Quantitative evaluation of smart bed comfort in different typical conditions during resting.

Xiangtian Bai  
Hunan University

Ming Zhong (zhongming@hnu.edu.cn)  
Hunan University

Yonghong Liu  
Hunan University

Yafan Hu  
Hunan University

Jun Ma  
Central South University

Article

Keywords: Comfort, health, quantitative assessment, resting, smart bed

Posted Date: May 19th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2916423/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.  Read Full License

Additional Declarations: No competing interests reported.
Abstract

In response to the general inability of smart beds to meet the health needs of chronic disease management and long-term care, this study proposed to investigate smart bed comfort in different typical conditions. The objective body pressure distribution and subjective comfort of participants were collected when the smart bed was in typical conditions. Pressure sensor mat was used to accurately measure pressure distribution. Participants reported in real time on the subjective comfort for each typical condition. Statistical data analysis intended to investigate changes in overall and local comfort when the smart bed is in different typical conditions, the correlation between perceived comfort and body pressure distribution. During the experiment, mean and peak pressures increased by up to 87.19% and 92.85%, respectively, owing to changes in smart bed conditions. However, major body pressure indicators correlated with the overall and local comfort of each area were not completely aligned. Statistical data analysis shows the importance of evening out forces and reducing peak pressures. Apart from mean pressure, peak pressure, particularly at the buttock, thigh and shank areas, is the key factor in comfort evaluation. Moreover, adequate bed board partitioning and linkage mechanism between adjacent boards better fit the body curve and enhance comfort. Accordingly, ensuring relatively balanced body forces and avoiding the feeling of weightlessness improve user comfort and health significantly. The succeeding study will further investigate the relationship between smart bed comfort and changes in free lying positions and moving activities, hoping to provide a comfort studies basis for long-term care.

1. Introduction

With the rising pressure of an accelerated pace of life, an increasing number of people have difficulty falling asleep or maintaining sleep, accompanied by such symptoms as irritability or fatigue during wakefulness1. Meanwhile, the duration and quality of sleep are closely related to health outcomes2. Globally, many researchers have investigated improving sleep health in many disciplinary perspectives, including bed and mattress design3,4, cognitive behavioral therapy5,6, exercise training7 and health education8. Unlike the pharmacologic approach, the aforementioned methods are likely to produce sustained benefits without risks or adverse effects. Note that apart from nocturnal sleep, the habit of taking short naps is effective in improving concentration and maintaining physical energy9.

In recent years, the rapid development of smart product technology has become an important turning point in the sleep health field10. Along with the global technology and intelligence revolution, particularly the continuous penetration of IoT, cloud computing and other AI technology, the sleep-related smart product industry has been developing rapidly towards diversification and ecology. The global markets of smart bed and smart medical bed, for use in healthcare facilities and residences, have reached their highest levels of development in the US and Europe, with the Asian market showing significant growth potential in the coming years11. Smart beds used in the 2022 Beijing Winter Olympic village have attracted considerable attention and have received unanimous praise from international athletes. With the development of the regional economy, smart beds had been gradually introduced in China and other Asian countries. A smart bed, as an extension of the ‘bed’, represents an emerging sleep health lifestyle model. Specifically, it consists mainly of the bed structure and software control system12. In terms of hardware structure, a smart bed often contains four parts: adjustable bed board, bed frame, mattress and the soft cover. The software system controls the bed board adjustment to optimise the user's sleeping position13. Excellent comfortable smart beds are characterised by spinal protection, muscle relaxation and smooth blood breathing. Hence, ergonomics research should be given higher priority in the smart bed development and design.

Pressure comfort of smart bed is critical. Past studies have indicated that inappropriate smart bed may lead to low back pain, back pain and other diseases after sleeping for a long time14. The users’ experience and health of such smart beds can be greatly compromised with prolonged use. The resulting poor sleeping postures can also be potential risk factors for several diseases, such as sleep apnea and pressure ulcers. Additionally, note that pressure comfort is not only related to the physical aspect15 but also the individual subjective characteristics, such as sensibility, mentality and experience, enabling people to experience different levels of comfort in similar environments15. Some researchers have combined physiological parameters with subjective comfort evaluations to better understand the pressure effects of resting products17–20, as well as to explore the statistical relationship between physiology and perception. However, such studies for smart beds have been limited.

