Basic research

Interface pressure mapping pilot study to select surfaces that effectively redistribute pediatric occipital pressure

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Abstract  Aim: The aim of this pilot study was to better inform clinical decisions to prevent pediatric occipital pressure ulcers with quantitative data to choose an appropriate reactive support surface.

Materials: A commercially available capacitive pressure mapping system (XSENSOR, X3 Medical Seat System, Calgary, Canada) was used to evaluate a standard pediatric mattress and four commercially available pressure-restricting support surfaces.

Methods: The pressure mapping system was validated for use in the pediatric population through studies on sensitivity, accuracy, creep, and repeatability. Then, a pilot pressure mapping study on healthy children under 6 years old (n = 22) was performed to determine interface pressure and pressure distribution between the occipital region of the skull and each surface: standard mattress, gel, foam, air and fluidized.

Results: The sensor was adequate to measure pressure generated by pediatric occipital loading, with 0.5—9% error in accuracy in the 25—95 mmHg range. The air surface had the lowest mean interface pressure (p < .005) and lowest peak pressure index (PPI), defined as the peak pressure averaged over four sensels, (p < .005). Mean interface pressure for mattress, foam, fluidized, gel, and air materials were 24.8 ± 4.42, 24.1 ± 1.89, 19.4 ± 3.25, 17.9 ± 3.10, and 14.2 ± 1.41 mmHg, respectively. The air surface also had the most homogeneous pressure distribution, with the highest mean to PPI ratio (p < .005) and relatively high contact area compared to the other surfaces (p < .005).

Conclusion: The air surface was the most effective pressure-restricting material for pediatric occipital pressure as it had the lowest interface pressure and a homogeneous pressure distribution. This implies effective envelopment of the bony prominence of the occiput and increasing contact area to decrease peak pressure points.

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1. Introduction

Pressure ulcers are chronic non-healing wounds that can be acquired in the hospital setting, with reported incidence of up to 27% in acutely ill infants and children [1] and an estimated $11 billion total yearly cost for treatment in the United States [2]. In addition to this cost, pressure ulcers can lead to infection and can leave behind permanent scars that can disfigure children or require plastic surgery to repair. Hospital-acquired pressure ulcers can be categorized as either immobility-related, which often occur over bony prominences, or medical device related, which result from unrelieved tissue compression on an area of the body in contact with a medical device [1]. Pediatric patients possess unique risk factors for pressure ulcers and have different anatomic sites at risk than adults.

The head is proportionately larger and heavier in infants and toddlers, so the occiput is a primary pressure point and therefore at higher risk for ulcer development [1]. Therefore, while most adults will develop pressure ulcers on the sacrum or heels, children are more likely to develop these injuries in the occipital region [3].

It is hypothesized that pressure ulcer etiology is distinct for superficial wounds and for deep tissue injuries, although the same underlying cell deformation processes are responsible. When mechanical load is applied for a long duration, for example if a patient lies on a hard surface for an extended time period, soft tissues are excessively compressed, which can lead to collapse of blood vessels and high cell deformation within the tissues [4]. When blood vessels collapse, it causes the tissues to suffer from ischemia and the subsequent oxygen deprivation eventually leads to cell death, soft tissue necrosis, and ulcer formation [5,6]. Alternatively, sustained loading may compromise tissue viability directly by geometrically distorting cells, which can cause cell death through a direct rupture of cytoskeleton, by distorting cellular organelles like the plasma membrane, or through internal pathways [7,8]. Superficial wounds result from a combination of shear forces and pressures at the interface between the skin and supporting surfaces while deep tissue injuries are the result of high stresses and strains adjacent to the bone.

The main root causes for pressure ulcer formation are pressure, shearing, friction and moisture. Pressure, when applied over time, is the most commonly known cause of pressure ulcer formation. Studies have shown that the deleterious effect of high pressure for a short duration is much more than the effect of low pressure for a longer duration [9].

