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Effectiveness of Using a Thermal Sweating Manikin Coupled with a Thermoregulation Model to Predict Human Physiological Response to Different Firefighter Turnout Suits²

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Abstract

Manikins have been used for almost 100 years to help understand the properties of clothing materials and garments. Data from sweating manikins also have been used within thermoregulation computer models to estimate the physiological responses of humans. In recent years, the development of the ManikinPC system has incorporated a thermoregulation model into a thermal sweating manikin system to provide a real-time analysis of predicted physiological response. This paper describes an experimental study that demonstrates the utility of this manikin–model system to predict the effects of three composite materials used in firefighter suits on human physiological response. This study addresses this question: Can ManikinPC emulate the physiological response of a controlled wear trial using three different sets of firefighter turnout gear in one environmental condition? The average core temperature, skin temperature, and sweat loss from human subjects are compared with the predicted values generated from the manikin coupled with the model. Results indicate similar trends and ranking of the three suits. The data revealed slightly higher predictive responses from the manikin–model system compared with the collected human data.

Keywords

protective clothing; firefighters; heat strain; total heat loss; thermal manikins; evaporative resistance

Introduction

Thermal manikins were invented to help scientists understand how clothing alters the heat transfer occurring between the body and environment. The first manikins were built in the late 1930s and early 1940s. These systems were simplistic in design and measured insulation only from the manikin as a whole.¹ With improvements over time, manikins have become more sophisticated and now include sweating systems to allow the measurement of evaporative resistance of clothing as well as insulation. Manikins now are commercially available that have integrated movable joints to measure clothing properties in different

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positions as well as in motion. They also are becoming more segmented to provide more detailed data on clothing ensembles to help scientists understand how clothing properties vary in different areas of the body.

To understand how clothing properties measured on a manikin relate to human performance, various thermoregulation models have been developed over the years. As with manikin technology development, the sophistication of these models has continued to improve. What started as single-node, single-segment models in the early 1970s² has evolved into a variety of different models.³⁻⁷ These models have various segments for the body and nodes that account for the properties of skin, fat, muscle, blood, and bone. Today, these models can even account for blood flow, shivering, sweating, vasoconstriction, and vasodilatation to give a reasonable estimate of how humans may physiologically respond when wearing different types of clothing in various environmental and working conditions.

Thermoregulation models have allowed researchers to understand how individuals may perform with heavy environmental stressors without endangering actual human subjects. Results, however, from models are only as good as the inputs they are provided. One challenge that exists is to model the properties of (protective) clothing under realistic changing conditions of the environment or the thermal physiology. Clothing properties from a manikin are measured in a steady-state environment and cannot account for transient conditions or changing properties.^{8,9} One way researchers have tried to improve this is by coupling thermoregulation models with a manikins to provide real-time boundary conditions for the model to provide better predictions.

Several manikins have been coupled with thermoregulation models with mixed results.¹⁰ One commercially available system has been produced by Thermetrics and Thermoanalytics. This system, known as ManikinPC, was initially validated quantitatively using data from the literature.¹¹ The literature conditions ranged from as low as 5.0°C up to 47.5°C; however, the data sets only included human subjects wearing limited clothing. Nevertheless, the authors concluded that the agreement between the data set and the manikin-model ranged from reasonable to excellent.

Another study looking how the ManikinPC predictions compared with human data in dynamic working conditions, while wearing firefighter personal protective equipment, demonstrated the usefulness of the system.¹² Results showed excellent reproducibility and excellent agreement among skin temperature data. Core temperature values, however, were significantly different. This difference was attributed to the fact that the model at that time predicted only the hypothalamus temperature, whereas the human study measured intestinal or rectal temperature.