Note that the sleep habits of Asians differ relatively from those in such regions as Europe and North America21. Most Asians prefer a supine sleep, and a smart bed is designed for the Asian market, with focus on the supine posture22. In China, residents of first-tier cities have gradually embraced softer beds23. However, when sedentary people experience such symptoms as back and cervical pains, doctors often advise them to switch to a medium-rim mattress and their symptoms subsequently improved24, with some of them using smart beds for rehabilitation and physiotherapy25. Given that people of different ages and genders have different needs for the softness and support of beds, there are some differences in perceived comfort26,27.

Smart bed comfort studies have involved multiple complex factors, such as bed structure, mattress material and physiological skeleton. These factors and their interdependencies should be recognised and considered in the evaluation of smart bed lying comfort experiences. Therefore, an essential aspect is to score comfort by scales.
This paper reports the main results of the smart bed comfort evaluation experiment. The experiment was designed to gather reliable data on the deficiencies of smart beds and to provide valuable suggestions for smart beds to the Asian market. It was considerably designed to minimise the effect of other factors, such as time, temperature and test sequence. These measures guarantee stable experimental environment.

The experiment results could provide better insights for improving smart bed comfort, thereby enabling the adaption of the new smart bed to the needs of the chronic disease management and long-term care of Asian market. We formulated questions focusing on the following issues: the relationship between overall body pressure distribution and bed condition change, characteristics of body pressure distribution in people with different body mass index (BMI), differences in perceived comfort amongst smart bed conditions, differences in local perceived discomfort by gender and time and the relationship between body pressure distribution measurement (BPDM) and subjective comfort evaluation (SCE) of smart bed comfort.

2. Materials and Methods

2.1 Participants

A total of 40 participants (20 males and 20 females), including engineers, designers and university students, were recruited for this experiment. The range, mean and standard deviation (SD) of the participants’ main anthropometric characteristics (viz. age, weight, height and BMI) are presented in Table 1. Young people are more sensitive to comfort and have a subjective demand for higher levels of comfort, which were the main reasons this study limited the participants’ age to 25–35 years.

<table>
<thead>
<tr>
<th></th>
<th>Males (20)</th>
<th>Females (20)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Age [year]</td>
<td>25–35</td>
<td>28.94</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>45–97.50</td>
<td>71.56</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>161–190</td>
<td>174.13</td>
</tr>
<tr>
<td>BMI [kg/m$^2$]</td>
<td>16.94–30.77</td>
<td>23.37</td>
</tr>
</tbody>
</table>

All participants had experience of using at least two types of smart health products, such as massage chair, neck pillow and treadmill. Moreover, each participant must have had experienced using a smart health product within two months. They were in self-reported good health and had the ability to participate in this experiment. If they had serious diseases, such as backache and musculoskeletal disorders (MSDs) or even required to do medical follow-ups, then they were excluded. Lastly, they were instructed to avoid strenuous exercises the day before participating in the experiment.

Before the experiment, all eligible participants received detailed process explanations, including BPDM and SCE. They were likewise provided informed written consents. Meanwhile, they had to complete a basic information questionnaire on their attitude and general impression towards smart health products and sleep health. Questionnaire results showed that they had some tough troubles with smart health products but were positive about sleep health as well.

2.2 Smart Bed

To avoid the interference of other factors, this study applied the basic smart bed model without massage, sleep aid, breathing monitoring and other functions. The basic smart bed is the prototype for all smart beds and can effectively represent main design characteristics of smart bed. The smart bed structure comprises mainly of an adjustable bed board, bed frame, mattress and the soft cover. The bed board consists of four parts, which are connected to one another by a pivot, and is pushed by an electric actuator and rotates at an angle around the pivot. These components work together to adjust the smart bed to different conditions. Smart bed adjustment has four limit conditions and one officially recognised zero-gravity condition, as presented in Table 2. Additionally, the bed frame is made of steel or aluminum alloy to ensure adequate stability. Mattresses of different thicknesses and support abilities can be covered according to the comfort needs of different users. The soft cover is mostly made of leather and wraps the exposed structure.

