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The effect of cushion properties on skin temperature and humidity at the body-support interface

Tzu-Wen Hsu, MD\textsuperscript{a}, Shu-Yu Yang, MS\textsuperscript{b}, Jung-Tai Liu, MD\textsuperscript{c}, Cheng-Tang Pan, PhD\textsuperscript{d}, and Yu-Sheng Yang, PhD \textsuperscript{e}

\textsuperscript{a}Department of Rehabilitation Medicine, Fangliao General Hospital, Pingtung County, Taiwan; \textsuperscript{b}Department of Rehabilitation Medicine, Chi-Mei Medical Center (Yong Kang), Tainan City, Taiwan; \textsuperscript{c}Department of Rehabilitation Medicine, Chi-Mei Medical Center (Liou Ying), Tainan City, Taiwan; \textsuperscript{d}Department of Mechanical and Electromechanical Engineering, National Sun Yat-Sen University, Kaohsiung City, Taiwan; \textsuperscript{e}Department of Occupational Therapy, College of Health Science, Kaohsiung Medical University, Kaohsiung City, Taiwan

\section*{ABSTRACT}
The purpose of this study is to explore the effects of various cushions on skin temperature and moisture at the body–seat interface during a 2-hour period of continuous sitting. Seventy-eight participants were randomly assigned to sit on one of the three types of wheelchair cushions for unrelieved sitting for over 2 hours. Skin temperature and relative humidity (RH) were measured under the subjects’ ischial tuberosities and thighs bilaterally with digital temperature and humidity sensors. Data were collected before sitting and at 15-minute intervals thereafter. Participants sitting on foam–fluid hybrid cushions showed significantly lower skin temperatures than those sitting on air-filled and foam cushions ($p < 0.05$), but RH did not differ significantly among the cushions ($p = 0.97$). The three cushions produced a similar increasing trend in RH over time and RH reached a plateau during the 2-hour sitting period. To select the appropriate wheelchair cushion, the microclimate (heat and moisture control) between the body–seat interface should be considered as well as pressure distribution. In comparison with foam–fluid hybrid cushions, the air-filled rubber and foam cushions tended to increase skin temperature by several degrees after prolonged sitting. However, cushion materials did not have significant differences in moisture accumulations.

\section*{Introduction}
Pressure ulcers, also known as decubitus ulcers or bedsores, are localized injuries to the skin and/or underlying tissue that usually occur over a bony prominence because of pressure alone or pressure in combination with shear and/or friction stresses. Pressure ulcers can be life threatening if left untreated or if underlying health conditions prevent them from healing. They tend to affect people with health conditions that restrict their movement—particularly those confined to a bed or seat for prolonged periods. Therefore, protection of the soft tissue over the buttock area is vital to individuals who are bedridden, chair-bound, or unable to reposition themselves. The prescription of a pressure-reducing cushion is a common prophylactic method for the prevention of pressure ulcers in wheelchair users, and many different styles of cushion are commercially available. The materials used in the manufacturing of wheelchair cushions include foam, gel, fluid, air, or a combination of these materials (Cooper, Ohnabe, \& Hobson, 2006). Many wheelchair users sit for long periods in their wheelchairs every day (Yang, Chang, Hsu, \& Chang, 2009; Yang, Chou, Hsu, \& Chang, 2010); thus, pressure relief is an essential requirement in a cushion. Previous studies have compared the pressure relief performance of different types of cushions (Apatidis, Solomonidis, \& Michael, 2002; Burns \& Betz, 1999; Ferrarin, Andreoni, \& Pedotti, 2000; Geyer, Brienza, Karg, Treffler, \& Kelsey, 2001; Gil-Agudo et al., 2009; Sprigle, Wootten, Sawacha, \& Thielman, 2003). However, cushion performance varies widely from person to person, and a universal cushion, which can reduce pressure equally for all users, does not currently exist. Therefore, disagreement remains regarding the most effective pressure-relieving cushion, although air cushions exhibit lower pressure distribution than other types (Gil-Agudo et al., 2009; Sprigle et al., 2003; Yuen \& Garrett, 2001).

