Design and Evaluation of Sport Garments for Cold Conditions Using Human Thermoregulation Modeling Paradigm

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Abstract

Thermo physiological comfort is an important aspect of apparel especially when worn under challenging environmental conditions, and relevant performance attributes of garments become even more important in active sportswear. The wide spectrum of performance materials and their combinations that can be selected for garment engineering indicates that during the design and engineering process it is impossible to test all possible combinations of materials and garment constructions before the final prototype is developed. In the present study, a Thermal Manikin was used with a physiological model for testing the multi-layered garment ensembles suitable for stop-go sport in sub-zero conditions. It was demonstrated that physiological indicators output from the experiments depend on the ensembles worn and their performance attributes relevant to human physiological comfort. The use of the model along with the Thermal Manikin is a valuable method for sportswear design and engineering.

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1. Introduction

Thermo physiological comfort is an important aspect of apparel especially when worn under challenging environmental conditions, and relevant attributes of garments become even more important in active sportswear [1, 2]. Thermal comfort is often defined as 'that condition of mind which expresses satisfaction with the thermal environment' [3]. The degree to which garments modify the heat exchange between the wearer and the environment depends upon the amount of the body surface area covered by the clothing, the characteristics of the component materials and their assemblies, and the amount and distribution of air trapped between the garment and the body and within the assemblies [1,4]. Wearing of clothing layers will either impede or aid the process of thermoregulation. Thermo physiological function of sport garments for stop-go winter sport is complex considering that it has to address extreme conditions of high physiological activity of the athlete, and periods of rest during which protection from cold, and often sub-zero conditions is required. An example of stop-go winter sport activities is downhill skiing where periods of high activity (e.g. skiing down the ski run) are interspersed with periods of...
The wide spectrum of performance materials and their combinations that can be selected for garment engineering indicates that during the design and engineering process it is impossible to test all possible combinations of materials and garment constructions before the final prototype is developed.

When assessing the comfort of a garment there are five levels of testing or assessment which are used. Level 1 assessment involves the testing and assessment of individual material layers; Level 2 is the assessment of clothing ensembles on a life-sized thermal manikin which is designed to represent the thermoregulatory system of a human being. The next levels include limited wearer trials (<10) in a climatic chamber (Level 3) and wearer field trials with medium-scale (20<n<100) and large-scale (n>100) of human subjects (Levels 4 and 5) [5].

For comparison and assessment of different fabrics or their assemblies several tests for thermal and vapour resistance are available and are defined as standard methods [6]. This then offers an opportunity to reduce the number of potential garment prototypes to be made of the candidate materials that are expected to perform well in a garment to a manageable quantity.

The selected materials could be then made into garment prototypes that can be exposed firstly to the manikin testing and then, after further selection, to human wear-testing. The testing on a thermal manikin allows transforming testing of a material from a 2D dimension into the 3D dimension close to a human shape, which increases the complexity, time and cost of the testing compared to the material testing for a single garment ensemble, but also increasing the relevance to the actual human form.

Thermal manikins can never and should never completely replace human subject testing. However, the high cost plus inter- and intra- subject variation inherent in testing with humans dictates that a properly designed measurement tool can be an asset to product engineering and testing.

To bring the testing results even further to the realism of using human subjects, the dynamic physiological model in addition to the manikin could be used [1].

In the present study, a thermal manikin was used with a physiological model to create a dynamic system for testing the multi-layered garment ensembles suitable for stop-go sport in sub-zero conditions at -10 °C ±0.5 °C.

2. Experimental Details

2.1. Materials

A series of sports garments suitable for skiing were used to assemble two full ski ensembles. All main experimental garments, except accessories, were of the same single-fibre content and made to the same size Medium to fit the Thermal manikin Newton. Ensemble 1 consisted of base layer long sleeve top; base layer long john; middle layer long sleeve top, with ski pant and jacket, gloves, hat, socks and ski face mask.

For the Ski Ensemble 2 the Main garments were doubled, e.g. 2 x base layer long sleeve tops, 2 x base layer long johns, 2 x middle layer long sleeve tops, with all accessories remaining the same as for the Ski Ensemble 1.

