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Assessment of a mattress with phase change materials using a thermal and perception test

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ABSTRACT

Mattresses composed by phase change materials (PCMs) may improve the thermoregulation of the human body. The aim of the study was to analyse the thermoregulatory efficiency of a PCMs and a conventional mattresses via the evaluation of the skin temperature, thermal comfort and thermal perception. Twenty participants lay on a PCMs and a conventional mattress for 20 min in each mattress on the same day. Skin temperature of the back of the participants and temperature of the sheet of the mattresses were measured before and immediately after lying on each mattress. Thermal comfort and thermal perception were also reported during the last minute of the lying test. The PCMs mattress resulted in a lower increase in skin temperature (0.3–1.0 °C, $p = 0.002$ and ES = 1.4) and a greater increase of the sheet temperature (0.2–1.6 °C, $p = 0.02$ and ES = 0.8). No differences in thermal comfort and thermal perception were observed between mattresses ($p > 0.05$ and ES < 0.8). The analysis of the superficial temperature (skin, sheet) was an adequate tool to identify differences in the thermoregulatory efficiency of different mattresses. The use of PCMs in mattresses improved the heat dissipation of the human body during lying in a proportion between 2.7% and 25.6%. However, the thermoregulatory differences were not big enough to alter the thermal comfort and thermal perception of the participants after 20 min of test.

1. Introduction

Sleep deprivation has been related to cardiovascular and neurodegenerative diseases [5,34,36], to a reduction of the ability to focus [37] and to an impairment of the cognitive function [27,40]. In this sense, sleeping on an adequate mattress has been observed to improve the sleep efficiency [28]. The quality of a mattress depends on a number of characteristics including the firmness, the hardness of the structure, the adaptability to the body shape, the distribution of pressure [35,10,30] or the ability to facilitate an adequate thermoregulation [6,25].

Thermal manikins have been used to assess the heat transfer efficiency of mattresses [21]. However, it is important to analyse the heat transfer efficiency of mattresses with human beings in order to take into account the human thermoregulatory mechanisms and observe their actual influence on people. In this line of thought, human thermoregulation can be studied through the assessment of skin temperature [32,44]. The analysis of the skin temperature provides a valuable insight of the thermal balance between humans and the environment [41,18]. With respect to the different techniques to measure the temperature of the skin, the infrared thermography is becoming more and more popular as it is a non-contact and non-invasive technique [16,3,43].

A number of strategies aiming to improve the thermoregulation of mattresses have been studied including heat blankets, circulating-water systems or gel-coated circulating-water mattress [39,7,2,26]. These methods have been used mainly in a clinical environment and were focused on the reduction of hypothermia. However, the reduction of the skin temperature should be an important objective of a mattress, especially in warm and hot environments. In this sense, mattresses composed by phase change materials (PCMs) could offer a better thermoregulation during the sleep due to its inherent properties. PCMs have a heat storage capacity 5–14 times greater compared to conventional thermal storage materials [22]. As a result, these materials have been researched specifically for heat storage in solar energy in the last decades [12,13,11]. After that, PCMs have been widely used in the last years in other applications including construction, in general containers for temperature-sensitive food, or in medical devices [22]. With respect to human thermoregulation, PCMs have been integrated in clothing, which has resulted in an improvement of the conductive cooling [17,20]. However, no study to date has analysed the effects of applied PCMs in mattresses on the human body thermoregulation.

Furthermore, the assessment of the skin temperature while lying on a mattress offers the possibility to associate the objective information provided by the thermography with the subjective perception ex-

Abbreviations: ΔT, difference between the temperature immediately after and before lying, expressed in °C; PCMs, phase change materials; VAS, visual analogue scale

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perienced by the person. Thermal comfort has been defined as the mental condition that expresses the level of satisfaction with the thermal environment [4]. Thermal comfort plays an important role during sleep and it is related to skin temperature [6,25]. Lee and Park [29] showed that participants who reported the lowest ratings of thermal comfort in different mattresses presented the lowest values of skin temperature. On the other hand, lower oscillations of the body temperature overnight were related to a deeper sleep [6]. As a result, it is of great interest to analyse the effect of the thermal properties of different mattresses on the thermal comfort and perception in order to better understand how these variables influence each other.

The aim of the study was therefore to evaluate the thermoregulatory efficiency of a PCMs mattress and a conventional mattress through the evaluation of the skin temperature, thermal comfort and thermal perception after 20 min of use. It was hypothesized that the mattress composed of PCMs would facilitate the human heat dissipation and would result in a cooler perception and greater thermal comfort compared to the conventional mattress.