Besides pressure, several other risk factors have been associated with pressure ulcer development, and these include elevated skin temperature. When skin is in contact with a support surface, heat accumulates between the support surface and the skin; thus, skin temperature increases. In combination with pressure loading, elevated skin temperature over a bony prominence increases the risk of developing pressure ulcers (Bergstrom \& Braden, 1992; Kokate et al., 1995). In addition, temperature also affects the mechanical strength of the stratum corneum (Wu, van Osdol, \& Dauskardt, 2006), thereby leading to weakening and breakdown of the skin.

Along with temperature, moisture appears to be a key extrinsic factor in the development of pressure ulcers (Bergstrom, 2005; Braden \& Bergstrom, 1987). Excessive moisture on the skin surface, which may be caused by perspiration, urinary or fecal incontinence, wound drainage, or vomit, increases the risk of developing pressure ulceration by the weakening skin. In addition, excessive moisture can significantly increase the
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skin’s coefficient of friction (Gerhardt, Strassle, Lenz, Spencer, & Derler, 2008), which can lead to an increased likelihood of skin damage from friction and shear stresses. Relative humidity (RH) also affects the strength of the stratum corneum; the stiffness of the stratum corneum decreases 75% with the increasing 10% to 98% RH ranges (Wildnauer, Bothwell, & Douglass, 1971). Therefore, it is important to thoroughly assess the temperature and moisture between the body and support surface because they both have an impact on pressure ulcer development.

Previously, few studies have investigated temperature and humidity at the body–seat interface (Ferrarin & Ludwig, 2000; Liu, Cascioli, Heusch, & McCarthy, 2011; McCarthy, Liu, Heusch, & Cascioli, 2009; Seymour & Lacefield, 1985; Stewart, Palmieri, & Cochran, 1980; Stockton & Rithalia, 2009). These studies were limited either by relatively small subject groups (sample size) or methodology. For example, the findings of Stewart et al. (1980) were restricted to just one young man sitting on 24 different seat cushions. Liu et al. (2011) recorded temperature data for only 20 minutes when the subjects sat on three different types of seat cushion; however, it is possible that skin temperature could continue to change asymptotically during a 2-hour sitting period (Stewart et al., 1980). Ferrarin and Ludwig (2000) compared the thermal transients of four seat materials under the ischial and thigh areas of the subjects, but they required subjects to stand for 30 seconds every 5 minutes to image the elevated seat temperature by thermography. In other previous studies, more than one sensor/probe was used for microclimate measurements at the body–seat interface (Seymour & Lacefield, 1985; Stewart et al., 1980; Stockton & Rithalia, 2009). In these cases, humidity and temperature sensors were not set up individually and then incorporated into a single data logger; these extra sensors would occupy more space and may increase the likelihood of subject discomfort. It is possible that the aforementioned limitations prevented an accurate investigation of normal physiological interactions between subjects and seat materials. Therefore, the purpose of the present study was to use a digital temperature and RH sensor module, which integrated temperature and humidity sensor elements, to investigate whether various cushion materials influence the temperature and humidity at the body–seat interface during a 2-hour sitting period. We hypothesized that the cushion types would differ in terms of their ability to handle heat and humidity during continuous unrelieved sitting for 2 hours.

Methods

Participants

Seventy-eight able-bodied participants (39 male and 39 female) were enrolled in the study, and each gave their informed consent prior to participation in the study in accordance with the procedures approved by the Institutional Review Board of the Kaohsiung Medical University Hospital (KMUH-IRB-2030365). Participants were included in the study if they met the following criteria: They were aged 20–40 years, had a body size that fit the test wheelchair, and had no history of pressure ulcers. Participants were excluded if they had any medical conditions that affected body temperature (e.g., if they had a fever or were taking drugs). Able-bodied participants were used in this study because natural differences occur in wheelchair users’ body types, diagnoses, and levels of injury that can affect body temperature regulation (e.g., hypothermia). Therefore, this study was conducted with a sample of young, able-bodied participants with relatively homogeneous physical conditions.

