

# Passive Control Of The Bed Micro-Environment By Quilts

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**Abstract.** An easy method to passively control the bed micro-environment and thus thermal comfort of people is to use a cover with appropriate thermal insulation. The purpose of this study was to find out the potential of generating uniform and non-uniform bed thermal micro-environment with quilts. The effect of the thermal resistance of quilts on the temperature field in the bed and dry heat loss of a human body was studied. Thermal manikin was used to resemble person in bed. Four quilts with different properties such as weight and non-uniform filling and type of filling material (Muscovy down and polyester fibre) were studied. Full-scale experiments were conducted in a ventilated climate chamber under four thermal conditions including two levels of relative humidity (50% and 70%) and two air temperatures (15°C and 20°C). The dry heat loss of the thermal manikin was higher with polyester fibre quilt than with quilt having the same weight but with Muscovy down filling. This was obtained under all tested room conditions. The studied non-uniformity in down distribution of the quilt provided similar thermal insulation on the feet and chest.

## 1 Introduction

People spend every day approximately 33% of their time sleeping. Sleep quality directly affects people's day time functioning. The thermal environment is one of the most important factors that influences the sleep quality [1-2]. A recent study showed that the bed micro-environment had a greater impact on the thermal comfort of people who used bedding covers such as quilts during the sleep period compared with the thermal environment in the bedroom [3].

There are numerous types of covers, quilts and mattresses on the market, offering different levels of thermal insulation. The correct choice of the bed cover together with appropriate sleepwear can modify perceived thermal conditions in bed in accordance with the season and the huge individual preferences of people. Quilts' properties such as thickness, weight, material and design makes it possible to change substantially their thermal insulation and thus the generated bed thermal environment. Quilts with non-uniform thermal insulation are available to provide different warmth of the body parts, e.g. with higher thermal insulation at the feet area than at the chest area. Furthermore, quilts with phase change materials that may buffer varying levels of temperature have been also developed.

The aim of this study was to investigate the effect of four quilts with different thermal characteristics on the heat loss of a full-size thermal manikin at two levels of room temperature and relative humidity. Another objective was to study how the temperature in the bed micro-environment changes under the studied conditions.

## 2 Methodology

### 2.1. Experimental set-up and equipment

Experiments were conducted in a climatic chamber (6.0 m × 4.7 m × 2.5 m, L × W × H). The chamber was ventilated by an upward piston airflow supplied from the entire floor area with an air velocity of less than 0.05 m/s. The upward piston flow of outdoor air ensured uniform air temperature and air velocity distribution in the chamber. The air was exhausted through openings on the ceiling. The chamber was constructed to ensure a mean radiant temperature equal to the room air temperature and negligible radiant temperature asymmetry.

A thermal manikin with a realistic female body shape (size 38, 1.68 m height) was used to simulate the dry heat loss from the body of an average woman lying in bed (Fig. 1). The manikin has 23 body segments, each with individually controlled heat output. The manikin was lying in supine position during all measurements. The bed was located at the centre of the chamber. The size of the bed was 2.4 m × 1.8 m (L × W). The bed was refitted from a single bed to a double bed using six pieces of polyfoam sheets with thickness 0.05 m to provide insulation. The polyfoam sheet were placed on top of the bed's frame below the polyfoam sheets. This design also helped to place more accurately the quilt over the manikin and to achieve better reproducibility of its tightness.

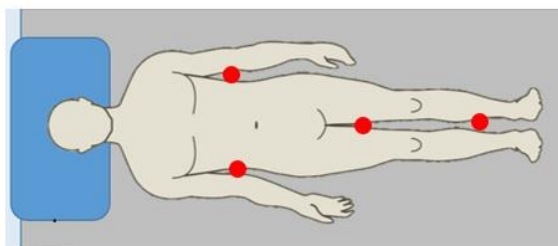
The thermal micro-environment established in the bed when the manikin was covered with a quilt was measured. Air temperature and relative humidity were measured in