2.3 Objective Measurements

During the entire smart bed testing session, the overall and local body pressure distributions were recorded using a pressure sensor mat placed on the smart bed (Fig. 1). The pressure sensor mat was composed of 50 × 250 thin resistive sensor cells (cell diameter: 5 mm; interval of two cells: 7 mm; sensing area: 38.5 cm × 192.5cm).
As the body pressure value varies considerably with the smart bed condition, the sampling frequency of pressure sensor mat was adjusted to 10 Hz to discover more details of pressure change. The pressure sensor mat recorded the pressure value corresponding to each sensor cell in real time, and the data matrix was saved to Excel. In each test, the overall pressure, mean pressure, contact area, peak pressure and peak pressure point of each participant in smart bed adjustment conditions were calculated according to the software.

### 2.4 Subjective Comfort

By asking the participants to express their feelings on resting experience, subjective comfort evaluations were collected during resting session. All subjective comfort evaluations must be completed when the smart bed was in its typical conditions. The typical conditions are as follows: original condition (A0); back board in the highest position (A3); back board and leg board in the highest position (B2); leg board in the highest position (C3); every 20° rotation from A0 to A3 (i.e. A1 and A2); every 20° rotation from A3 to B2 (i.e. B1); every 20° rotation from B2 to C3 (i.e. C1 and C2); every 20° rotation from C3 to D2/A0 (i.e. D1) and "zero-gravity condition E" (see Table 3).

The participants were required to evaluate their overall perceived comfort and local perceived comfort using a 7-point Likert scale\(^2\), with ‘−3’ indicating least comfortable and ‘+3’ indicating most comfortable. By considering the characteristics of the smart bed board arrangement, the body was broadly divided into four parts (Fig. 2): upper back, lower back, buttocks and thigh and shank areas\(^3\). Consequently, assessment items are as follows: ‘Please assess the present overall comfort level of your body’, ‘Please assess the present comfort level of upper back area’, ‘Please assess the present comfort level of lower back area’, ‘Please assess the present comfort level of buttocks and thigh area’ and ‘Please assess the present comfort level of shank area’ (see Table 4).

The other subjective evaluation was conducted at the beginning and end of the experiment to investigate changes in users’ desire to purchase a smart bed. The question will be mentioned again the day after the experiment.

### 2.5 Experimental Protocol

In the sleep laboratory environment, a mixed experiment design was used to compare the somatosensory changes caused by the smart bed’s different adjustment conditions. The detailed testing procedure is provided in Table 3. Considering the continuous changes of the participants’ body pressure distribution data, the smart bed program remained stable for one minute per typical condition.

The total duration of each user test was 20 minutes (i.e. 12 minutes for body comfort evaluation, 8 minutes for the in-depth interview). The participants performed the body comfort evaluation testing while listening to light music. Each participant lied comfortably in a fixed posture: buttocks at the middle mark of the bed board, with the head, back and legs naturally extended in a supine posture.

In the experiment, the most critical independent variable was the smart bed board adjustment and rotation, with four limit conditions (see Table 2). Moreover, there were two between-subjects independent variables: BMI and gender. In each test run, body pressure distribution was recorded continuously, whilst subjective comfort evaluations were collected at fixed typical conditions of the smart bed to study the effects of operating modes settings.

### 2.6 Statistical data analysis.

Statistical data analysis focused on several major issues: (1) relationship between the overall body pressure distribution and bed condition change, (2) characteristics of body pressure distribution in people with different BMI, (3) differences in perceived comfort amongst smart bed conditions, (4) differences in local perceived comfort by gender and time and (5) relationship between BPDM and SCE.

BPDM data, such as overall pressure, contact area and mean pressure, were obtained directly during the testing process (see Table 3). Let \( k, l \) be a generic occupant and \( P_{l,ij}^k \) be the available pressure value over cell \( ij \) of the sensor matrix recorded at condition \( l \) by participant \( k \). Correspondingly, \( S_{l,ij}^k \) is the available contact area where the pressure value is not zero of the sensor matrix. The mean pressure \( \bar{P}_{l}^k \) is obtained as follows:

\[
\bar{P}_{l}^k = \frac{\sum_{i=1,j=1}^{I,J} P_{l,ij}^k / S_{l,ij}^k}{I,J}
\]

, where \( I, J \) is the total number of sensor cell, in which \( 1 \leq i \leq 50, 1 \leq j \leq 250 \).