Instrumentation

Three commercially available pressure-relief wheelchair cushions were used in this study (Figure 1): (1) a dual compartment air-filled rubber cushion (ROHO Low Profile Cushion, ROHO Inc., Belleville, IL, USA), (2) a foam–fluid hybrid cushion incorporating a top layer of viscous fluid and a bottom layer of foam (Model HS-017, Hueishen Enter. Corp., Pingtung, Taiwan), and (3) a medium density foam cushion (Model WA-2550, Karma Medical Products Co., Ltd, Chia-Yi, Taiwan). To avoid possible confounding effects of different cushion covers, all cushions were tested without covers. All participants were asked to wear cotton short pants in the experiments to avoid the influence of different trouser materials in the results. This study was a randomized controlled trial. All participants had an equal chance of being assigned to one of three groups. Participants were randomly assigned (using computer-generated methods with stratification by gender at 1:1) to sit on one of the three types of cushion. They were asked to sit naturally for 2 hours without lifting their buttocks and thighs from the seat cushion. Previous findings by McCarthy et al. (2009) indicated data from a 20-minute sitting time would be sufficient to show representative temperature curves reach their plateau, but Stewart et al. (1980) pointed out that skin temperature could continue to change asymptotically during a 2-hour sitting period. Therefore, a 2-hour continuous sitting protocol was used in this study. A randomized controlled trial was conducted because taking repeated measurements from subjects over time would more

![Figure 1. A photograph of cushions used in the present study: (a) air-filled rubber cushion; (b) foam-fluid hybrid cushion; (c) medium density foam cushion.](image-url)
likely be affected by heat/humidity accumulation between the body–seat interface during long periods of sitting regardless of the type of cushion used. The seat cushion was placed on a lightweight folding manual wheelchair (Model KM-8520, Karma Medical Products Co., Ltd, Chia-Yi, Taiwan) with a 45-cm seat width. The footrests were adjusted according to the leg length of participants with the aim of maintaining the lower leg perpendicular to the thigh and eliminating air gaps between the body–seat interface.

**Data collection**

Skin temperature and RH were measured under the subjects’ ischial tuberosities and thighs bilaterally (Figure 2) with digital humidity and temperature sensors (Model SH15, Sensirion AG, Staefa, Switzerland) attached to the skin via a single strip of surgical tape. Before placing the sensor, each sensor site was verified by placing hand on the subject’s buttock when sitting. After that, the skin and sensors were thoroughly rubbed with 75% alcohol for cleanup. The sensor placements were confirmed again when the subject sat on a tested cushion. The SH15 digital humidity and temperature sensor (dimensions: 2 cm × 2 cm × 0.25 cm) is factory-calibrated and the calibration data are stored in on-chip non-volatile memory. The temperature measurement range was −40°C to 123.8°C. The accuracy reported by the manufacturer when measuring temperatures at 25°C is ±0.4°C. The RH measurement range was 0%–100% RH with an accuracy within ±2% between 0% and 90% RH. Response times for temperature and RH readings were 5 and 8 seconds (both τu 63%, which means the time required for the response to rise 63% of a step function), respectively.

The trial began with a 30-sec baseline data collection period for skin temperature and RH when subjects sat on their assigned cushions, and data were subsequently collected every 15 minutes during the 2-hour sitting periods with a constant data acquisition rate of 30 seconds. Because human body temperatures are not expected to vary abruptly over short periods (e.g., <1 second), the sampling frequency of the measurement system was set at 1 Hz/sensor. All temperature and humidity data from the sensors were read by an Arduino Uno microcontroller (Arduino Uno Rev3, Modern Device, Providence, RI, USA) that served as a data logger. Matlab (MathWorks, Natick, MA, USA) was used to process and analyze acquired data sets. Measurements were collected in the same research space with a monitored ambient temperature of 25.0°C ±0.5°C and ambient RH of 45%–55%, which were measured by using an additional SH15 sensor throughout the experimental period.