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the air gaps between the quilt and the manikin's body (Fig. 2). At each location, air temperature sensors were placed on a small stand. The heights of stands were based on the shape of the quilt when placed over the manikin. The height of the stands placed between the torso and the upper arms of the manikin was 18.6 cm. The height of the stand placed between the thighs was 22.4 cm. The height of stand between the ankles was 16.0 cm. Three temperature sensors and one humidity sensor were attached on each stand. The temperature was measured at the top, middle, and bottom of the stand. Air temperature and surface temperature were measured by platinum resistance temperature sensors (class A, accuracy 0.2 °C; measuring interval time was 10 seconds). Humidity was measured by Sensirion digital humidity sensors SHT31 (accuracy  $\pm 2$  %; measuring interval 1 second). The temperature sensors and the manikin were calibrated before the experiments. The humidity sensors were already calibrated by the manufacture.



**Fig. 1.** Experimental set-up.



**Fig. 2.** Measuring locations around the manikin (marked with red bullet points) of the temperature and relative humidity.

## 2.2 Experimental procedure

The surface temperature of manikin was fixed using a proportional integrate (PI) control mode of the thermal manikin: 31 °C for the feet and for the hands and 35 °C for the other body segments of the manikin. In this way a mean skin temperature of 34.6 °C for the whole body was generated, which is the thermo-neutral skin temperature in a sleeping environment [4]. A software recorded the manikin's heat loss of the whole body and each body segment. The logging interval was set to be 10 seconds. The measurements were taken under steady state room conditions. After placing the quilt on top of the manikin,

the measuring period lasted 2 hours. It took about 1 hour until the heat loss of the manikin reached steady state.

A recent study has investigated the different factors that influence the uncertainty in determination of the bed micro-environment and the thermal insulation of quilts [5]. Factors such as design of the mattress, tightness between the manikin and the quilt and placement of the quilt, are important for the reproducibility of the measurements of manikin's heat loss. They are also important for the measurements of other parameters in the bed-microenvironment including air temperature and relative humidity. In the current study, the method and recommendation described by [5] were followed. Each quilt was placed to cover the entire body of the thermal manikin including the neck (see Fig. 1). The air gap near the neckline was closed to avoid infiltration from the room air.

## 2.3 Experimental conditions

A series of experiments was conducted under four different room conditions, i.e. at low and high levels of relative humidity (50% and 70%) and two air temperatures (15°C and 20°C). Four quilts with different properties were studied:

- (1) quilt with 1100 g 90 % Muscovy down, named Natural 1100 g;
- (2) quilt with 1100 g polyester fibre, named Synthetic 1100 g;
- (3) quilt with 600 g 90 % Muscovy down, named Natural 600 g;
- (4) quilt with 810 g 90 % Muscovy down, named Non-uniform filling 810 g.

All quilts had the same sizes: 140 cm wide and 200 cm long. However, the number of the cassettes from which each quilt consisted was different. Table 1 shows the numbers of the rectangular cassettes for each quilt and the filling material per cassette. The quilt with 810 g 90 % Muscovy down, named Non-uniform filling 810 g, had more Muscovy down in the cassettes covering the feet (30 g per cassette) and 14 g in the remaining cassettes.

All studied quilts with down filling had the same filling power. The filling power is a measure of the height of a volume occupied by a filling material which is subjected to a specific pressure [6]. The higher the filling power the more air a certain weight of down can trap.

**Table 1.** Quilts' filling distribution

Quilt type	Nº of rectangular cassettes	Size of cassettes, L x W, cm	Filling quantity per cassette, g	Filling quantity, g/m <sup>2</sup>
Natural 600 g	8 x 6	25 x 23,3	12,5	214.3
Synthetic 1100 g	7 x 5	28,5 x 28	31,4	393
Natural 1100 g	6 x 4	33,3 x 35	45,8	393
Non-uniform 810 g	7 x 5	28,5 x 28	30/14	376/175

## 2.4 Data analyses

The mean body heat loss of all body segments except for the manikin's Crown, Left and Right face was calculated. These three body segments exposed to the room conditions were excluded in order to quantify the effect of only the thermal conditions in the bed-microenvironment on the manikin's dry heat loss. The power supplied to the manikin was calculated as the area-weighted average of the heat loss from the body parts covered by the quilt. The average values of the manikin's power supply (W/m<sup>2</sup>) for each body segment were used. The last 15 minutes of the logged data were averaged (under steady state). The measured temperatures in the bed were also averaged for each location when steady state was reached.