2. Material and methods

2.1. Participants

20 physically active participants volunteered to take part in this study: 10 males and 10 females, age [23.5 ± 3.0 years], body mass [68.4 ± 13.1 kg], and height [170.1 ± 8.5 cm]. They all gave written informed consent signed before participation. The study procedures complied with the Declaration of Helsinki, and were approved by the University ethics committee.

In order to measure the temperature of the skin under similar conditions among the participants, all of them were informed that they should not drink alcohol or smoke at least 12 h before the test, should not carry out high-intensity or exhaustive exercise at least 24 h before each test, and should avoid drinking coffee or other stimulants, avoid wearing any jewellery, sunbathing or being exposed to UV rays, as well as refraining from using sunscreen/sun blockers, body lotions and creams before the test. They were also asked not to eat at least two hours before the test and refrain from heavy meals. With respect to the female participants, 5 were tested during the follicular phase and 5 were measured during the luteal phase of the menstrual cycle.

2.2. Mattresses

Two mattresses with the same appearance and design were used in the present study. Both mattresses were polyurethane mattresses with a thickness of 10 cm, mass of 8.9 kg and a bottom sheet composed of 50% polyester and 50% cotton. However, whereas one of the mattresses included PCMs in the outer textile layer of the mattress and in the bottom sheet (termed as “MATTRESS-PCMs”), the other mattress of the study was a conventional mattress without PCMs (“CONTROL”). The PCMs consisted in microencapsulated paraffin with a concentration of 750 g/l and 90% of absorption.

2.3. Protocol

All participants assessed both mattresses on the same day in order to reduce the variability of the skin temperature between days [14] (Fig. 1). Participants performed the tests without t-shirts. Firstly, they remained in a standing position at rest for 10 min to adapt their body temperature to the room temperature [31]. Then, participants lay for 20 min in a supine decubitus position without moving on one of the mattresses chosen at random. Subsequently, participants repeated the 10 min thermal adaptation to the room temperature and then lay on the second mattress. Skin temperature of the back of the participant and of the bottom sheet of the mattress was measured before and immediately after lying on each mattress (approximately 2 and 5 s after lying for the sheet and for the back, respectively). Thermal comfort and thermal perception were reported during the last minute of the lying test on each mattress. Tests were carried out in mild environmental conditions: 24.3 ± 0.92 °C of room temperature and 38 ± 6.5% relative humidity.

2.4. Skin temperature measurement

Skin temperature was determined by an infrared thermography camera with infrared resolution of 320 × 240 pixels, thermal sensitivity <0.05 °C, and accuracy of ±2 °C or 2% (*FLIR E-60, Flir Systems Inc., Wilsonville, Oregon, USA*). A black body (BX-500 IR Infrared Calibrator, CEM, Shenzhen, China) was used to ensure a correct calibration of the camera. The camera was positioned 1 m away from the participant and it was kept perpendicular to the body regions of interest.

Environmental conditions were controlled (e.g. lighting and temperature controlled room, no person apart from the investigator and the participant as well as no electronic equipment were within a range of 5 m). An anti-reflective panel was placed behind the participant to minimise effects from infrared radiation reflected in the wall [19]. Reflected temperature was measured according to the standard method ISO 18434-1:2008 [23]. For all tests, air temperature and relative humidity were measured using a thermo-hygrometer with an accuracy of ±1 °C for the air temperature and ±3% for the relative humidity (Digital thermo-hygrometer, *TFA Dostmann, Wertheim-Reicholzheim, Germany*) and were included in the camera settings.

Regions Of Interest (ROIs) were defined on the back of the participant and on the sheet (Fig. 2). To define the ROIs on the back of the body, markers were positioned in both acromions and in the C7 vertebra in order to define lateral and upper sides of the frame of analysis, respectively. The upper part of the trousers was considered the lower side of the frame of analysis. For the thermographic analysis of the sheet, a ROI with a surface of 120 ∗ 70 pixels (∼15 cm ∗ 9 cm) was determined in the center of the sheet where the back of the participant had been located throughout the lying test. The absolute mean temperature of each ROI was obtained using a thermography software (Thermacam Researcher Pro 2.10 software, FLIR, Wilsonville, Oregon, USA), with an emissivity factor of 0.98 for the skin in the ROI of the back [42], and with an emissivity factor of 0.95 for the cotton fabric in the ROI of the sheet [8].

In addition to the absolute temperature values, the temperature variation was also calculated: ΔT (difference between the temperature immediately after and before lying, expressed in °C).

2.5. Thermal energy transference estimation

Heat energy transferred in the tests in the 20 participants was calculated using the following equation [46]:

Eq. (1). Thermal energy transference equation:

$$Q = m \times c \times \Delta T \text{ (J)} \tag{1}$$

where Q is the estimation of the thermal energy transferred to the sheet in Joules, m is the mass of the portion of sheet when temperature was calculated (0.05 kg), c is the specific heat of the sheet (estimated as approximately 1300 J/kg/°C) and ΔT is the variation of temperature of the sheet during the test.