**Statistical analysis**

Descriptive statistics were used to describe the basic features of each group’s demographic composition, skin temperature, and RH at each time interval. One-way analysis of variance (ANOVA) was used to test for any differences among three groups with respect to demographic data. A Kolmogorov–Smirnov test was initially used to determine the normality of the data. A previous study indicated the temperatures from three measurements positions (right mid-thigh, left mid-thigh, and coccyx) during sitting showed differences regardless underlying seating materials (Liu et al., 2011). Therefore, in order to study the relationship among sensors between the right and left lower limbs and different positions (ischial tuberosities and mid-thighs), a paired t-test was performed on time matched data. Afterward, the Pearson’s correlation was used to determine correlations between the left-side and the right-side data on ischial tuberosities and thighs respectively. Moreover, in order to detect an appreciation of the effect of the seating materials on heat and moisture retention, the time to 50% of the total changes (50% max) of temperature and RH were reported respectively. This is a simple measurement of the point in time from the start of sitting at which 50% of the difference between the maximum and minimum value first appeared (Liu et al., 2011). For this calculation, maximum and minimum values of skin temperature and RH during the 2-hour sitting period were obtained from the sensor. Afterward, the mid-point value between the maximum and minimum values was determined. The 50% value then was determined by locating the point in time from the start of the sitting period where the mid-point value first appeared. In order to determine the differences in subjects’ skin temperature and RH according to seat cushion material, output variables were compared using one-way ANOVA. An alpha level of 0.05 was used as an indicator of significance. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 21.0 (IBM Corp, Armonk, NY, USA).

**Results**

The demographic characteristics of the participants in each of the three seat cushion groups are shown in Table 1. There were no significant differences among the groups with respect to age (p = 0.76), height (p = 0.93), weight (p = 0.80), and body mass index (p = 0.78). A paired t-test revealed there were no significant differences between left and right sides at the same measurement position regarding humidity and temperature.
detection. Data from the left and right sides then were averaged to obtain representative values. But, there were highly significant differences between ischial tuberosities and thighs regardless of underlying seating materials. The recorded temperatures from the ischial tuberosities were high at baseline initially \((p < 0.01)\), then being significantly lower than these from thighs at each time interval \((p < 0.01; \text{Figure 3})\). On the other hand, the recorded humidities from the ischial tuberosities were significantly higher for the first 60 min \((p < 0.05)\), and then it sustained high but did not reach statistical significance at 75 minutes \((p = 0.13)\), 90 minutes \((p = 0.10)\), 105 minutes \((p = 0.21)\), and 120 minutes \((p = 0.42; \text{Figure 4})\).

Baseline temperature and RH were similar between the three cushion groups (Table 1); however, clear differences in thermal change related to seat material were observed (Table 2). Skin temperatures on either the ischial tuberosities or thighs differed significantly according to cushion type after 2 hours of unrelieved sitting \((p < 0.01)\). The skin temperature over time of subjects who sat on the foam–fluid hybrid cushion was significantly lower than that of subjects who sat on the other two cushion types (Figure 3). Sitting on the foam–

<table>
<thead>
<tr>
<th>Cushion type</th>
<th>Air-filled rubber ((n = 26))</th>
<th>Foam–fluid hybrid ((n = 26))</th>
<th>Foam ((n = 26))</th>
<th>(P) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>21.9 ± 1.8</td>
<td>22.5 ± 2.4</td>
<td>22.2 ± 3.8</td>
<td>0.76</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>165.1 ± 7.6</td>
<td>165.9 ± 8.7</td>
<td>165.1 ± 6.5</td>
<td>0.93</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>59.3 ± 11.2</td>
<td>61.3 ± 12.7</td>
<td>59.3 ± 9.1</td>
<td>0.80</td>
</tr>
<tr>
<td>Body mass index</td>
<td>21.6 ± 2.8</td>
<td>22.2 ± 3.8</td>
<td>21.7 ± 2.1</td>
<td>0.78</td>
</tr>
<tr>
<td>Baseline temperature at ischial tuberosities (°C)</td>
<td>30.8 ± 1.2</td>
<td>31.2 ± 1.6</td>
<td>31.4 ± 1.0</td>
<td>0.87</td>
</tr>
<tr>
<td>Baseline temperature at thighs (°C)</td>
<td>30.2 ± 1.1</td>
<td>30.1 ± 1.3</td>
<td>30.3 ± 1.1</td>
<td>0.93</td>
</tr>
<tr>
<td>Baseline RH at ischial tuberosities (%)</td>
<td>77.6 ± 11.4</td>
<td>80.3 ± 10.7</td>
<td>77.2 ± 12.4</td>
<td>0.59</td>
</tr>
<tr>
<td>Baseline RH at thighs (%)</td>
<td>73.4 ± 10.5</td>
<td>71.7 ± 9.3</td>
<td>71.7 ± 11.7</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 3. Averaged thermal changes in the region of the ischial tuberosities and thighs between three cushions during 2 hours sitting.