## 3 Results and Discussion

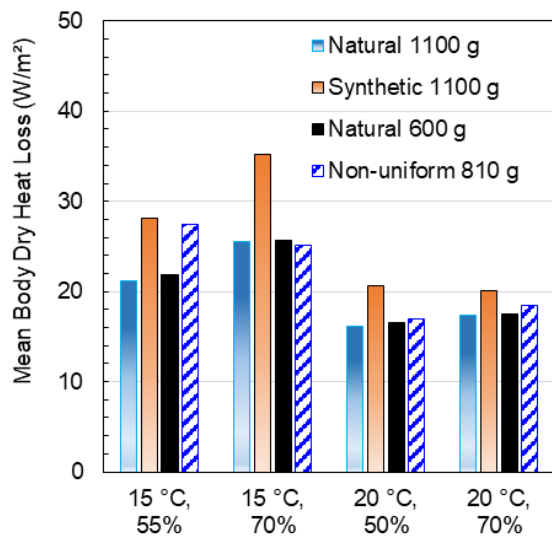
The results in Fig. 3 show that during all room conditions the mean body dry heat loss of the manikin covered with the Natural 600 g quilt was almost the same as the mean heat loss when the Natural 1100 g quilt was used. This results were unexpected because the weight of the down in the two quilts was almost twice different. One possible reason for this result could be that the fit of the quilts over the manikin was different. As a result, the air pockets formed below the quilts varied around the manikin's body segments. It was found, for example, that the segmental heat loss of the back and arms of the manikin was lower with the Natural 600 g quilt than with the Natural 1100 g quilt (these results are not part of this paper). On the other hand, the heat losses of the chest and feet were higher with the Natural 1100 g than with the Natural 600 g quilt (Fig. 4 and Fig. 5). Existing air pockets increase the boundary air layer insulation below the quilt. Thus, the total thermal insulation increases as well [7]. The different fit of the quilts over the body can be attributed to the different number and size of the quilts' cassettes (Table 1). These results suggest that quilts' cassettes construction is important for the overall thermal insulation. Further work is required to establish the

viability of this implication. Nevertheless, in practice the air gaps under the covers will be changing due to people's movement in bed.

In Fig. 3, it is shown that the mean heat loss with the Synthetic 1100 g quilt was the highest under all conditions. These results show that Muscovy down has better insulation properties than the polyester fibre. The Natural non-uniform 810 g quilt provided similar mean heat loss as the Natural 1100 quilt except during the condition at '15°C, 55%'. The results suggest that quilts' thermal insulation depends on many factors including their filling power, down weight and distribution in the cassettes as well as room temperature and RH.