These previous ManikinPC studies were carried out using version 9.2 and 10 of the ThermoAnalytics regulation model^{12,13} and were all carried out in collaboration with the manufacturers. Current versions of the software have a better control of sweat rates and now can estimate rectal core body temperature to allow for easier comparison with human data. This study examined how a newer version of the model coupled with the manikin compared with a physiological wear trial of 10 subjects wearing three different firefighter suits. These

suits were identical in design but contained different material composites that yielded some significant differences in human response.¹⁴ This study provided an independent assessment of whether the ManikinPC model predictions and human data were within the standard deviation of each other and whether the trends and statistical differences among suits were similar.

Method and Materials

In this study, a 10-subject human physiological protocol¹⁴ was replicated comparing three different sets of turnout gear with ManikinPC. The paper by DenHartog, Fang, and Deaton details the subjects' parameters, along with the methods of measurement for core temperature, heart rate, and skin temperature.¹⁴ One set of each of the firefighter suits (X, Y, and Z) was acquired from the human study. The suits were identical in design and size (pants size 34 and coat size 44) and all suits used the same outer shells but contained different moisture barriers or moisture barrier–thermal liner systems. The differences in moisture barriers or moisture barrier–thermal liner systems yielded similar total heat loss (THL) results but different evaporative resistance results (Ret) as measured according to a sweating guarded hot plate (table 1).^{14,15} These different materials did not result in large variations in ensemble weight (X = 7.1 kg, Y = 6.8 kg, and Z = 6.7 kg). The goal of this study was to determine how the predicted physiological responses from the manikin plus model compared with the human data wearing the suits.

The ManikinPC system is composed of a 34-zone Newton manikin (Thermotronics) coupled with TAItherm v.12.1.1 (ThermoAnalytics). The manikin is articulated to allow for standing and sitting positions. The manikin system also included an external walking stand that allowed for a simulated walking motion. The TAItherm model, based on the Fiala thermoregulation model,^{3,4} collects information from the environment and the manikin surface and uses metabolic inputs from the user to predict the physiological response (e.g., core and skin temperature, sweating, respiration) for an average 80-kg male. An explanation of how TAItherm works with the manikin is available in the paper by Burke, Curran, and Hepokoski.¹⁶

Before replicating the protocol,¹⁴ a set of starting temperatures (skin and core) was determined for ManikinPC. In the human study, subject were allowed to acclimatize in a small room (~23°C, 50% RH), while wearing only a t-shirt, underwear, shorts, and socks for 1 hr before entering the chamber. To provide realistic and consistent starting skin and core temperatures, the manikin was placed in the same room at ~23°C and 50% RH and dressed in the same type of t-shirt, underwear, shorts, and socks while being controlled by the model. Once stable temperatures were achieved, the skin temperature for each body section and estimated core body temperature was recorded so it could be used as the starting point for testing suits X, Y, and Z.

All elements of the ensemble (excluding the helmet) were conditioned in a 21°C, 65% RH environment for at least 24 hr before testing on the manikin. Following conditioning, the manikin was dressed in the same base ensemble (socks, underwear, t-shirt, and shorts) as in the human study. Following the base layer, the manikin was dressed in one of the

three turnout suits (X, Y, or Z) along with fire-fighting gloves, helmet, and tennis shoes. The bottom of the pants were taped up as in the human study to simulate the pant-to-boot interface. The dressed manikin was placed in a wheelchair and set to the starting temperature noted previously. Once the temperature for all the manikin's sections was determined to be within 0.2° C of the desired set point, the manikin was allowed to condition for an additional 10 min to ensure a stable starting temperature.

Once the manikin completed its stability check, the thermoregulation model was started and the manikin was moved into the chamber and placed in the same area as the subjects had sat for their initial rest period. The protocol in table 2 was followed throughout the remainder of the test for each suit. The work rates needed for the model were determined by calculating the average metabolic equivalent of the task rate (the Met rate) of the 10 human subjects using the Pandolf equation.¹⁷ These calculations yielded 4.1 Mets in the first walking period and 2.5 Mets in the second walking period. The double steps per minute (DSPM) setting on the walking stand was fixed to mimic a 3.3 and 2.2 mph walking speed.