Figure 4. Averaged relative humidity changes in the region of the ischial tuberosities and thighs between three cushions during 2 hours sitting.
fluid cushion appeared to produce a slower rate of elevated temperature (50% max; \( p < 0.01 \)) and lower final temperature compared with either the air-filled rubber or foam cushions (\( p < 0.01 \)).

Among the three cushion types, the recorded RH did not differ significantly (Table 2); indeed, RH tended to increase over time regardless of cushion material (Figure 4). Furthermore, there was no significant difference in the rate of RH change (50% max) at the ischial tuberosities or thigh regions among the three cushion types (Table 2).

### Discussion

Dissipation of heat and moisture on seat cushions is important for preventing pressure ulcers and tissue maceration and for comfortable sitting. The present study demonstrated the type of seating material influenced the thermal properties of a cushion but not the accumulation of moisture. Regardless of the material employed, the skin temperature at the ischial tuberosities and thighs was elevated by several degrees after the 2-hour sitting period. Moreover, the results from the paired statistical analysis indicated obvious temperature differences existed between the ischial tuberosities and thighs. A higher temperature in thighs compared to the ischial tuberosities during the 2-hour sitting period regardless underlying seating materials. This might have been a consequence of individual sitting preferences related to the perception of the comfort. It also was noticed in a previous study by Liu et al. (2011). In our study, although participants sat in wheelchair for a 2-hour period, they allowed access to a desk to do regular office work—just like regular wheelchair users did. Therefore, they might lean their trunk forward to use the notebooks and take some of the weight off their regions of the ischial tuberosities. They might shift their weight forward to put more weight over their thighs. As a result, the accumulated heat could increase if there was poor exchange of air in the compression area, and the area was thermally insulated by the cushion. Our results further indicated this finding was more prevalent in the air-filled rubber and foam cushions than the foam–fluid hybrid cushion.

The foam–fluid hybrid cushion used in this study was made from a combination of materials as follows: a 2.5-cm-thick top layer of fluid for gentle immersing and optimal sitting temperature, and a 5-cm-thick support foam for stability and durability. This combination cushion allows more than one clinical goal to be met, such as pressure redistribution and stability with a low cushion weight. The fluid component of this hybrid cushion keeps the nature of a fluid to move away from areas of high pressure to areas of low pressure. This means that this fluid-type cushion will allow immersion and also provide levels of envelopment as the cushion adjusts to the shape of the user sitting on it, but envelopes slower than air-filled cushions. Moreover, viscous fluid material has high thermal conductivity and specific heat. The specific heat of a given fluid will influence skin temperature at the sitting surface. The fluid material has higher heat flux than rubber and foam due to high specific heat, thereby tending to maintain or reducing the contact skin temperature. Therefore, our finding that skin temperature was lower in subjects sitting on the foam–fluid hybrid cushion compared with subjects sitting on the other two cushion types was perhaps unsurprising.