In the clinical setting, patients are assigned a pressure ulcer risk score based on their status in risk factor categories, through a structured assessment. There are multiple pediatric pressure ulcer risk assessment scales (Braden Q, Starkid, etc.) that score different risk factors and assign them varying weights, however there is no unanimously preferred scale [10]. Pressure ulcer risk scales can be used to effectively target higher risk patients, however all current scales are subjective and there are no quantitative methods to measure pressure ulcer risk that are regularly used in the clinical setting.

Clinicians often place pressure-redistributing surfaces underneath high-risk patients in an attempt to lower peak pressure points at the skin surface. These support surfaces can be used to prevent or treat pressure ulcers and they aim to reduce the magnitude and/or duration of pressure between the individual’s skin and the surface [11]. Despite these interventions, pressure ulcers are still a problem in the pediatric population and there is a need for quantitative risk detection methods to identify and effectively treat patients at high risk for developing pressure ulcers.

Pressure mapping allows clinicians to visualize the distribution of pressure exerted on a patient’s body to help select appropriate pressure-redistributing surfaces and to effectively position patients. Interface pressure measurement has been used in various studies, for example, to compare alternating pressure air mattresses for heel pressure relief [12] and to examine the influence of bed sheet materials and bed making methods [13]. The literature confirms that there is a qualitative relation between interface pressure and pressure ulcer development but it is important to note that interface pressure alone cannot predict pressure ulcer formation [14]. However, pressure mapping technology provides information that allows for more informed clinical decision-making and will therefore contribute to better pressure ulcer prevention protocols, more informed care decisions, and better optimized pediatric pressure-redistribution surfaces.

There are two types of pressure-redistributing surfaces, active and reactive. Active support surfaces are powered to mechanically vary pressure, while reactive support surfaces may be powered or non-powered and can only change load distribution properties in response to an applied load. Active surfaces periodically shift areas of support so that deformation is not sustained over any one area [8]. Reactive surfaces are often a less costly alternative and include mattresses or overlays filled with materials such as air or gel. They are typically designed to reduce pressure ulcer risk by deforming in response to an applied load to provide
immersion and envelopment [8] so that pressure is dispersed over a larger surface area [11]. Pressure mapping studies that are specific to pediatric subjects are lacking in the literature. Two studies by McLane et al. measured interface pressure localized to the occiput and found statistically significant pressure differences for the surfaces tested [15,16]. These studies confirm the efficacy of using pressure-redistributing surfaces to decrease pressure at the occiput in pediatrics, however the measurements were not taken over time and they utilized a single pressure-sensing cell. In a study by Garcia-Molina et al. (2012), there was a significant decrease in pressure ulcers in children in intensive care associated with a continuous, reactive low pressure support surface compared to a retrospective cohort that used a standard hospital mattress [17]. Despite these initiatives, no studies have been found that compare different types of pressure-redistributing surfaces in the pediatric population using pressure mapping.

The aim of this research was to evaluate the pressure-redistributing properties of contemporary surfaces used for hospitalized pediatric patients through a pilot pressure mapping study with healthy children, following protocols outlined in the literature [18,19].

2. Materials and methods

2.1. Equipment

The XSSENSOR X3 Medical Seat System, LX100 Cleanable Seat Sensor (XSSENSOR, Calgary, Canada), which is a 45 x 45 cm capacitive pressure sensor with 1296 sensels, was utilized for this pilot study. A standard pediatric mattress (Kolcraft, Chicago, IL) and four commercial pressure-redistributing support surfaces: gel (DandleLion Medical, Danbury, CT), foam (Sage Products LLC, Cary, IL), air (EHOB, Indianapolis, IN), fluidized (Sundance Solutions, White Plains, NY) were evaluated in this study.

Data analysis was performed using the X3 Software, Microsoft Excel, SPSS, and MATLAB.

2.2. Sensor accuracy

The factory calibration of 5–200 mmHg is optimized for wheelchair seating assessments and was determined to be inadequate for measuring pediatric occipital loading. Therefore, the sensor was recalibrated to 5–100 mmHg according to the manufacturer’s instructions using 5 calibration intervals (5, 25, 50, 75, 100 mmHg), which accounted for lower weight subjects. To test calibration accuracy, the sensor and air bladder were placed in a calibration jig. Data was collected for 30 s with a recording frequency of 0.1 Hz. Each sensor calibration was tested in this manner five times and the average pressure was determined. The 5–100 mmHg calibration was more accurate than the 9 interval factory calibration with error ranging from 0.5 to 9% in the 25–95 mmHg range, Fig. 1.