With the estimation of the difference on thermal energy transference between both conditions, the percentage of energy transferred as a result of the PCM was estimated.

2.6. Thermal comfort and perception

Thermal comfort and thermal perception were measured with a 150-mm visual analogue scale (VAS) developed by Mündermann et al. [33]. The scale is labelled at the left end as 'not comfortable at all' and "cold perception" (0 comfort points) and at the right end as 'most comfortable condition imaginable' and "hot perception" (15 comfort points), for the thermal comfort and thermal perception, respectively.

2.7. Statistical analysis

The statistics package SPSS 21 (SPSS Statistics, IBM) was used for the statistical analysis. The normality of each variable was confirmed by the Shapiro-Wilk test ($p > 0.05$). A between-sexes comparison was conducted in order to verify if this factor had influence. For this reason, potential differences between the two mattresses (MATTRESS-PCMs vs CONTROL) for absolute temperatures were examined by mixed-design ANOVA with a two within-subjects factors (measurement moment and condition) and one between-subjects factor (sex). The same analysis but with one within-subjects factor (condition) was performed for temperature variations, thermal comfort, and thermal perception. Bonferroni post hoc was carried out to provide details as to the whereabouts of significant differences. A dependent Student's *t* test was used to examine the differences in thermal energy transference (Q) between both tests. Effect sizes (ES) [9] were calculated using a purpose-designed Excel spreadsheet (Microsoft Inc., USA). Data are reported as mean ± SD with the 95% confidence intervals (CI 95%). The level of statistical significance was taken to be $p < 0.05$ and ES > 0.8 [9].

3. Results

The effect of the different mattresses on the temperature and perception variables of the study was not modified by the sex of the participants, as no significant interaction ($p > 0.05$) was found between the two factors analysed (sex and mattress condition) for any of the dependent variables. Therefore, results of all the participants, without taking into account the sex, are presented in this section.

Fig. 3 presents the skin temperature of the back before and after lying on the two mattress conditions and skin temperature variation between both moments. No significant differences were observed in absolute skin temperatures before and after 20 min of lying in a supine decubitus position on the two mattresses (MATTRESS-PCMs vs CONTROL before: 33.8 ± 0.6 °C vs 33.5 ± 0.8 °C, and after: 34.7 ± 0.6 °C vs 35.0 ± 0.6 °C, $p > 0.05$ and ES < 0.8). However, in the analysis of the temperature variation (ΔT), MATTRESS-PCMs presented a lower increase in temperature compared to the CONTROL mattress (MATTRESS-PCMs vs CONTROL: 0.8 ± 0.6 °C vs 1.5 ± 0.4 °C, $p = 0.002$ and ES = 1.4, 95%CI of the difference between conditions [0.3, 1.0 °C]).

Fig. 4 presents the sheet temperature before and after lying on the two mattress conditions and sheet temperature variation between both moments. Same sheet temperature was observed in the two conditions before lying (MATTRESS-PCMs vs CONTROL: 24.5 ± 0.9 °C vs 24.4 ± 0.8 °C, $p > 0.05$ and ES < 0.8). MATTRESS-PCMs presented a higher sheet temperature after 20 min of lying (MATTRESS-PCMs vs CONTROL: 30.7 ± 0.9 °C vs 29.8 ± 1.1 °C, $p = 0.01$ and ES = 0.9, 95%CI [0.2, 1.5 °C]). Also, the sheet temperature of MATTRESS-PCMs presented a greater increase of temperature (MATTRESS-PCMs vs CONTROL: 6.2 ± 0.9 °C vs 5.3 ± 1.3 °C, $p = 0.02$ and ES = 0.8, 95%CI [0.2, 1.6 °C]).

Thermal energy transference estimation was greater for MATTRESS-PCMs than CONTROL (MATTRESS-PCMs vs CONTROL: 403.3 ± 56.8 J vs 346.5 ± 82.3 J, $p = 0.02$ and ES = 0.8, 95%CI [10.7, 103.1 J]). Therefore, MATTRESS-PCMs presented between 2.7% and 25.6% of greater heat transference estimation than CONTROL.

Finally, no differences were observed between mattresses ($p > 0.05$ and ES < 0.8) in thermal comfort (MATTRESS-PCMs vs CONTROL: 9.9 ± 2.3 cm vs 9.8 ± 2.5 cm) and thermal perception (MATTRESS-PCMs vs CONTROL: 7.6 ± 2.4 cm vs 8.7 ± 1.6 cm).