Our finding was also consistent with previous studies demonstrating that gel/viscous fluid cushions maintained lower skin temperature under the ischial tuberosities and thigh areas than foam and air-filled cushions (Ferrarin & Ludvig, 2000; Seymour & Lacefield, 1985; Stewart et al., 1980). Furthermore, viscous fluid pads had higher heat flux and thereby reduced the contact temperature in the first 30 minutes (Figure 3). However, compared to previous studies (Seymour & Lacefield, 1985; Stewart et al., 1980), skin temperature in the present study started to elevate after 30 minutes of sitting. After 2 hours of unrelieved sitting on foam–fluid hybrid cushions, skin temperature increased by up to 2.8°C, and 4.7°C on the ischial tuberosities and thigh regions, respectively (Table 2). This might have been a consequence of small chambers filled with viscous fluid/gel materials. Decreased heat transfer indicated the heat reservoir was beginning to fill up so that skin temperature might well begin to rise over prolonged sitting periods (Stewart et al., 1980). Consequently, as a cold fluid-type cushion was heated to absorb body heat, it will take more time to dissipate the higher amount of heat absorbed by the cushion at the same rate of heat loss. It can be either conduction or radiation by which the cushion gives up the heat. Therefore, although foam–fluid hybrid cushions could absorb heat accumulation, the skin temperature eventually increased over prolonged sitting, and took more time to reset the temperature to a physiologically desirable temperature. In addition, our finding indicated RH increased considerably at both the ischial tuberosities and thigh regions. This could be the result of the nonporous nature of the viscous fluid pad.

The air-filled rubber cushion tended to increase skin temperature—probably because the rubber material and entrapped air were poor conductors of heat with low thermal mass. Most of the heat was confined to the rubber surface; thus, skin temperature increased quickly. Indeed, the 50% value of the maximum value of temperature differences was reached in only 26 min (Table 2). Therefore, the air-filled

### Table 2. Changes in measured parameters after the 2-hour sitting period.

<table>
<thead>
<tr>
<th>Cushion type</th>
<th>Ischial tuberosities</th>
<th>Thighs</th>
<th>Ischial tuberosities</th>
<th>Thighs</th>
<th>Ischial tuberosities</th>
<th>Thighs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-filled rubber</td>
<td>Mean temperature</td>
<td>34.7 ± 0.9**</td>
<td>35.7 ± 0.6**</td>
<td>34.0 ± 1.3**</td>
<td>34.8 ± 1.4**</td>
<td>35.3 ± 1.2**</td>
</tr>
<tr>
<td></td>
<td>Temperature difference (°C)</td>
<td>3.0 ± 1.4*</td>
<td>5.6 ± 1.3**</td>
<td>2.8 ± 1.7*</td>
<td>4.7 ± 1.4**</td>
<td>3.0 ± 1.3*</td>
</tr>
<tr>
<td></td>
<td>Time to 50% total change (minutes)</td>
<td>26.3 ± 9.6**</td>
<td>19.5 ± 8.6**</td>
<td>65.3 ± 9.0**</td>
<td>52.5 ± 9.8**</td>
<td>32.3 ± 9.1**</td>
</tr>
<tr>
<td></td>
<td>RH after 2 hours (%)</td>
<td>89.6 ± 8.6</td>
<td>88.7 ± 3.8</td>
<td>91.3 ± 4.8</td>
<td>90.8 ± 2.1</td>
<td>88.3 ± 7.8</td>
</tr>
<tr>
<td></td>
<td>RH difference (%)</td>
<td>12.0 ± 9.1</td>
<td>17.0 ± 7.9</td>
<td>13.0 ± 10.0</td>
<td>17.4 ± 10.5</td>
<td>11.1 ± 9.3</td>
</tr>
<tr>
<td>Foam–fluid hybrid</td>
<td>Mean temperature</td>
<td>34.0 ± 1.3**</td>
<td>34.8 ± 1.4**</td>
<td>35.3 ± 1.2**</td>
<td>36.6 ± 0.4**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature difference (°C)</td>
<td>3.0 ± 1.4*</td>
<td>5.6 ± 1.3**</td>
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</tr>
<tr>
<td></td>
<td>RH difference (%)</td>
<td>12.0 ± 9.1</td>
<td>17.0 ± 7.9</td>
<td>13.0 ± 10.0</td>
<td>17.4 ± 10.5</td>
<td>11.1 ± 9.3</td>
</tr>
<tr>
<td>Foam</td>
<td>Mean temperature</td>
<td>34.0 ± 1.3**</td>
<td>34.8 ± 1.4**</td>
<td>35.3 ± 1.2**</td>
<td>36.6 ± 0.4**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature difference (°C)</td>
<td>3.0 ± 1.4*</td>
<td>5.6 ± 1.3**</td>
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</tr>
</tbody>
</table>