All analyses were performed using statistical analysis software (SPSS Version 26.0, SPSS Inc., Chicago, IL, USA). Graphs were generated by selecting key objective data to reflect variations in overall pressure, mean pressure, contact area, peak pressure and peak pressure point with smart bed different conditions. Moreover, the differences in objective data changes across different BMI groups were worth examining. Differences in perceived comfort amongst the smart bed conditions were tested via the Kruskall–Wallis test for pairwise comparisons with the \( p \) value adjusted using the Bonferroni correction. The correlation between overall comfort and the comfort of each smart bed condition was investigated via
Spearman’s rank correlation coefficient. Differences in local perceived comfort by gender were tested via the Mann Whitney U test. Effects of resting duration on perceived comfort were analysed via the Wilcoxon Signed-Rank test on the overall and local comfort scores collected at a fully lying posture (i.e. A0, D2). To investigate the relationship between BPDM and SCE, the mean and peak pressure values were correlated to perceived discomfort (see Table 3).

All statistical tests were considered “significant” for p value ≤ 0.05.

2.7 Ethics statement

This study was approved by the Ethical Review Committee in the School of Design at Hunan University and conducted in Hunan University in accordance with the approval including all guidelines and regulations. All methods have been performed in accordance with the Declaration of Helsinki.

3. Results

3.1 Relationship between overall body pressure distribution and bed condition change

The key indicators of overall body pressure distribution include overall pressure, contact area, mean pressure, peak pressure and peak pressure point. The relationship between these indicators and bed condition change is presented in Figures 3 and 4.

Generally, trends of the overall, mean and peak pressures were consistent. When the participants were in supine posture on the smart bed, the overall, mean and peak pressures increased initially with the lifting of the back board. When the back and leg boards were in the highest position (i.e. B2), the overall, mean and peak pressures were at maximum. As the bed board began to lower, the indicators decreased, except for peak pressure, which had minimal rebound in the C3 and D1 conditions. However, note that the contact area was at the peak when the back board was in the highest position and the leg board was not lifted (i.e. A3).

For peak pressure point, there was minimal variation in the X-direction (i.e. perpendicular to the torso) but showed an overall trend of ‘brief downward shift followed by gradual move upward’ in the Y-direction (i.e. parallel to the torso). As the leg board started to lift (i.e. B1), the peak pressure point gradually moved upwards. As the back board started to lower (i.e. C1), the rate of upward movement of the peak pressure point was further enhanced. No significant downward movement was observed until condition D2, in which the coordinates of the peak pressure point deviated slightly from the original condition (i.e. A0).

3.2 Characteristics of body pressure distribution in people with different BMI.

BMI is an internationally used measure of body fatness and health. By combining the participants’ BMI data (see Table 1) and the different countries’ BMI classification standards (e.g. the US, China, the UK), the Smart Bed BMI Classification in this study was defined as ‘<18.5’, ‘18.5–20.9’, ‘21–22.9’, ‘23–24.9’, ‘25–26.9’, ‘27–29.9’ and ‘≥30’. Accordingly, the participants’ body pressure data were classified into seven groups. Overall pressure, contact area and mean pressure as key indicators are illustrated in Fig. 5.

As shown in Fig. 5, the tendency of overall pressure was generally consistent across groups as the smart bed was adjusted. In most cases, the group with higher BMI value also had higher overall pressures. However, pressure values did not constantly correlate positively with the BMI values, such as in the ‘BMI < 18.5’ and ‘18.5 ≤ BMI ≤ 20.9’ groups. In these groups, the overall pressure value of the former was consistently higher than the latter, regardless of board condition changes. Similarly, contact area was significantly correlated with BMI, increasing as the BMI value increased, thereby showing a significant positive correlation. For mean pressure, the lower BMI groups (i.e. <18.5, 21.0–22.9) showed considerably higher mean pressure than the other groups. Combined with biological knowledge, the assumption is that this phenomenon is due to the fact that people with lower BMI have less fat and insufficient skeletal cushioning in contact areas. Additionally, the values and trends of mean pressure were generally consistent in the other groups, whatever the BMI value.