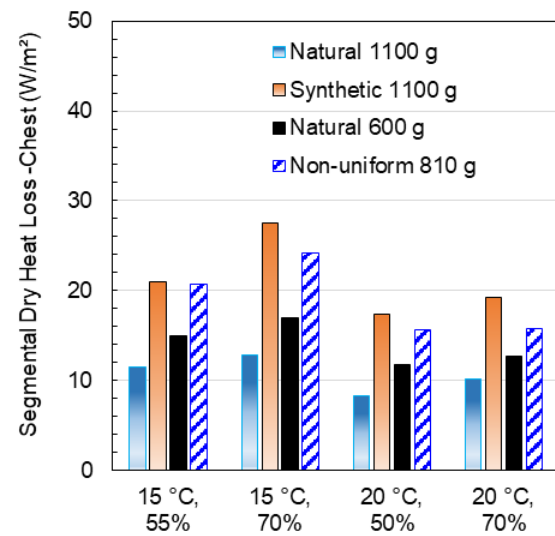
The increase of the relative humidity (RH) in the room increased the mean body heat loss of the manikin when the Natural 600 g and the Natural 1100 g quilts were used at room air temperature of 15°C. The Synthetic quilt provided also lower insulation at 15 °C 70% RH than at 15 °C 55 % RH. These results are due to the fact that it takes more heat energy to warm moist air. If the air layer next to the surface of the manikin was damp, it therefore took more of the manikin's heat energy to warm it in order to keep its mean surface temperature 34.6 °C. This effect was not observed for the Non-uniform quilt, which could be due to some other quilt's characteristics such as thickness and shape adaptability. The cassettes over the manikin's torso were with much less down which increased their adaptability over the complex shape of the body. At 20 °C, the effect of the increased RH was not observed. Only slight increase was seen in the mean body heat loss obtained with the Natural 600 g and the Non-uniform quilts, when the RH was 70%.

The results of this study show that the mean body heat loss while a person is in bed depends on the thermal insulation of the quilt and the room air temperature and relative humidity. On the other hand, the insulating effect of the quilts depends on their filling material and the filling quantity. A quilt with less down filling is expected to provide less insulation than a quilt made of the same material but with double filling quantity. However, the current study shows that 1.83 times lower down quantity provided the same mean body heat loss. These results supports previous findings, which showed no difference in the human subjects' acceptability of the whole body thermal sensation when they were covered with either the Natural 600 g quilt or Natural 1100 g quilt at room conditions of 15°C and 20°C and 30-44% RH [8]. The subjects in the study were wearing only underwear and they were covered up to the neck. It has been reported that the insulation of a quilt depends also on the type of stitching, the capacity of the filling to confine the air (i.e. filling power) and the shape adaptability of the quilt [9] as well as its thickness [2, 7]. These quilts' properties were not studied here.



**Fig. 3.** Mean body heat loss under all room conditions with all studied quilts.

Fig. 4 compares the heat loss of the chest. The results show that unlike the mean body heat loss the local heat loss of the chest was affected by the weight of the quilt. The local heat loss decreased with the increase of the weight of the quilt, i.e. the Natural 1100 g heated more the chest than the Natural 600 g. However, the decrease was not proportional to the increase of the weight of the quilt. The local heat loss with the Natural quilt (1100 g) was lower than the local heat loss with the Synthetic 1100 g quilt. The heat loss with the Non-uniform 810 g quilt was higher than with the Natural 600 g and the Natural 1100 g quilts. The down in the cassettes of the Non-uniform quilt located over the torso had similar weight as that of the cassettes of the Natural 600 g quilt. However, the two quilts had different number of cassettes. As a result, the down per square meter was 175 g/m<sup>2</sup> and 214 g/m<sup>2</sup> for the Non-uniform and the Natural 600 g, respectively (see Table 1). This difference in down per m<sup>2</sup> may have affected the thermal insulation of the two quilts. With the Non-uniform quilt the local heat loss from the chest was equal or lower than that with the Synthetic 1100 g. The Non-uniform quilt and the Synthetic quilt had the same number and size of cassettes. But, the Synthetic quilt had filling quantity of 31.4 g per cassette and the Non-uniform quilt only 14 g per cassette. These results confirm that the natural down filling provides better thermal insulation of the body than the polyester fibre. The same effect of increasing the RH at 15°C on the dry heat loss of the chest can be observed as in Fig. 3 for the mean body dry heat loss. The heat loss of the chest with the Non-uniform quilt also increased with the increase of the RH at 15°C. At 20°C, only slightly the heat loss of the chest increased when the RH was 70% with all quilts except the Non-uniform quilt. For this quilt the heat loss remained the same.