Note: *Denotes a significant difference at \( p < 0.05 \).
**Denotes a significant difference at \( p < 0.01 \).
rubber cushion caused a significant increase in skin temperature with a mean change of 3.9°C and 5.6°C at the ischial tuberosities and thigh regions, respectively. However, since this rubber-type cushion has air channels between air cells, when a person does a forward lean or a pressure-relief lift, air that rushes in during that pressure-relief lift and then washes back out is able to carry a large portion of the heat which the cushion had trapped with it due to the low thermal mass of the rubber materials. Hence, the air-filled rubber cushion can easily get hot over prolonged sitting, but actually can be fairly cool if the user is trained properly. For humidity, the tufted balloon construction may have allowed some air circulation when the users changed posture; however, the tufted balloons were squeezed together during sitting so that such a circulation effect was not apparent. Consequently, unrelieved sitting on an air-filled rubber cushion could produce high humidity similar to that produced when sitting on a cushion made of impermeable material.

The foam cushion increased skin temperature to a similar level as the air-filled rubber cushion—probably because foam materials have low heat conductivity. Foam has low thermal mass because it acts as an insulator; therefore, it can quickly accumulate heat. Consequently, it helps dissipate heat from the cushion’s surface as well. Our results showed it only took 28 and 17 minutes to reach the 50% value of the maximum value of temperature differences, and produce a mean rise in skin temperature of 4.0°C and 6.9°C on the ischial tuberosities and thigh regions, respectively (Table 2). However, humidity did not rise as high with the foam cushion as with the other two cushions. The open cell structure of the foam might provide a pathway for air circulation, which could reduce moisture through vapor flow. Additionally, body movement while sitting on the foam cushion could increase this action. However, participants in the present study were asked to sit continuously for 2 hours without self-repositioning and off-loading movements. Therefore, the advantage of the open-cell foam on moisture dissipation was not so obvious in this study.

All three cushions produced a similar trend whereby RH increased over time and reached a plateau during the 2-hour sitting period. This indicated the type of cushion material influenced heat dissipation but not moisture dissipation. In the present study, skin temperatures increased by about 2°C–4°C within 2 hours while subjects were seated on certain wheelchair cushions. There is evidence that each 1°C increase in skin temperature results in an increase in tissue metabolic requirements of approximately 10% (Brown & Brengelmann, 1973). A 2°C–4°C increase in skin temperature would therefore increase metabolic rate by approximately 20%–40%. Thus, the oxygen requirements of high-risk patients who already possess compromised tissue may increase with increasing skin temperature. Any increase in temperature in combination with pressure may reduce tissue viability and therefore promote ulcer formation (Patel, Knapp, Donofrio, & Salcido, 1999; Tamura, Fujimoto, Tsuji, Togawa, & Nakano, 1990).

In the present study, a 10%–20% increase in RH was measured at the skin-cushion interface within 2 hours (Table 2). This was probably mainly due to sweating and was likely aggravated due to insufficient airflow at the interface. Moisture softens the skin and causes skin condition to deteriorate. Maceration, which is the softening of the stratum corneum, is the most common cause of skin breakdown due to moisture. In a study by Wildnauer et al. (1971), the tensile strength of the stratum corneum decreased by 85% with an increase in RH from 0% to 100%. In addition, excessive moisture can significantly increase the skin’s coefficient of friction (Gerhardt et al., 2008), which may increase the likelihood of skin damage from friction and shear stresses.

