, so estimating the impact of sensor saturation on pressure distribution parameters is not a straight-forward enterprise. Firstly, it is necessary to select an appropriate imputation method. This is a complicated matter, as there are no reports known to the authors of a widely accepted method for restoring data from saturated pressure sensors in application to wheelchair study. We infer that this is the reason for the extreme measures described by research groups above (i.e., discarding data sets and wholesale change in study design).

Here, we selected a k-Nearest Neighbor approach, on the basis of its wide use in other applications, and for its simplicity and ease of implementation. Many computational software packages, including Matlab, R, and SAS support kNN imputation, and it can easily be reproduced by non-programmers in a spreadsheet environment either by “hand calculation” or by using a simple macro. While the kNN is likely to underestimate the censored value if it is a global maximum (as is the case here), we decided that more sophisticated imputation methods were less well-supported in the literature, less intuitive, required more complex implementation, and that selecting among these methods would be beyond the scope of this paper.

With this context in place, we reflect on the imputation performed here, and its implications for estimating the effect of saturation on pressure distribution parameters. In short, we believe that while our reported effect sizes were small to moderate (1–9% decrease in parameter values versus the GT), this is likely to be an underestimate of the true effect that would be seen in real world application to sensors saturated above the 200 mmHg.

Table 2. Number and duration of saturated sensors.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Percentage of frames with saturated sensor(s)</th>
<th>Number of saturated sensors</th>
<th>Number of unique saturated sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>98.3%</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Subject 17</td>
<td>100%</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>Subject 20</td>
<td>100%</td>
<td>—</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2. Number and duration of saturated sensors.
It cannot be known what the GT for the saturated sensors might be, but extrapolating this trend to GT > 200 mmHg suggests that the imputation error would increase further. Please see Figure 4–top component for illustration of these results.

For each of the three parameters, we plotted parameter estimate error (parameter from imputed data – parameter from GT data) and found that as the imputation error increased, so did the parameter estimate error (again: uniformly a decrease in the parameter). While the caveat remains that it is impossible to know how far these should be extrapolated to inform the real world application to GT > 200 mmHg, we propose that for GT near 200 mmHg (corresponding to imputation error near 80 mmHg, per Figure 4–top), the parameter errors might be double what we report here (i.e., near 10–12% for maximum pressure, 1.3–1.4% for average pressure, and 5–6% for pressure gradient). Please see Figure 4–lower frames for illustration of this result. For GT values above 200 mmHg, this effect might be even greater. This result justifies that additional research is needed for devising and validating new methods for imputing global maxima, particularly with respect to clinical pressure mapping. Moreover, these results show how, understandably, an investigator might be inclined to discard saturated data, and retain only robust data for which all values are known.

**Study Impacts**

We believe that this study has important benefits to the future of empirical study involving pressure mapping—in particular: study design. An essential practice in the design of experimental protocols is the pre hoc estimation of sample size (i.e., the determination of the number of subjects required to test an anticipated effect given with a pre-defined statistical power). This action has implications for the ethics of a research study: An “under-powered” study is more likely to miss an effect that truly exists, confusing the literature and potentially obscuring important, realizable outcomes; an “over-powered” study exposes participants to risk unnecessarily. In particular, for investigators electing to discard their saturated data, it is important to have some estimate of an anticipated rate of data loss: how many subjects, and how much of the data. Furthermore, we believe that this study will reduce the barrier for investigators to assess and report their own rates of saturation. As evidence gradually clarifies the conditions under which saturation increases or decreases, the community of clinical researchers and device developers can cooperate towards the development of a set of best practices.

**Study Limitations**

As with all studies, this study was not without limitations. The small sample size used in this study certainly limits the precision of the results obtained. Smaller sample may explain the equivocal correspondence to findings of others that saturation is more frequent in patients with low BMI. Particularly in the case of Kernozek et. al. study design might be a confounding factor: Increasing our sample size and stratifying the patient pool into discrete groups on BMI would bring our design into closer conformity with this earlier result. We note that our sample was selected from a mixed population of older adult wheelchair users (similar to Kernozek et al., 2002), whose interface pressure

Fig. 4. Results of imputation error estimation and its effects on three commonly used pressure mapping parameters—maximum pressure, average pressure, and pressure gradient.
characteristics certainly could differ from other populations of wheelchair users (e.g. spinal cord-injured patients).

Furthermore, sensor saturation in this population may have occurred due to many factors, which were not investigated in the current study. However, our interest was in making a first attempt at quantifying this potentially serious problem with use of interface pressure data, and we feel this data set would be representative of commonly used clinical or research data set in this arena. Furthermore, we assert that the saturation effects reported here, or elsewhere but with a similar device pertain to the saturation associated with a resistive element; several industrial suppliers have capacitive sensors available which would have very different force-transducing properties. However, we note that a large share of the pressure sensing market remains heavily invested in resistive sensors. Lastly, we observe that this study is the first of its kind—known to the authors—to report extensively on the effects of saturation in pressure mapping; as a consequence, this study is limited in its ability to draw connections to relevant research reported elsewhere. We hope that future studies will make efforts to provide detailed information about saturation.

Future Directions

For the sake of clarity, only one type of pressure mat was used in the data collection, however, we used a widely available mat with good representation in the existing literature (Aissaoui et al., 2001; Brienza et al., 2001; Crawford et al., 2005; Giesbrecht et al., 2011; Maurer & Sprigle, 2004). We recognize that a wide variety of mats could have been used, and a future direction worth considering might be a benchmark study comparing several popular pressure mapping systems on a standardized test bed so as to test impact of manufacturer/design, sensor type and density, and surface on the propensity for saturation.

This study may be used to establish performance targets. Moreover, whereas a common response to saturation to discard the data or to alter protocols, it may be desirable to take on a community effort to establish conventional signal processing protocols for remediating these data so that a larger proportion of data can be saved and maximally naturalistic protocols can be implemented.

From a hardware perspective, researchers in this arena are making efforts to improve the performance of pressure mapping devices in the clinical and research environments (personal communication—Evan Call, 2013). Additional efforts in understanding a variety of pressure mapping parameters has also been undertaken in a laboratory setting (Sprigle et al., 2003). Efforts to expand the capabilities of pressure mapping arrays, including changing calibration protocols to allow calibration to a maximum of 300 mmHg are also employed in the application of this technology (Maurer & Sprigle, 2004). This expanded calibration range is not available for all pressure mats and requires specialty calibration equipment; therefore, it is not widely employed. Regarding the more recent studies in which sensor saturation is reported (see Background section), it is not clear whether these issues arose despite adoption of the suggested modifications of Sprigle et al. (2003) and Maurer & Sprigle (2004), or whether these modifications were simply not practicable. Nevertheless, that saturation persists as a potential confounder in research studies evidences the need for a direct address of the issue.

Sensor saturation may be related to resolution of the mat itself. We did not compare a higher resolution system with the system we used in testing, so this remains an open question worthy of further investigating.

Conclusion

Though small, this study has potentially important implications for the community of researchers and practitioners who integrate pressure mapping into their daily work with wheelchair users. Most importantly, we report the first known rate of sensor saturation at the seating interface to be greater than 10%, both in terms of number of frames with saturated sensors (13.7%) and number of subjects with some saturated data (16.6%). Our study incorporated a maximally generalizable design, but incorporated only one device in estimated saturation prevalence. Replication of this study, and extension into more focal test scenarios, is encouraged.

References