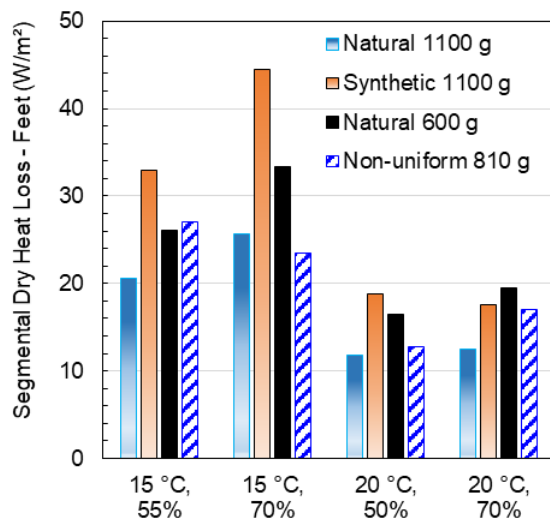
**Fig. 4.** Segmental heat loss from the chest (average of left and right chest segments) under all room conditions with all studied quilts.

Fig. 5 shows the segmental dry heat loss from the feet. The highest heat loss of the feet was obtained with the Synthetic quilt during all conditions. The most unexpected result to emerge from the data is that the Non-uniform quilt did not provide better thermal insulation at the feet than the Natural 600 g quilt during the room condition '15°C, 55%'. The Non-uniform quilt had less number of cassettes with more down in them compared to the Natural 600 g, which had more cassettes with less down. As a result, the two quilts most probably had different fit over the feet. As already mentioned, the air pockets contribute to an increase in the air layer insulation. Although the quilts were positioned in the same way, the difference in their number of cassettes and distribution of the filling, influences their fit around the body and thus their thermal insulation. This factor maybe further studied in the future. In Fig. 5, it can be seen also that the increase of the RH at room air temperature of 15°C increased the heat loss of the feet when the manikin was covered with the Synthetic quilt, the Natural 600 g and 1100 g quilts. This effect of the high RH was observed also at 20°C with the Natural 600 g and the Non-uniform quilts. The heat loss of the feet with the other two quilts did not change with the increase in the RH at 20°C.

The results from the manikin's segmental body heat loss showed that the dry heat loss of the chest was lower during all conditions compared to the dry heat loss of the feet obtained with the same quilt (except for those obtained with the Non-uniform quilt). This is probably because the chest was not in contact with the surface of the mattress compared to the feet. The heat losses from the other body segments not in contact with mattress (the results are not presented in this paper) such as pelvis and front upper thighs were lower than the body parts feet, back, back thighs, etc. Another reason for the higher heat loss at the feet compared to the one at the chest could be the fact that the air gap between the feet was the largest. The current study did not examine the insulation effect of the quilts on the body heat loss compared to the thermal



manikin was lying in other than supine position. With different postures such as supine and lateral reclining, the effective areas through which the heat transfer between a human body and a bedding system occurs will be different. It should be noted that the difference between the segmental heat losses of the chest and feet with the Non-uniform quilt was much lower than with the other quilts. In addition, the difference between the heat losses of the feet and chest obtained with the other quilts at 20°C, 50% RH were small in the range of 1.6 - 4.7 W/m<sup>2</sup>.



**Fig. 5.** Segmental heat loss from the feet (average of left and right foot) under all room conditions with all studied quilts.

In Table 2, the mean temperature measured at the inner surface of the quilts is shown for all four room conditions. The mean temperature was obtained under steady state by averaging the surface temperature measured at the four locations (see Fig. 2). Although the polyester filling per m<sup>2</sup> of the Synthetic quilt was the same as the down filling of the Natural 1100 g and 179 g more than the Natural 600 g quilt, the mean inner surface temperature of the Synthetic quilt was the lowest compared to the surface temperature of the other quilts. This result can be observed for all conditions. The highest inner surface temperature during all conditions was obtained with the Natural 1100 g quilt. These results suggest that the thermal insulation of a quilt is associated with not only its weight per unit area. This finding is consistent with that of Lin and Deng 2008 [2], which showed that a cotton blanket with higher weight per unit area than that of a summer quilt provided less thermal insulation than the quilt. According to [2, 7], the thermal insulation of a material including bedding component is mainly influenced by its thickness. The results in Table 2 show also that increasing the weight of the quilt almost twice (comparing Natural 600 g with Natural 1100 g) did not increase much the inner surface temperature of the quilt. These results support the results obtained for the mean dry body heat loss with these two quilts (Fig.3). This means that that the heat transfer between the bed microenvironment and the room environment through the quilts was similar regardless their weight. These results together with the results obtained for the mean dry body heat loss show that there is no need of using more than