3.3 Differences in perceived comfort amongst smart bed conditions

Significant differences in perceived comfort amongst smart bed conditions were found via the Kruskal–Wallis test (H = 70.036, p < 0.001). After pairwise comparisons (see Table 5), significance values that have been adjusted can indicate some results. Firstly, there were significant differences in perceived comfort between A3 and A0/A1/C1/C2/E (p = 0.004, 0.000, 0.000, 0.002, 0.000). Secondly, there were significant differences between C3 and C1/E (p = 0.023, 0.000). Thirdly, there were significant differences between B1 and C1/E (p = 0.026, 0.000). Fourthly, there were significant differences between B2 and C1/E (p = 0.029, 0.000). Lastly, there were significant differences between A2 and E (p = 0.029, 0.000). The smart bed in condition A3 had the lowest perceived comfort level. Thus, the ergonomic analysis and iterative design of this typical condition require special attention.
The results of Spearman’s rank correlation showed a positive correlation between overall perceived comfort and local perceived comfort for all smart bed typical conditions (see Table 6). Compared with the other conditions, there were stronger correlation ($r_s >0.80$) between overall comfort and upper back area comfort in the back board lifting process (i.e. A0, A2, A3).

### 3.4 Differences in local perceived comfort by gender and time

The results of the Mann–Whitney U test showed no major differences between genders in terms of local perceived comfort (see Table 7). Exceptions were the upper and lower back areas in conditions A3 and A2, respectively, during the back bed board lifting. When targeting gender-specific smart bed users, the design points of A2 and A3 conditions can be appropriately given focus.
Condition A0 corresponds to comfort level in the initial condition. Condition D2 corresponds to comfort level after 12 minutes of the smart bed testing. Both conditions are identical same bed conditions. The Wilcoxon Signed-Rank test (A0–D2) showed that a significant increase in perceived discomfort over time in the upper and lower back areas (see Table 8). However, there was no significant change in overall or local comfort in the buttocks, thigh and shank areas.

Table 8
Results of the Wilcoxon Signed-Rank test (*, p ≤ 0.05).

<table>
<thead>
<tr>
<th>Area</th>
<th>Comfort Statements</th>
<th>A0–D2</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall comfort</td>
<td>−1.387</td>
<td>0.166</td>
<td></td>
</tr>
<tr>
<td>Upper back area</td>
<td>−2.331*</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>Lower back area</td>
<td>−3.127*</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Buttocks and thigh area</td>
<td>−1.328</td>
<td>0.184</td>
<td></td>
</tr>
<tr>
<td>Shank area</td>
<td>−1.724</td>
<td>0.085</td>
<td></td>
</tr>
</tbody>
</table>

3.5 Relationship between BPDM and SCE

The correlation analysis between BPDM and SCE are presented in Table 9. Generally, correlation intensity was moderate. Stronger correlations were found between the following variables: (1) comfort evaluations at the upper back area and overall pressure at the upper or lower back area, (2) comfort evaluations and mean pressure at the upper back area, (3) comfort evaluations and peak or mean pressure at the shank area, (4) peak pressure at the shank area and comfort evaluations at the lower back area and (5) overall comfort and peak pressure at the buttocks and thigh area. A brief summary of other information showed that overall pressure was mainly correlated to overall and local comfort, particularly at the upper and lower back areas. Note that peak pressure was the main key factor affecting comfort evaluation. Peak pressure in the area below the buttocks was mainly correlated to overall and local comfort at the lower back or shank area.
<table>
<thead>
<tr>
<th>Objective Measures</th>
<th>Subjective Measures</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>B1</th>
<th>B2</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>D1</th>
<th>D2</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall pressure over the smart bed</td>
<td>Comfort at the upper back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.437*</td>
</tr>
<tr>
<td>Comfort at the lower back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.458*</td>
</tr>
<tr>
<td>Overall pressure at the upper back area</td>
<td>Overall comfort</td>
<td>-0.401*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.496*</td>
</tr>
<tr>
<td>Comfort at the upper back area</td>
<td></td>
<td>-0.600*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.526*</td>
</tr>
<tr>
<td>Overall pressure at the lower back area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.422*</td>
</tr>
<tr>
<td>Comfort at the upper back area</td>
<td></td>
<td>0.512*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfort at the lower back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.405*</td>
</tr>
<tr>
<td>Overall pressure at the shank area</td>
<td>Comfort at the upper back area</td>
<td>-0.410*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.440*</td>
</tr>
<tr>
<td>Comfort at the shank area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.427*</td>
</tr>
<tr>
<td>Mean pressure over the smart bed</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.401*</td>
</tr>
<tr>
<td>Comfort at the upper back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.403*</td>
</tr>
<tr>
<td>Comfort at the shank area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.517*</td>
</tr>
<tr>
<td>Mean pressure at the upper back area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.431*</td>
</tr>
<tr>
<td>Comfort at the upper back area</td>
<td></td>
<td>-0.511*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.598*</td>
</tr>
<tr>
<td>Objective Measures</td>
<td>Subjective Measures</td>
<td>A0</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>B1</td>
<td>B2</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>D1</td>
<td>D2</td>
<td>E</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------------</td>
<td>-----</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Mean pressure at the lower back area</td>
<td>Comfort at the upper back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.431*</td>
</tr>
<tr>
<td>Mean pressure at the buttocks and thigh area</td>
<td>Comfort at the upper back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.462* 0.407*</td>
</tr>
<tr>
<td>Mean pressure at the shank area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.405*</td>
</tr>
<tr>
<td>Peak pressure at the upper back area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.474*</td>
</tr>
<tr>
<td>Peak pressure at the lower back area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.401*</td>
</tr>
<tr>
<td>Peak pressure at the buttocks and thigh area</td>
<td>Overall comfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.508*</td>
</tr>
<tr>
<td></td>
<td>Comfort at the upper back area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.440*</td>
</tr>
</tbody>
</table>
### 4. Discussion