All testing was conducted in an environmental test chamber set to 40°C, 20% RH. All three suits were tested three times to account for variation in dressing, taping, placement of the manikin, movement of the manikin, and natural chamber variations. The predicted mean skin temperature, core body temperature, and the sweat rates from ManikinPC were compared with the human data set to determine whether the predictions fell within the standard deviation of each other and whether the trends and statistical relevance were similar. In addition, the cardiac output (CO) prediction from ManikinPC was compared with the human heart rate data for trends and statistical differences. Considering that the manikin should be less variable than human data, statistical comparison between suits were made with a 99% confidence interval.

Results

MEAN SKIN TEMPERATURE

Figures 1 through 3 plot data for the average human mean skin temperature and the average manikin temperature for all three suits (X, Y, and Z). For the most part, the averaged data from both sets of data fell within the standard of one another. All of the manikin results, however, had areas of the temperature profile that fell outside the standard deviation of the human data with most of it falling between 15 and 30 min. Suit Y also yielded another small section falling outside the standard deviation at the start of the second work cycle (~55 to 60 min). Toward the end of the protocol, the suit Z manikin results fell outside the human data set. This, however, was attributed to the fact that after the 64-min mark, subjects were being pulled while wearing this suit and the population changed. In general, all mean skin temperature data obtained from manikin tended to heat up more slowly but ended up with higher overall mean skin temperature predictions than the human data.

Figures 4A and 4B highlight the changes in mean skin temperature for the human data set and the predicted manikin data. Temperature change often is used to compare differences between physiological results because of the differences in starting temperatures and temperature responses from human subjects.

Data indicate that the change in skin temperature response from the manikin was slightly higher than that of the human data set. At the 64-min mark, when all subjects were still present, there was an approximately 0.8°C difference between the skin temperature changes in human versus the manikin predictions. With the human data set, there was no statistical differences reported in mean skin temperature between any of the suits at this point in time.¹⁴ A statistical difference could be found, however, with the manikin prediction with suit Z and the other two suits at the 64-min mark (X vs. Z, $p < 0.0001$; and Y vs. Z, $p = 0.0003$) when all subjects were in the study. It is unknown whether any mean skin temperature difference would have been observed with suit Z in the human data at the end of the protocol if all subjects had been able to finish the protocol. Nevertheless, at the end of both the human and manikin test (95 min) no statistical difference was observed between X and Y, but in the manikin test, the statistical difference remained the same between Z and the other two suits (X vs. Z, $p < 0.0001$; and Y vs. Z, $p = 0.0004$).

CORE TEMPERATURE

When determining how much heat the body is storing, the core body temperature is often the best indicator. Figures 5 through 7 plot the average human data core temperature response along with the predicted response of the manikin. From the data, all the manikin core body temperature predictions fall within the human standard deviation for suit X and Y. This was also true for the subjects wearing suit Z up to the point at which most of the subjects were pulled from the experiment while wearing suit Z.

As with the mean skin temperature when making statistical comparisons, the change in core body temperature often is used to account for the variations in starting temperatures and responses. Figure 8A and 8B detail the changes among the three suits between the human data set and the manikin data set.

The overall change in core temperature response indicates an approximately 0.3°C higher change in temperature with the manikin compared with the human data at the 64-min mark. This is also true at the 95-min mark for suits X and Y, but is not true for suit Z because subject were pulled early in the human evaluation. Nevertheless, the trends and the ranking of suits were the same. In addition, the paper by DenHartog, Fang, and Deaton¹⁴ indicated a statistical difference between suit Z and suit Y in absolute temperature right before the first subject was pulled; however, no difference is found between any suits when looking at changes in core temperature. Statistical analysis of the manikin data did show a significant difference between suit Z and the other two suits (X vs. Z, $p = 0.0004$; and Y vs. Z, $p = 0.0009$) at the 64-min mark and at the end of the test (X vs. Z, $p < 0.0001$ and Y vs. Z, $p = 0.0004$). No difference between suits X and Y were present between the manikin and human data set at the 64-min mark or at the end of the protocol.