600 g down material under the studied room conditions. Only the increase of the RH at 15°C affected the surface temperature of the Synthetic quilt, which decreased with 1.2°C. This result strongly correlates with the increased mean body dry heat loss and the segmental heat loss with the Synthetic quilt at 15°C and 70% RH.

The mean air temperature measured in the air gaps under the quilts was in the range of 29.6 – 33.1°C and 32.2 – 34.2°C during all conditions at room air temperatures of 15°C and 20°C, respectively (see Table 3). The lowest air temperature measured around the manikin was with the Synthetic quilt during all room conditions. At both room conditions at 15°C, the Natural 1100 g quilt and the non-uniform quilt provided the same mean temperature in the gaps. The air temperature with the Natural 600 g quilt was 0.5°C lower than with the Natural 1100 g quilt. With all quilts, except with the Non-uniform quilt, the air temperature around the manikin increased with 1-2°C at room air temperature of 20°C. With the Non-uniform quilt, the air temperature in the gaps was about 33°C during all room conditions. This result is unexpected and requires further investigation. The increase of the RH to 70% at 15°C affected the temperature in the gaps only with the Synthetic quilt. The mean air temperature increased with 0.6°C at 15°C and 70%RH compared to the temperature at 15°C 55%RH. This was most probably due to the increased mean body heat loss at 15 °C and 70 % RH with this quilt. As a result, the air temperature in the bed micro-environment increased. The high RH did not affect the mean temperature around the manikin with the other quilts. At 20°C, the increase of the RH decreased the mean temperature in the gaps with 0.5°C under the Natural 600 g quilt. The opposite effect was observed with the Natural 1100 g quilt where the temperature increased with 0.5°C. These results are unexpected since the mean body heat loss with these quilts at the conditions '20°C 50%' and '20°C 70%' were the same or slightly higher at the higher relative humidity. The change in the room RH did not affect the other two studied quilts at 20°C.

The mean surface temperature of the mattress (shown in Table 4) under all studied quilts was in the range of 30.6 – 32.6°C and 31.3 – 33.4°C during both conditions at air temperatures of 15°C and 20°C, respectively. The increase of the RH to 70% at 15°C decreased the temperature with 0.6°C under the Natural 600 g quilt, with 0.8°C under the Synthetic quilt and with 0.4°C under the Non-uniform quilt. The high RH did not affect the mean temperature around the manikin with the Natural 1100 g quilt. The increase of the RH to 70% at 20°C affected the surface temperature of the mattress only with the Non-uniform quilt. The surface temperature of the mattress under this quilt decreased with 0.7°C. These results can be due to the fact that when the moisture content in the air increases, the thermal conductivity of the air decreases and thus the heat transfer between the mattress and the room environment decreased.

The present study shows that there is a difference between the mean surfaces temperatures of the quilts and the mattress as well as the mean temperature measured in the gaps around the manikin. Liu et al. [10] based on results from experiments with people reported that a