4. Discussion

The purpose of the present study was to evaluate the thermoregulatory efficiency of a PCMs mattress and a conventional mattress through the evaluation of the skin temperature, thermal comfort and thermal perception. The main findings were a greater increase of the sheet temperature of the PCMs mattress after 20 min of use compared to the conventional condition (mattress without PCMs) as well as a lower increase of the skin temperature of the participants' back when lying on PCMs mattress. However, these differences did not alter the thermal comfort and thermal perception of the participants.

Different studies have focused on monitoring and improving thermoregulation in hospital patients due to the relationship between body temperature, morbidity and mortality [1]. Interestingly, most of these studies were focused on avoiding hypothermia, instead of investigating the reduction of hyperthermia. The present study shows that the use of PCMs in a mattress is an effective new technology that can improve thermoregulation. MATTRESS-PCMs showed a greater increase of its temperature (between 0.2 and 1.6 °C) and a lower increase of skin temperature (between 0.3 and 1.0 °C) compared to a conventional mattress after 20 min of use. These findings are related to each other showing that the heat was transferred better between the skin and the mattress through conduction (by the increase of the thermal gradient between the skin and the sheet) and are in agreement with the greater heat storage ability previously attributed to PCMs [22]. This idea is also supported by the thermal energy transference estimation, which showed that MATTRESS-PCMs presented between 2.7% and 25.6% greater heat transference than a conventional mattress.

However, it is important to state that no significant differences were found in the skin absolute temperatures. This finding is in agreement with those of previous studies that showed significant temperature variations after their interventions with no differences in absolute temperatures [15,38]. The lack of differences in absolute temperatures could be explained by the variability of the skin temperatures between participants as well as to the different environmental temperatures between studies [45]. Hence, it has recently been suggested that the analysis of the temperature variation rather than the absolute temperatures could be more appropriate when assessing the thermal effects of an intervention on the human body.

To the authors' knowledge, this is the first study that has analysed the influence of a mattress with PCMs on human heat transference during lying. Therefore, the results will be compared with those obtained in the application of PCMs in clothing [17,20], which can be considered the most similar application to the present study. Gao et al. [17] observed, during the application of PCMs in a vest during running, a reduction of 3–4 °C in the torso skin temperature compared to a control condition. Similarly, House et al. obtained lower skin temperatures during stepping and during the resting recovery (∼2–10 °C in abdomen and ∼2–8 °C in chest) when using a PCMs cooling vest under fire-fighting clothing. Both studies presented greater efficiency of the PCMs than the present study (between 0.3–1.0 °C of lower increase of the skin temperature). These differences in the efficiency of the PCMs between studies could be due to different factors such as the temperature gradient between the skin and the PCMs, the PCMs latent heat capacities, or the surface and mass amount of PCMs [17,20]. It is important to consider that both vest systems were designed to be used during exercise and in hot conditions, which is not applicable to the mattress assessed in the present study.

Although the use of MATTRESS-PCMs provoked the aforementioned thermal effects, no differences in thermal comfort and thermal perception at a mild environmental temperature (24.3 ± 0.92 °C) were observed. This finding may indicate that thermal differences should be greater in order to be perceived by the participants. As a result, the different thermoregulatory behavior of the two mattresses analysed would not be perceived by the consumer, thereby questioning whether thermal comfort and thermal perception are good indicators of thermoregulatory efficiency when purchasing a mattress [24].

Finally, the methodology used in the present study was adequate to assess the thermoregulatory differences of two mattresses, although these differences were not related to the subjective perception of participants. Future studies should investigate if different environmental temperatures (e.g. warmer, cooler) and different durations of the lying tests improve the perception assessment. Furthermore, future studies could assess the effect of mattresses with a different proportion or composition of PCMs, and relate these differences to the user's preference. The methodology used in the present study showed a number of positive aspects: (1) the use of thermography provides a non-contact, low cost and a fast method to register skin and mattresses temperatures [14], (2) the skin temperature variability between days is reduced since the two mattresses are evaluated in the same session, and (3) the thermoregulatory efficiency of two mattresses can be assessed in only one hour per participant.

5. Conclusions

The current work presents an adequate methodology to measure the thermoregulatory efficiency of mattresses. It was observed that the use of PCMs in mattresses resulted in a lower increment of the skin temperature of the back after lying in a mattress with PCMs compared to the conventional mattress (0.3–1.0 °C), and a greater increase of the sheet temperature (0.2–1.6 °C). The use of PCMs in mattresses improved the human heat dissipation between 2.7% and 25.6% compared to a conventional mattress. Therefore, mattresses composed of PCMs could be recommended when aiming to improve heat dissipation during resting. However, these differences were not big enough to alter the thermal comfort and thermal perception after 20 min of use and, as a result, the advantages of using this type of mattress may not be large enough to be perceived by users.

Conflict of interest

The authors declare that they have no conflict of interest.

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