SWEAT RATES

Figures 9 shows the average normalized sweat rate from the human data set and from the ManikinPC model. This average normalized sweat rate was used to allow us to compare each suit as equally as possible. To calculate the average normalized sweat rate, the total sweat loss was divided by the total time each subject remained in the study, in each suit (in

kilograms per hour [kg/hr]). Human data indicated a significant difference between suit Z and the other two suits. Suits X and Y, however, showed no differences.¹⁴

The manikin data indicate a higher sweat rate as compared with the human data. Considering the slightly higher core and mean skin temperature data from the manikin, this result should be expected. The difference between the human and ManikinPC sweat rates ranged from 0.16 to 0.23 kg/hr, but the standard deviation did overlap one another.

In terms of ranking, the manikin results predicted the same trends as found in the human study. When a statistical analysis was done, comparing the three sweat rates from the manikin results, a significant difference was found between suit Z and the other two suits (X vs. Z, $p < 0.0001$; and Y vs. Z, $p = 0.0004$). There was no significant difference, however, between suits X and Y. These same statistical results were found in the human study.¹⁴

HEART RATE AND CARDIAC OUTPUT

As stated previously, four subjects wearing garment Z were pulled from the human study because their heart rate approached their calculated maximum. Unfortunately, ManikinPC does not report values of heart rate, but it does predict and report CO. This value is the total amount of blood flowing from the heart in liters per minute (L/min) and is a function of heart rate (beats/min) and the stroke volume of the heart (liters). Because stroke volume is not a constant, it is not possible to convert CO to heart rate; however, clear correlations should be expected as heart rate and stroke volume changes generally coincide.

With this study, we were interested in finding out how these two parameters compared. To assess this, we simply plotted the average heart rate from the subjects and the CO from ManikinPC side by side in figure 10A and 10B. The profiles from both graphs look similar until the 64-min mark, at which point the first subject was pulled. Conducting a statistical analysis of the CO from ManikinPC indicates that there is a difference in suit Z compared with suits X and Y (X vs. Z, $p < 0.0001$; and Y vs. Z, $p = 0.0002$). No differences were found between suits X and Y. This was the same statistical results reported in the human study when conducting an analysis of heart rate among the different suits.

Discussion

This study sought to determine whether a manikin coupled with a thermoregulation model could emulate the physiological response of human subjects while wearing three different turnout suits in a work-rest cycle protocol. To understand whether the absolute mean skin and core temperature responses from ManikinPC were similar to human data both responses were plotted. For core temperature, all predicted responses fell within the human standard deviation when all 10 subjects were present. For mean skin temperature response, the manikin data fell within the human data standard deviation for most of the protocol. There was a small period of time (no more than 15 min) when the manikin predictions were lower than that of the human data set in the first walking cycle. In addition, there was a 2- to 3-min window in which the manikin response was higher than the standard deviations of the human data set for suit Y at the start of the second work-rest cycle. For sweat rates the manikin data fell within the standard deviations of values collected during the human trial.

When comparing the change in mean skin and core temperature of the manikin to the human data set, the manikin did overpredict the thermophysiological responses. The sweat rate also performed similarly with a slight overprediction. It is not exactly known why this occurred. The model may be based on the average population and there are uncontrollable variations between the complex human thermoregulation responses. In the human study, a small subset of a particular group of people (firefighters) was utilized. They are not the average population and more than likely acclimatized to this type of work and heat. Nevertheless, even with the slight overprediction, the manikin ranked materials the same as to what was observed while all 10 subject were in the study for each suit. The paper by DenHartog, Fang, and Deaton¹⁴ detailing the results indicated a significant difference between suit Z and the other two suits in regards to sweat rate but was unable to predict any significant differences in the change in mean skin or core temperature at the 64- or 95-min mark. The manikin, however, was able to predict the same statistical differences in sweat rate and found additional differences between the core and mean skin temperature between suit Z and the other two suits. Neither study indicated a difference between suit X and suit Y in core or mean skin temperature at the 64- or 95-min mark nor any statistical difference in sweat rate between suit X and suit Y.