2.2. Methods and equipment

Firstly, all the comprising textile materials were first tested in 2D form as individual layers for their physical and performance attributes relevant to the thermo-physiological performance [6-8] (thermo-physiological aspect of the study is not covered in this paper).
Furthermore, in the present study the thermal manikin was used with a physiological model which implements the Fiala thermoregulation model [9]. The manikin provided the boundary layer interface to the clothing and environment and generated metabolic heating levels as determined by the model. Manikin software is adapted from the RadTherm finite difference thermal analysis program (ThermoAnalytics, Inc). A test protocol was adapted from previously performed human trials with metabolic rates appropriate to modeled stop-go physical activity and covered step-change multiples of the resting metabolic rate (MET) from 2MET to 8MET during a warm up cycle and three stop-go cycles. 1MET is approximately equal to a person’s resting energy expenditure. During the series of tests the relative humidity was maintained at 75%±5; air temperature at -10 °C ±0.5 °C.

The model output data covered the following aspects of thermo-physiological comfort: sensation, global comfort, skin temperature (Tsk), core temperature (Thy), shivering and sweat production.

The sensation scale is similar to the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) 7-point scale, adding “very hot” and “very cold” to accommodate the extreme environments: 9-point scale: (4) “very hot”, (3) “hot”, (2)“warm”, (1) “slightly warm”, (0) “neutral”, (-1) “slightly cool”, (-2) “cool”, (-3) “cold”, (-4) “very cold”. The comfort scale ranges from “just comfortable” (0), to “comfortable” (2), to “very comfortable” (4), to “uncomfortable” (-2), to “very uncomfortable” (-4) [10].

The variance analysis was carried out with the test-to-test repeatability and demonstrated to be excellent. Same-operator variability was indiscernible, and operator-specific test execution resulted in a slight response variation over time. To remove short-time variations a moving average trend line was used where necessary (Fig. 1(b), Fig. 2). The evaluation of thermal comfort took into consideration three conditions for a person to be in whole-body thermal comfort [11]: the body is in heat balance, sweat rate is within comfort limits, and mean skin temperature is within comfort limits.

3. Results and Discussion

3.1. Core Temperature, Skin Temperature, Shivering and Sweating

Experimental results for core temperature, skin temperature, shivering and sweating are presented in Fig 1,2

![Fig. 1. (a) core temperature; (b) skin temperature](image-url)
Core temperature has no definition, as core tissues are not defined, however it is generally considered as inner body temperature or the temperature of the vital organs including the brain $Thy$. These core tissues are maintained within a narrow range of temperatures by thermoregulation [11,12]. It is clear from Fig 1(a) that the change in ski ensemble worn did not affect the $Thy$ of the wearer where the $Thy$ rose very slightly through the cyclic activity. This is understandable as the physiological thermal mechanisms of the human body are designed to keep the $Thy$ as stable as possible: in this case this is achieved through clothing worn, and sweating and shivering processes.

However the double-layer Ensemble 2 resulted in slightly higher $Tsk$ which is likely due to the higher thermal resistance of this ensemble. The $Tsk$ varies with external environment conditions, the thermoregulatory state of the body (vasodilation, sweating, etc.) and can, however vary from the mean. In this study mean $Tsk$ was calculated as a weighted average of the body of the manikin. It is worth noting that $Tsk$ steadily increases with the length of the activity and number of stop-go cycles involved (Fig. 1(b)), however it is fair to state that $Tsk$ in both cases are within comfortable range, apart from the initial period of about 16min of skiing to the chair lift and then sitting in the chair. From that point on, the $Tsk$ for both ensembles starts to steadily rise with some cyclical drops due to “stop” periods of inactivity. It is worth noting that the raises in $Tsk$ correspond with “go” periods of high activity, however each raise is somewhat delayed as the body adjusts to the new thermal conditions with increased metabolic heat being produced. However with every following cycle this lag becomes smaller due to body becoming quite warm and the presence of clothing.

Both $Thy$ and $Tsk$ affect the onset of shivering which can be both voluntary and involuntary. If the body temperature falls then the metabolic rate begins to increase, first due to an increase in muscle tone (causing stiffness) and then due to shivering. Shivering can vary from “mild” to “violent” and can greatly increase metabolic heat production with the purpose of keeping the core temperature stable.

It is clear from Fig 2(a) that the initial stage of the cycle where a skier is going up to the run in the chair lift, shivering occurs in order to maintain $Thy$ stability. However, as Fig 1(b) demonstrates during this initial phase, the skin temperature drops by approximately 12% and does not begin to recover until well into the first “go” cycle of high activity. This $Tsk$ drop results in a “very cold” sensation as well as comfort being at “very uncomfortable” to “uncomfortable” through this segment of activity (Fig. 3).