satisfactory and comfortable thermal condition during sleep could be reached when the mean bed climate temperature (MBT) was in the range of 30.2°C - 31.0°C while the room operative temperature was 15.8°C or 18.3°C. In the study, the MBT was calculated based on the average temperature measured at the inner surface of the quilt above the chest and waist and at the surface of the mattress below the back. In the current study the mean temperatures corresponding to the comfortable MBT range in [10] was measured at the inner surface temperature of the quilts and at the mattress. However, the mean air temperature measured in the gaps around the manikin was higher than 31°C during all room conditions with the quilts with down filling. At 20°C room air temperature with the Natural 1100 g quilt this temperature reached up to 34.2°C. These high temperature in the bed microenvironment may cause thermal discomfort. However, in the study by Liu et al. [10] the human subjects were dressed with a pajamas. In the current study the manikin was naked. Bivolarova et al [8] showed that at 20°C room air temperature, subjects' whole body thermal sensation was clearly acceptable when they were covered with the used in the current study Natural 600 g quilt and Natural 1100 g quilt. As already mentioned, the subjects in this study were dressed with only underwear. The current study shows the dependency of the mean body and segmental dry heat loss on such factors as room air temperature and relative humidity as well as quilts' different characteristics. However, the practical implication of this study should be verified with human subject experiments.

**Table 2.** Mean inner surface temperature of the quilts under all room conditions

Room condition:	15°C, 55 %	15°C, 70 %	20°C, 50 %	20°C, 70 %
Quilt type	Mean inner surface temperature of the quilts, °C			
Synthetic 1100 g	28.4	27.2	30.0	30.0
Natural 600 g	29.9	29.7	30.8	30.6
Natural 1100 g	30.4	30.9	31.8	31.3
Non-uniform 810 g	29.2	29.1	30.2	30.3

**Table 3.** Mean air temperature in the gaps around the manikin under all room conditions

Room condition:	15°C, 55 %	15°C, 70 %	20°C, 50 %	20°C, 70 %
Quilt type	Mean air temperature around the manikin, °C			
Synthetic 1100 g	29.6	30.2	32.2	32.3
Natural 600 g	32.6	32.5	33.1	33.6
Natural 1100 g	32.9	33.0	34.2	33.7
Non-uniform 810 g	33	33.1	33.3	33.3

**Table 4.** Mean surface temperature of the mattress under all room conditions

Room condition:	15°C, 55 %	15°C, 70 %	20°C, 50 %	20°C, 70 %
Quilt type	Mean surface temperature of the mattress, °C			
Synthetic 1100 g	32.6	31.8	33.1	33.4
Natural 600 g	31.4	30.8	32.2	32.4
Natural 1100 g	31.3	31.4	32.3	32.5
Non-uniform 810 g	31	30.6	32	31.3

## 4 Conclusion

The effects of four quilts with different thermal characteristics on the mean body dry heat loss and the segmental heat loss was investigated by experiments with thermal manikin. The study has identified that for quilts with the same weight at low room velocity, dry heat loss with synthetic quilt is higher than natural quilt regardless the room temperature and humidity. This applies for the mean heat loss of the body as well as the local heat loss from body segments, including chest and feet. In addition, a quilt with 1100 g polyester fibre (synthetic quilt) provides less thermal insulation than a quilt with 600 g down. The results also show that increasing the weight of the quilt twice has not proportional impact on its thermal insulation. Another finding is that quilts' cassettes construction is important for the overall thermal insulation. Further work is required to establish the viability of this implication. At all studied conditions there was small difference between the mean body dry heat loss with the natural quilts of 600 g and 1100 g. The studied non-uniformity in down distribution of quilt provides similar thermal insulation on the segmental dry heat loss of feet and chest. Quilts with uniform filling distribution provides non-equal local heat losses. In practice this might cause overheating or overcooling of different body segments and thus might cause discomfort. The most obvious finding to emerge from this study is that an increase of the relative humidity to 70 % in the room may decrease the thermal insulation of quilts with down and polyester fibre. This effect is clearer at room air temperature of 15°C than at 20°C.

The results from the current study show that the temperature of the bed micro-environment depends on the quilts' thermal insulation as well as the room air temperature and relative humidity. No substantial differences were found in the mean temperatures in the bed microenvironment under the Natural quilt of 600 g and the Non-uniform quilt. The Natural 1100 g quilt provided about 1°C higher mean temperatures in the bed climate compared to other two natural quilts. It was noticed that the mean temperatures in the bed with the

synthetic quilt to be 1 °C to 2 °C lower compared to the natural quilts.

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