This study focused on the effects of smart beds’ different typical conditions on body pressure distribution and perceived comfort during resting. The experiment used measured data on overall pressure, contact area, mean pressure, peak pressure and peak pressure point as objective measures. Moreover, the relationship between SCE and BPDM should be given focus. This study aimed to better understand how smart bed condition changes affect perceived comfort and body pressure distribution, amongst others, as well as the effect of other factors, such as gender and resting time, on perceived comfort. Finding correlations between objective and subjective variables can facilitate the discovery of comfort evaluation mechanisms based on objective data and also provide a comfort prediction model for smart bed design and development.

Firstly, we can tentatively determine that as the smart bed board was lifted (i.e. A0→A1→A2→A3→B1→B2), overall, mean and peak pressures increased, leading to users' uncomfortable experience. This result was consistent with previous body pressure studies of other furniture products. Secondly, the results of the correlation analysis between BPDM and SCE showed that the overall pressure at the back area was the major factor influencing SCE, whilst peak pressure in the lower body plays a secondary role. Furthermore, the more even the pressure distribution, the greater the overall comfort for users. As the smart bed used in the experiment was composed of four bed boards linked to complete the lifting operation, the upper back area of users corresponded to only one bed board, resulting in higher material requirements for the mattress, which cannot meet users' comfort needs. The recommendation is to further partition the bed boards and combine them with coconut palm latex mattress to better fit the human body curve and improve smart beds' overall comfort performance.

Specifically, during the smart bed back board lifting process (A0→A1→A2→A3), one of the main reasons for the body pressure indicators increase of the user was that lifting of the back board would fold with the buttocks board and form a certain angle, which would generate a certain amount of extrusion pressure on the human torso. Moreover, the extrusion state was further aggravated by the continuous downward shift of the body's gravity centre. Indirectly, this situation also resulted in the contact area being at its peak in condition A3. If this pressure was not evenly distributed, then it would directly lead to an increase in all pressure indicators and significant reduction in general comfort. Particularly, the back board in condition A3 was lifted to the maximum of 60°. As shown in the pressure nephogram, the extrusion pressure of the bed board on the lower back reached its maximum, whilst the contact area surged. The overall pressure over the smart bed and overall pressure at the back area were close to the peak, and comfort level was relatively low.

During the smart bed leg board lifting process (A3→B1→B2), although the overall pressure did not change significantly, leg lifting enabled the gravity centre to move upwards, effectively improving the discomfort of extrusion pressure owing to the back board lift. Indirectly, this situation also resulted in the contact area being at its peak in condition A3. If this pressure was not evenly distributed, then it would directly lead to an increase in all pressure indicators and significant reduction in general comfort. Particularly, the back board in condition A3 was lifted to the maximum of 60°. As shown in the pressure nephogram, the extrusion pressure of the bed board on the lower back reached its maximum, whilst the contact area surged. The overall pressure over the smart bed and overall pressure at the back area were close to the peak, and comfort level was relatively low.