Fig 2(a) also shows that the level of shivering is higher for Ensemble 1 in the first cycle and the shivering returns for a short period during the first “stop” cycle. This is likely due to the lower thermal and vapour resistance of the single-layer Ensemble 1.
When the body temperature rises, sweat is secreted over the body to allow cooling by evaporation. As seen in Fig. 2(b) sweating occurs towards the end of the first “go” cycle of high activity at approximately the point where $Tsk$ starts to raise as well as a result of high metabolic output. During acclimatization, (e.g. due to repeated exposure to heat stress over a number of “go” cycles) the sweat rate production is greatly increased.

Fig 2(b) demonstrates that whilst sweating processes lag well behind the commencement of the initial “go” cycle- perhaps termed the “warm up cycle” - sweating rate increases tend to be aligned with subsequent “go” cycles. Further, overall sweating rates show a sharper gradient rise as more high-activity “go” cycles are completed. In addition, Ensemble 2 results in higher sweating rates than the single layer Ensemble 1, with these differences further increasing as high-activity “go” cycles are repeated. This is likely due to higher thermal and vapour resistance of Ensemble 2. Heat balance where heat generated by the body is transferred through the skin and then through clothing to the environment is a necessary but not a sufficient condition for comfort. The body can be in heat balance but uncomfortable due to sweating or uncomfortably cold due to vasoconstriction and low $Tsk$. Comfort and sensation are also a function of mean $Tsk$. In a warm environment with presence of sweat an increase in $Tsk$ will trigger quite substantial increase in sensation [12].

![Diagram of sensation and MET](image1)

![Diagram of comfort and MET](image2)

Fig. 3. (a) sensation; (b) global comfort

The data for Ensemble 1 in Fig 3(a) shows sensation levels that raise and lower significantly from -4 to +4 indicating “very cold” to “very hot” sensations during test cycles. These appear to have a relationship with sweating rate increases with the “go” cycles, as $Thy$ levels remain stable and $Tsk$ levels fluctuate within comfortable limits. However, it is interesting to note that during the first “go” cycle and latter stages of the mid “stop” cycle, levels fluctuate between -1 and -4 indicating a “slightly cool” to “very cold” sensation. This may indicate that feelings of wetness on the skin and the relatively low thermal and vapour resistance levels due to the single layer ensemble create a greater feeling of “coolness” when the skier undertakes a stop-go regime of activities in sub-zero temperatures. The data for Ensemble 2 in Fig 3(a) shows similar upper and lower sensation levels to Ensemble 1 from -4 to +4 indicating “very cold” to “very hot” sensations during test cycles. However, it is interesting to note that from the completion of the first “go” cycle sensation levels trend upwards from “slightly warm” to “very hot”, with Ensemble 2 cycles not dropping into feelings of “coolness”. This appears to indicate that the process of physiological thermal regulation in combination with a double layer clothing ensemble is effective in controlling wide fluctuations in feeling cold and hot as $Thy$ remains stable and $Tsk$ remains within comfortable limits.
The data in Fig 3(b) shows low global comfort levels during “go” cycles with comfort levels hovering between -2 “uncomfortable” and -4 “very uncomfortable” levels. Further, these low levels of comfort have a sequence closely aligned to the “go” cycles of the test. This sequence of low levels appear to have a strong relationship with sweating rate increases with the “go” cycles, as core temperature levels remain stable and $T_{sk}$ levels fluctuate within comfortable limits. This may indicate that feelings of wetness on the skin have a plausible link with low global comfort levels. Whilst there is some difference in comfort levels between Ensemble 1 and Ensemble 2 they are not significant, which may indicate that when next to skin clothing becomes saturated with increase in sweating rates, additional layers of clothing do not create any great differences in wearer feelings of comfort. It is interesting to note that the process of physiological thermal regulation (in this case sweating) in combination with clothing, is effective as $Thy$ remains stable and $T_{sk}$ remains within comfortable limits.

4. Conclusion and Recommendations

A series of sports garments suitable for skiing were used to assemble two full ski ensembles that were used to dress the Thermal Manikin for two series of tests. It was demonstrated that physiological indicators output from the experiments depend on the ensembles worn and their performance attributes relevant to human physiological comfort.

The use of the physiological model which implements the Fiala thermoregulation model [9] along with the Thermal Manikin is a valuable rapid prototyping method for sportswear design and engineering.

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