Air with low humidity could increase evaporation and thereby reduce moisture and temperature at the interface (Reenalda et al., 2001). Some cushions naturally pump air that is trapped at their structures when compressed (e.g., foam or air-filled rubber cushions); however, the pathway for air circulation would be squeezed once users sat on these cushions. Frequent postural movement, which increases airflow, is a good method for dissipating heat and humidity; additionally, it could alter shear force and redistribute loading pressure. Although previous studies reported favorable results from encouraging frequent postural movements in individuals at risk of developing pressure ulcers (Linder-Ganz, Scheinowitz, Yizhar, Margulies, & Gefen, 2007; Reenalda et al., 2009), some community-dwelling wheelchair users do not frequently engage in pressure relieving movements (Yang et al., 2009); hot skin with high humidity at the skin–cushion interface would be anticipated in these users. This scenario would create a harmful microclimate between the skin and cushion, which could lead to pressure ulcer development. Therefore, individuals at risk of developing pressure ulcers should be educated to regularly perform pressure-relieving movements and advised not to sit for longer than 2 hours in the same position, regardless of their use of a pressure-relieving cushion (National Pressure Ulcer Advisory Panel and European Pressure Ulcer Advisory Panel, 2009).

Study limitations

We acknowledge that this study has some limitations. First, the cushion cover is a very important part of the cushion design and should be thoroughly evaluated. But, the material and size of the cover from cushion manufacturers were quite different. In order to remove confounding effects, cushion covers were removed from cushions and not investigated in this study. Cushion covers could have an effect on skin protection through their abilities to allow air exchange, heat and moisture dissipation, and to minimize shear forces. Many cushion manufacturers now offer cushion covers with a breathable fabric or mesh top layer to help prevent excessive heat and moisture accumulation. Consequently, additional research is also needed to explore the thermal and humidity effects caused by various cushion cover materials. Although young, able-bodied participants have a relatively low variance in physical health compared with wheelchair users, we acknowledge that this may limit the generalizability of our findings. However, subnormal body temperature is a frequent finding in individuals with chronic spinal cord injuries (Khan, Plummer, Martinez-Arizala, & Banovac, 2007). The temperature differences between cushion materials might therefore be even greater among wheelchair users with spinal cord injuries. Besides, in the present study, we utilized relatively sensitive sensors directly attached to the skin to measure humidity and
temperature; therefore, the values of these parameters were somewhat higher than those in a previous study that used an infrared thermograph system (Ferrarin & Ludwig, 2000). Another possible interpretation of this finding was the testing laboratory was located in a subtropical zone. Although temperature and humidity were controlled during the tests, the skin temperature and humidity of participants who were acclimated to their living conditions in a hot and humid subtropical climate may be overestimated. Third, different combinations of cushion materials have different capacities for handling heat and humidity at the skin–cushion surface interface. This study only measured three commercially available cushions; the generalizability of the results to other cushion types may therefore be limited. Moreover, our study was conducted in static sitting positions, which are obviously different from the typical daily living situation of wheelchair users. During functional mobility, wheelchair users may negotiate uneven surfaces, which would result in vertical vibration of wheelchair cushions. Such cushion “bouncing” may cause a certain amount of air infiltration across cushions, especially in foam and air-filled cushions. Therefore, skin temperatures and RH during functional mobility may be much lower than those recorded in this study. Furthermore, previous studies indicated certain seat cushions had a great impact on reducing vibration transmission during manual wheelchair propulsion (DiGiovine, Cooper, Wolf, Fitzgerald, & Boninger, 2003; DiGiovine et al., 2003; Wolf, Cooper, DiGiovine, Boninger, & Guo, 2004). Thus, further research is needed to assess the effect of different cushion materials on skin temperature, RH, and the transmission of vibration at the body–seat interface during dynamic sitting.

**Conclusion**

Clearly, no single cushion is ideal from all standpoints. The successful selection of an appropriate wheelchair cushion for a particular individual cannot be based on just one factor or clinical judgment. During the selection process, not only pressure distribution, but also the microclimate (heat and moisture control) between the body–seat interface should be considered. In this study, foam–fluid hybrid cushions produced the slowest rise in user skin temperatures, but the cushion material used did not significantly alter moisture accumulation.

**Disclosure statement**

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**ORCID**

Yu-Sheng Yang  
http://orcid.org/0000-0002-2767-9354

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