Previous studies on body pressure comfort have demonstrated that users' body pressure comfort was significantly enhanced by evenly distributing pressure and reducing the extrusion sensation. To improve the overall comfort performance of the smart bed lifting, designers and ergonomic researchers could focus on the bed board partitioning at the existing back board area and linkage mechanism between adjacent boards to avoid the resulting extrusion pressure.
As the smart bed back board began to lower (B2→C1→C2→C3), there was a rapid decrease in all body pressure indicators, whilst peak pressure point gradually moved upwards in the Y-direction. Adequate support of the lower back was observed to be one of the main reasons for this result\textsuperscript{37}. When the leg board began to lower (C3→D1→D2), only the peak pressure still changed significantly with the bed condition adjustment. However, the C3 and D1 conditions corresponded to poorer comfort during the bed board lowering. Through in-depth interviews with the participants, the poorer comfort performance could be related to a strong sense of weightlessness and body inversion, with some participants even reporting extreme discomfort caused by an increase in head pressure.

Amongst all typical conditions, comfort was at a relatively high level when the smart bed was in the C1 and E conditions. By combining the body pressure distribution result with human skeleton knowledge, this comfort performance is most likely caused by the fact that most areas of the body, including the back, buttocks and legs, are well supported. Moreover, there is no pulling or extrusion sensation on the body, and the overall forces are relatively balanced. The more the body is pulled or extruded, the more the body has to actively exert force (i.e. the more uncomfortable it is). The preceding situation indicates that the existing officially recognised zero-gravity condition (i.e. E) has some scientific evidence. Accordingly, the succeeding smart bed optimal design can be combined with the partitioned bed board for zero-gravity condition optimisation.

The participants were divided into seven groups based on BMI values. Changes in body pressure indicators, such as overall pressure, contact area and mean pressure with smart bed conditions, were observed in the different BMI groups. Firstly, the tendency of the preceding indicators are generally consistent across the different BMI groups, suggesting that BMI can be used as one of the bases for smart bed product segmentation for different groups of people. In other studies, smart beds can also utilise pressure data collected from sensor matrix array to estimate the BMI values of users by using a deep multitask neural network\textsuperscript{38}. Secondly, the mean pressure values and tendency were generally consistent across most groups, thereby demonstrating again that mean pressure and its derivative indices can be used as important bases for furniture product development and evaluation\textsuperscript{39,40}. Note that there was higher mean pressure in the lower BMI groups (i.e. <18.5, 21.0–22.9). The possible reason is that the lower BMI groups have less fat and their bones are in almost direct contact with the smart bed, which is not sufficiently cushioned. When smart beds are designed exclusively for the leaner group, the cushioning performance of the bed board or mattress is suggested to be increased appropriately.

Significant differences were observed in the perceived comfort performance amongst smart bed conditions, particularly in condition A3, which presented poorer comfort performance, as reflected by the indicators of overall pressure and contact area in BPDM. Meanwhile, the C1 and E conditions with better comfort ratings showed significant differences from the A2, A3, B1, B2 and C3 conditions. The latter conditions have one of the following main characteristics: (1) the back board lifting angle was at a maximum of 60° and (2) the difference in lifting angles between the back and leg boards was over 20. Combined with the body pressure data, the assumption is that the main reason is the instability of the body's gravity centre. The participants needed to actively exert force to relieve discomfort, which is consistent with the objective measurements.

Statistical analysis of the local perceived comfort data showed no significant differences in smart bed comfort perception between males and females, with the few differences occurring only at the back area in specific conditions (i.e. A2 and A3). In the in-depth interviews on discomfort, no significant differences in perceptions between genders were found. This finding differs from those of other furniture product comfort studies, in which gender was judged to be an important factor in perceived comfort\textsuperscript{26,61}. By comparing the local perceived comfort data from before and after the experiment, excluding the effects of other factors, such as temperature\textsuperscript{42} and mattress thickness\textsuperscript{43}, the perceived discomfort in the upper and lower back areas increased significantly over time. Again, this result emphasises that the back board design and mattress selection of smart beds should be given focus.