The model prediction of CO trended similarly to the human heart rate data. A statically significant difference was found between suit Z and the other two suits at the 64-min mark in CO. In the human study, there was also a significant difference observed at this time for heart rate. Future studies should use a noninvasive measurements to get an estimation of stoke volume so that each subject's CO can be compared with the models to truly understand its benefit.

Conclusion

The Manikin PC system has been shown to be an effective tool at predicting the output of a human physiological study. Although slightly higher predictions in changes of mean skin–core temperature and sweat rate occurred, the manikin and model system had the same trends and rankings as compared with that of the human subject study and did not underestimate the significant difference found between the three garments. In fact, more differences were found because the manikin was less variable than human data. Although this system never would be a replacement for a true human physiological study, it has demonstrated that it certainly could be used to aid researchers in selecting garments and predicting human thermoregulation response without endangering actual human subjects.

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FIG. 1. Average mean skin temperature of human subject data compared with ManikinPC prediction while wearing suit X. Error bars indicate standard deviation.

FIG. 2. Average mean skin temperature of human subject data compared with ManikinPC prediction while wearing suit Y. Error bars indicate standard deviation.

FIG. 3.

Average mean skin temperature of human subject data compared with ManikinPC prediction while wearing suit Z. Error bars indicate standard deviation. Data after 64 min had less than 10 subjects, resulting in some shifts in the graph.

FIG. 4. The average change in temperature from (A) the human data set and (B) the ManikinPC. Data from the human data set for suit Z had less than 10 subjects after the 64-min mark, resulting in shifts in the graph.

FIG. 5. Average core temperature of human subject data compared with ManikinPC prediction while wearing suit X. Error bars indicate standard deviation.

FIG. 6.

Average core temperature of human subject data compared with ManikinPC prediction while wearing suit Y. Error bars indicate standard deviation.

FIG. 7.

Average core temperature of human subject data compared with ManikinPC prediction while wearing suit Z. Error bars indicate standard deviation. Data after 64 min had less than 10 subjects resulting in some shifts in the graph.

FIG. 8.

The average change in core temperature from (A) the human data set and (B) the ManikinPC. Data from the human data set for suit Z has less than 10 subjects after the 64-min mark, resulting in shifts in the graph.

FIG. 9.

Average sweat rate from human subject data compared with ManikinPC prediction while wearing suit Z. Error bars indicate standard deviation.

FIG. 10. The average heart rate from the (A) human data set and the CO predictions from (B) the ManikinPC. Data from the human data set for suit Z had less than 10 subjects after the 64-min mark, resulting in shifts in the graph.

TABLE 1

Composite material data as measured according to ASTM F1868, *Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate*, Parts B and C^{14,15}

ID Moisture Barrier-Thermal Liner System	Evaporative Resistance, Ret, Pa · m ² /W	Total Heat Loss, THL, W/m ²
X	26.2	226
Y	37.6	215
Z	66.5	220

TABLE 2

Testing protocol/Manikin manual inputs

Time Duration, min	Subject Activity	Description	Manikin Inputs
0–15	Seated	Seated rest	1.0 Met
15–40	Treadmill	3.3 mph, 1% Incline	4.1 Met, 47 DSPM
40–55	Seated	Seated rest, drink water	1.0 Met
55–80	Treadmill	2.2 mph, 1% Incline	2.5 Met, 30 DSPM
80–95	Seated	Seated rest, drink water	1.0 Met