2.3. Repeatability

To test repeatability of each sensor calibration, weighted head forms were used to simulate loading of a child’s occiput. By combining data from body segment mass of children’s heads [20,21] and anthropometric data for children [22], occiput weight for children of different ages was calculated to be 20% of total body weight for a child’s occiput. A smaller head form was weighted with sand to 1.15 kg to simulate an infant and a larger head form was weighted to 3.20 kg to simulate a toddler. In a randomized experiment, the pressure from each head form was measured 10 times on all four pressure-redistributing surfaces. Fig. 2 illustrates the experimental setup.

For each weighted head form, pressure mapping data were collected for 1 min with a recording frequency of 0.5 Hz. Peak pressure index (PPI) was calculated as a 4 sensel average for each time step and was then averaged over the
entire time interval. The PPI is defined as the highest recorded pressure within a $9 \times 10 \text{ cm}^2$ area, the approximate area of most adult bony prominences [23]. As such, a four-sensel average was used in this study to correspond to pediatric occipital loading.

The PPI analytical approach is an attractive interpretation of interface pressure because it increases reliability and accuracy through its use of multiple sensels compared to a single peak. However, when an average pressure measurement is utilized, particularly over larger surface areas, there are fewer differences found between rival products [24]. In the clinical setting, observation of the 3D pressure map plot over time is advantageous due to its real-time display capabilities [24]. Maximum interface pressure is another commonly used analytical method, and while it aids in distinguishing differences in rival products, it is susceptible to errors caused by sensor surface folds [24].

Repeatability for the 5-interval calibration resulted in a coefficient of variation (COV) for PPI less than 11% for the gel, foam and fluidized surfaces and approximately 20% for the air surface, Fig. 3. For contact area, the COV was under 18% for

Fig. 2 Experimental setup, weighted head form on XSENSOR with test surface underneath.

Fig. 3 Coefficient of variation for PPI and contact area for 5 interval calibration with weighted head forms — (a) gel, (b) foam, (c) air, (d) fluidized ($n = 10$ for each case).
the fluidized surface and under 11% for the gel, foam and air surfaces.

2.4. Creep and sensitivity

A constant load was applied to each surface for a 5 min interval and 0.17 Hz recording frequency to determine creep of the sensor and surfaces. Infant and toddler head forms were used to approximate pediatric occipital loading conditions, 1.15 kg and 3.20 kg, respectively.

Regarding sensitivity, a glass jar, weighted with sand, was used to apply a constant load to the sensor. Subsequently, the load was decreased by 100 g increments from 4.62 kg to 1.02 kg to encompass the range of expected pediatric occipital loading. Each measurement was taken for 10 s, with a 0.5 Hz recording frequency, to determine the average pressure.

Results indicated that creep was below 11% for five minute recording intervals for both head forms on all four surfaces. This amount of creep was assumed negligible for the 30 s measurements planned for this study. Regarding sensitivity, the XSSENSOR system was capable of measuring 100 g increases in load over the range of interest, Fig. 4. The results of creep and sensitivity studies indicated that the pressure mapping system can detect small differences in pressure over 30 s intervals with negligible creep and therefore, it is adequate for this study.

2.5. Pressure mapping study

The Tufts University Social, Behavioral and Educational Research Institutional Review Board approved this study as described. The study was carried out in February 2015. Children aged 0–6 were recruited for this study and experiments were held at participant’s homes. Twenty-two healthy children under 6 years old were recruited for this study according to a protocol approved by the Tufts University Institutional Review Board. Table 1 shows the subjects’ demographic data.

![Fig. 4 Sensitivity study results for measurement of average pressure for an applied load increasing in 100 g increments.](image)

Table 1  Subject profiles.
<table>
<thead>
<tr>
<th>Subject characteristics (n = 22)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>4.5 months</td>
<td>5.5 years</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>10</td>
<td>46</td>
</tr>
<tr>
<td>Height (in)</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>Gender</td>
<td>8 female</td>
<td>14 male</td>
</tr>
</tbody>
</table>

Before the experiment began, the parent gave informed consent. A standard pediatric mattress was placed on the floor in an empty area. Then, the pressure sensor was placed on top of the mattress, with a thin sheet covering the entire surface so that children would not be alarmed. Next, the child lay on top of the sheet. Measurements of pressure were taken for 30 s, with a recording frequency of 0.5 Hz. For the first measurement, baseline, the child lay down on the mattress without using any pillows or test surfaces. Subjects were instructed to remain as still as possible and parents were encouraged to distract young babies to keep them preoccupied and lying relatively still. After the baseline measurement was complete, each of the four test surfaces was placed underneath the pressure sensor and sheet, beneath the child’s head, and data was collected for 30 s.

3. Results

3.1. Pressure mapping study

Raw pressure mapping data was captured by using the XSSENSOR software and exported to Excel and MATLAB for processing and analysis. Individual frames were omitted if the child moved off the sensor. Fig. 5 shows a representative pressure map for each surface, with the occipital region outlined.

3.2. Interface pressure

Interface pressure was quantified by mean interface pressure and peak pressure index, while pressure distribution was measured through mean to peak pressure index ratio and contact area, see Table 2.

Normality was assessed using the Shapiro–Wilk test (p > .05) and by checking histograms of the data. SPSS (version 22) was used to perform paired t-tests and the Bonferroni Correction was applied for pairwise comparisons, which adjusted the significance value to .005.

The air surface had a statistically significantly lower mean interface pressure than all other
surfaces (p < .005). Mean interface pressure for mattress, foam, fluidized, gel, and air materials were 24.8 ± 4.42, 24.1 ± 1.89, 19.4 ± 3.25, 17.9 ± 3.10, and 14.2 ± 1.41 mmHg, respectively, Fig. 6.

The air surface had a statistically significantly lower PPI than all other surfaces (p < .005) and the pediatric mattress had a statistically significantly higher PPI than all other surfaces (p < .005). Average PPI for mattress, foam, gel, fluidized, and air materials were 56.0 ± 13.8, 43.4 ± 4.2, 40.7 ± 9.9, 38.5 ± 8.9 and 23.8 ± 4.0 mmHg, respectively, Fig. 7.

3.3. Pressure distribution

Mean interface pressure (mmHg) was exported and used to calculate the mean-to-peak pressure index ratio, which was then averaged across all subjects and compared. The air surface had the highest average mean-to-peak pressure ratio (0.61) of all surfaces (p < .005), which implies that the air surface had the most homogenous pressure distribution, see Fig. 8.

The XSENSOR system measures contact area in addition to pressure. Contact area (cm²) for the

<table>
<thead>
<tr>
<th>Surface</th>
<th>N</th>
<th>Mean interface pressure (mmHg)</th>
<th>Peak pressure index (mmHg)</th>
<th>Mean to peak pressure index ratio</th>
<th>Contact area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Air</td>
<td>22</td>
<td>14.2</td>
<td>1.41</td>
<td>23.8</td>
<td>3.96</td>
</tr>
<tr>
<td>Foam</td>
<td>22</td>
<td>24.1</td>
<td>1.89</td>
<td>43.4</td>
<td>4.23</td>
</tr>
<tr>
<td>Fluidized</td>
<td>22</td>
<td>19.4</td>
<td>3.25</td>
<td>38.5</td>
<td>8.87</td>
</tr>
<tr>
<td>Gel</td>
<td>22</td>
<td>17.9</td>
<td>3.10</td>
<td>40.7</td>
<td>9.91</td>
</tr>
<tr>
<td>Mattress</td>
<td>22</td>
<td>24.8</td>
<td>4.42</td>
<td>56.0</td>
<td>13.71</td>
</tr>
</tbody>
</table>

Fig. 5 Pressure maps of each surface, with occipital region outlined.

Fig. 6 Mean interface pressure for all subjects (n = 22). Error bars indicate ± standard deviation. P-value (*) < .005 for paired t-tests.

Fig. 7 Mean interface pressure for all subjects (n = 22). Error bars indicate ± standard deviation. P-value (*) < .005 for paired t-tests.
The XSENSOR system is manufactured as a seat cushion sensor to assess interface pressures for wheelchair cushions and other seating applications and is factory calibrated to 5–200 mmHg. However, occipital pressure measurements for pediatrics are much lower than adult seating pressure measurements, and thus a sensor calibration of 5–100 mmHg can more accurately capture lower pressure. Sensor creep and sensitivity are adequate to measure pediatric occipital pressure and compare pressure-redistributing effects of various materials.

PPI measurements vary in repeatability based on which surface is tested. The air surface has the highest variability in bench top testing applications because the head form does not mimic the whole part of the body in contact with the material and therefore causes the air surface to bottom out. This problem does not occur with the other surfaces because they are stiffer and smaller than the air surface.

There are primary indications that an air surface is the most effective pressure-redistributing material for pediatric occipital pressure as it has the lowest PPI and mean interface pressure of all surfaces tested and the most homogenous pressure distribution with the highest mean to PPI ratio of all surfaces tested and a relatively high contact area. The low PPI, low mean interface pressure, high mean-to-peak pressure ratio, and high contact area imply effective envelopment of the bony prominence of the occiput and increasing contact area to decrease peak pressure points. The PPI for the standard mattress is significantly higher than all of the pressure-redistributing materials tested, which implies that all surfaces are more effective than a standard mattress. The gel material also has a high contact area, showing some envelopment, however it does not decrease PPI as significantly as the air surface and has a low mean to PPI ratio, and therefore has a less homogeneous pressure distribution.

All subjects in this pilot study were healthy children, who may have different pressure ulcer risk factors than hospitalized children. However, the statistically significant results over a range of subject profiles (n = 22) implies that the results can be applied to hospitalized children as well.

Ideally, all subjects would have been immobile during pressure mapping, however many subjects were not able to lie still. Averaging measurements over the thirty-second time period helps to attenuate the effects of this movement, however,
future studies should utilize longer measurement periods.

To the author’s knowledge, this is the first pressure mapping study to compare effectiveness of pressure-redistributing surfaces in the pediatric population. Previous studies have utilized the Mini-Texas Interface Pressure Evaluator, a single pressure-sensing cell that is not as sophisticated as current pressure mapping technology, to compare interface pressure of different surfaces in the pediatric population [15,16]. However, these studies are somewhat dated (2002, 2008) and do not consider commonly used surfaces that have been introduced into the market since these studies were completed. Additionally, these studies took isolated rather than continuous measurements and did not analyze contact area. However, previous studies show the same trend as the current study, where all pressure-redistributing surfaces are more effective than a standard mattress.

Future work could include testing additional parameters that characterize pressure-redistributing surfaces, including immersion and heat/water vapor dissipation. The Support Surface Standards Initiative (S3I) is creating standards for evaluating these properties and should be used to carry out these types of experiments in the future [25]. Additionally, it would be useful to measure pressure-redistribution over longer time periods and with critically ill children to see if the same trends hold true. Additional support surfaces, including active pressure-redistributing surfaces, should be evaluated and compared to the reactive pressure-redistributing surfaces used in this pilot study.

5. Conclusion

This pilot study provides preliminary indications for a clinical recommendation to use an air surface to redistribute pediatric occipital pressure. The air surface is the most effective pressure-redistributing material of those tested with the most homogeneous pressure distribution and lowest pressure profile. Pressure mapping is an important technological tool that, in combination with consideration of additional risk factors, can contribute to quantitative risk detection for pressure ulcers. The bench top testing performed in this study validates the use of a recalibrated XSENSOR system in the pediatric population and can translate to future use in the clinical environment to quantitatively determine pressure ulcer risk and to design appropriate prevention protocols.

Conflict of interest

There are no conflicts of interest. The authors state that no financial and/or personal relationships exist with other people or organizations that have inappropriately influenced our work.

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References

Interface pressure mapping pilot study for pediatrics