Many studies have investigated the correlation between pressure variables and perceived comfort\textsuperscript{16,20,44}. In our study, correlation analysis between SCE and BPDM showed that the major body pressure indicators correlated with the overall and local comfort of each area were not in complete alignment. Comfort at the upper back area is strongly correlated with overall pressure at the back area and mean pressure at upper back area, which is easier to understand. In succeeding smart bed designs, transfer of partial pressure on the upper back area when the bed is raised to the lower back area or lumbar area is expected to effectively improve the comfort performance of the upper back and the entire body. Additionally, comfort at the shank area is strongly correlated with the peak and mean pressures at this area. Experiment observations showed a significant over-concentration of pressure at the shank area, and that the bed structure can be optimised to increase the contact area to relieve discomfort. The different area pressure indicators have an effect on the comfort level of the area but also partly on the comfort level of other areas. For example, a strong correlation exists between peak pressure at the shank area and lower back comfort, the mechanism of which should be further investigated.

In summary, peak pressure, particularly at the buttocks, thigh and shank areas, is the key factor in comfort evaluation. Therefore, optimising the smart bed structure is practical to achieve a more even pressure distribution throughout the body. The main implementation paths include reducing the back area load pressure and reducing the peak pressure at the lower body area, which can effectively improve the comfort of smart beds.

5. Limitation
The experiment was a body pressure comfort study conducted whilst the participants were awake. Moreover, the experiment length was strictly controlled owing to software limitations. In the succeeding study, we need to guarantee a short rest of at least 30–45 minutes to ensure a realistic
simulation of users’ sleep behavior, as recommended by previous research. This study focuses on the body pressure comfort of smart beds. Thermal comfort indicators, such as temperature, humidity and ventilation, which have been used to assess bed comfort performance in some previous studies, were not precisely quantified.

The smart bed used in the current study is a basic model without additional functions, such as massage, sleep aid, breathing monitoring and snoring intervention. In future studies, more controlled experiments are expected to be conducted based on the findings of body comfort studies, combined with medical knowledge, thereby providing comprehensive measure system and indicator weights that affect smart bed comfort.

6. Conclusion

The strategy for body pressure comfort evaluation (i.e. experimental design, materials and method, statistical data analysis) proposed in this paper produced statistical evidence that can be applied in succeeding research to provide comfort prediction model for smart bed design and development for long-term care of Asian populations.

The results of the evaluation highlight that the bed board partitioning and linkage pattern optimisation better fit the human body curve and improve the smart bed overall comfort and health performance. Accordingly, a crucial aspect is to maintain the relative stability of the body’s gravity centre during changes in smart bed conditions. Additionally, comfort is at a relatively high level when the smart bed is in the C1 and E conditions, mainly because major areas of the body are well supported, whilst there are no additional pulling or extrusion forces. Future smart bed optimal designs can be combined with the subdivided bed board for zero-gravity condition optimization.

The results of this study can only be applied to the sampled population. Moreover, the participants expressed their evaluations under constrained test conditions (i.e. fixed posture and activity). Lastly, future studies should further investigate the relationship between smart bed comfort and changes in free lying positions and moving activities.

Declarations

Data availability

The data used in this study can be obtained from the corresponding author upon request.

Funding

This work was supported by National Key Research and Development Program of China (Grant Number 2021YFF0900600) and the Key Project Supported by the National Social Science Fund of China (Grant Number 20ZD09-4). The funding sources was not involved in any process of this study: data collection, analysis, or interpretation; trial design; participant recruitment; or any aspect pertinent to the study.

Acknowledgments

The authors would like to thank Knowledge/Growth Support (English language document review and editing specialists, Hong Kong), for language editing of this manuscript. The authors would like to thank Tianyu Zhang, Deqi Ouyang, Ke Liang for data collection and all participants for helping completing the study.

Author contributions statement

X.B. contributed to the conception of the study, experiment implementation, statistical data analysis and wrote the manuscript. M.Z. and Y.L. contributed significantly to analysis and manuscript preparation and helped review the constructive discussions. Y.H. conducted experiment and statistical data analysis. J.M. contributed significantly to the experimental design and wrote the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to M.Z.

References


32. Hamandi, F. *Design a model for human body to determine the center of gravity.* (2012).


**Tables**

Tables 2 to 4 are available in the Supplementary Files section.

**Figures**
**Figure 1**

Smart bed with pressure sensor mat.

**Figure 2**

Contact area division between the body and smart bed
Figure 3

Relationship between overall pressure, contact area, mean pressure and peak pressure and bed condition change.

Figure 4

Relationship between peak pressure point and bed condition change.
Figure 5

Characteristics of the overall pressure, contact area and mean pressure of the different BMI groups.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx