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Human Thermal Comfort Model and Manikin

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ABSTRACT

Current vehicle climate control systems are dramatically overpowered because they are designed to condition the cabin air mass in a specified period of time. A more effective and energy efficient objective is to directly achieve thermal comfort of the passengers. NREL is developing numerical and experimental tools to predict human thermal comfort in non-uniform transient thermal environments. These tools include a finite element model of human thermal physiology, a psychological model that predicts both local and global thermal comfort, and a high spatial resolution sweating thermal manikin for testing in actual vehicles.

INTRODUCTION

Current vehicle climate control systems are dramatically overpowered because they are designed to condition the entire cabin air mass from an extreme condition to a comfortable temperature in a specified period of time. Typical vehicle air conditioning systems require 4,000 Watts of mechanical power, whereas the human body only dissipates roughly 100 Watts. The real objective and one that is much more efficient is to ensure the thermal comfort of the passengers. The key to obtaining this objective is to understand human thermoregulation and perception of thermal comfort, and to develop predictive models of these processes. The objective of the work in this project is to develop computational and experimental models of human thermo-physiology and perception of thermal comfort. Specifically, NREL is developing a numerical model of human thermal physiology and psychology, and a thermal manikin that can be placed in actual vehicles, all of which will respond to the transient and extremely non-uniform thermal environments inside vehicle cabins. Industry can then use these tools to develop climate control systems that achieve optimal occupant thermal comfort but at minimum power consumption.

The computational tool under development is a Human Thermal Comfort Model. The purpose of this model is to predict the physiological and psychological response of a human to a transient non-uniform thermal environment. The physiological model is a finite element model of the human thermal physiological systems and thermoregulatory systems. It is based on a prototype model from Kansas State University and is currently being upgraded and improved. The output from the physiological model will be the static and dynamic temperatures of the skin and internal tissues with a spatial resolution of a few centimeters. A psychological model will then convert the distribution of static and dynamic temperatures into local and global perceptions of thermal comfort. The human thermal comfort model can then be coupled to models of external environmental conditions to evaluate the performance of climate control systems.

The experimental tool under development is an Advanced Thermal Manikin. The Thermal Manikin is also being engineered to respond to a transient non-uniform thermal environment in the same manner as a human. The manikin will generate similar thermoregulatory responses and perception of thermal comfort as humans. The reason for building a manikin is that it can experimentally validate the external heat transfer that occurs on a real three-dimensional body. The manikin will sense the local sweat evaporation, convection, and radiation processes that might not be correctly numerically modeled. The manikin will possess a more accurate human geometry and can be placed in an actual automobile geometry that a numerical simulation might not fully capture. The manikin can also be clothed so that an accurate simulation of a clothed human involving sweat transport and other clothing effects can be obtained. The thermal manikin could also be used to study human interaction in many other environments, such as buildings, aircraft, and spacecraft.

MAIN SECTION

The Thermal Comfort Project at NREL is organized into the development of three predictive tools. These include a physiological model of the human thermal system, a psychological model of human thermal comfort, and a thermal comfort manikin for real vehicle testing.

HUMAN THERMAL PHYSIOLOGICAL MODEL

Many models of the human thermal physiological system have been developed (Wissler 1964&1985, Gagge 1970, Gordon 1974, Fiala 1999). These models are generally characterized as multi-node models in which the human thermal system has been simplified into a series of nodes that represent segments of the body. The heat transfer processes in these models are either 1-D or quasi 2-D. They typically possess a very crude model of the circulatory system, which is responsible for roughly 85% of human internal heat transfer. There is also no true geometry of the human body due to the nodal nature of these models. A finite element model of the human thermal system was developed at Kansas State University in 1990 and improved in 1995 (Takemori 1995, Shoji 1997). NREL has chosen to upgrade and improve the KSU finite element model for the NREL Human Thermal Comfort Model. A finite element model will allow a much more precise simulation of the detailed interface between the human body and complex geometry of the seats and vehicle cabin. A finite element framework can possess a high degree of spatial resolution, which will be required to model the highly asymmetric thermal field in a vehicle consisting of solar rays and air jets. The finite element representation will also allow a more accurate model of the human circulatory system and geometry of the human body.

The NREL Human Thermal Model is a three-dimensional transient finite element model, which contains a detailed simulation of human internal thermal physiological systems and thermoregulatory responses. The model consists of two kinds of interactive systems: a human-tissue system and a thermoregulatory system. The thermoregulatory system controls physiological responses, such as vasomotor control, sweating, and shivering. The human-tissue system is a representation of the human body, which includes the physiological and thermal properties of the tissues. The model is being developed using the commercially available finite element heat transfer software ANSYS. This software has the ability to simultaneously solve conduction and convection heat transfer, which makes it ideally suited to simulate human heat transfer. ANSYS is also used by most of the large companies involved in the development of vehicles. The human limb body shapes are shown in Figure 1. The shapes were developed using circular functions, which are fully parametric and are easily scalable for different body sizes. Within each body segment there are layers for brain, bone, abdomen, muscle, fat, and skin tissues. Figures 2 and 3 show cross-sectional cutouts of the tissues in the leg. Figure 4 displays three-dimensional representations of the tissues. Figure 5 displays the torso shape and associated tissues. The finite element mesh and physiological systems are scalable across the human population distribution factors of height, weight, and fat content. The model can then simulate the response of an individual person or the response of a population distribution.

The vascular network in the body consists of the heart and artery system for macro-circulation and a capillary system for microcirculation. The macro-circulation system is used to distribute nutrients and oxygen within the body. The blood flow-rate in the macro-circulation system is essentially constant and does not change with variations in the external temperature field. The macro-circulation system is modeled as a right-angled network of pipes. Figure 6 shows the pipe network for the leg. The microcirculation system is used to modulate the local blood flow in response to changes in thermal conditions. Blood flow then conveys heat from the core to the shell layers within each cylinder and between cylinders. A finite element mesh of nodes is distributed within each layer and body segment, and heat transfer equations modeling conduction and convection from the blood are solved at those locations. A respiratory tract is also present in the head, neck, and torso to account for latent and sensible heat loss due to respiration. Integrating the distribution of warm and cold receptors throughout the body controls the thermoregulatory response system. The thermoregulatory response rates are determined by correlations from medical experiments. The response rate correlations are a function of the core temperature, mean skin temperature, and local skin temperature. The thermoregulatory responses that are activated include sweating, shivering, vasomotor constriction and dilation, and variable metabolic or cardiac rates.

The NREL Human Thermal Model also contains a detailed clothing model. Clothing forms a microclimate within the clothing, which is characterized by temperature, humidity, and airflow in the air gap between the skin surface and fabric layer. The microclimate in the clothing is affected by the sweating rate, skin temperature distribution, fabric transport of heat and moisture, fabric material, and clothing design. Clothing is modeled by several cylindrical clothing layers covering each body part. Each clothing element is divided into thin rectangular elements along the skin surface. Heat transfer, moisture adsorption, and transfer equations are then solved between clothing nodes. An extensive library of clothing thermal and moisture transfer properties is present in the model.

The model is currently being refined and validated against human subject tests. The input/output GUI's are being developed and network interfaces created. The model will be available for public use by the end of 2002.

PSYCHOLOGICAL THERMAL COMFORT MODEL

Many models of the human thermoregulatory system have been developed over the years (Wissler 1964; Gagge, Stolwijk et al. 1970; Gordon 1974; Wissler 1985; Wang 1994; Fu 1995; Takemori, Nakajima et al. 1995; Fiala and Stohrer 1999; Smith 1991). These models address the complex human response to the environment at varying levels of detail to predict physiological responses including skin temperature, core temperature, metabolic heat production, sweating, shivering, vasodilation and vasoconstriction. In addition to the physiological response, some of these models predict psychological response using statistical models to match subjective responses obtained from human subject tests.

The vast majority of human subject tests have been done under steady state conditions in thermally uniform environments (e.g. Nevins, Rohles et al. 1966; McNall, Jaax et al. 1967; Fanger 1970; Rohles and Wallis 1979). Far fewer tests have been done in transient uniform conditions (e.g. Gagge, Stolwijk et al. 1967; Gagge, Stolwijk et al. 1969; Griffiths and McIntyre 1974) and even less have been done under steady-state conditions in non-uniform thermal environments (e.g. Wyon, Larsson et al. 1989; Bohm, Browen et al. 1990; Wahl 1995). Taniguchi has done a limited amount of work investigating the effects of cold air on facial skin temperature during transient conditions in an automobile (Taniguchi, Aoki et al. 1992), but no other body areas were considered.

The two most common thermal sensation models are Fanger's PMV (Fanger 1970) model and Gagge's ET* (Fanger 1970; Gagge, Stolwijk et al. 1970). Both of these models are based on uniform, steady-state test data and although they work quite well under those conditions, they have severe limitations under transient and spatially non-uniform conditions.

Wyon, Bohm, and others used Equivalent Homogenous Temperature (EHT) to characterize non-uniform environments. A thermal manikin was used to assess the physical environment and subjective responses of occupants riding in vehicles were obtained to develop an EHT "piste" of the upper and lower comfort bounds for each body segment. The current EHT piste is based on a relatively small amount of data, is limited to the clothing and metabolic conditions tested, and applies only to steady-state conditions.

There are a few other models for non-uniform conditions. Matsunaga proposed a simplified Average Equivalent Temperature (AET) as a basis for predicting PMV (Matsunaga, Sudo et al. 1993). AET is a surface area-weighted average for three regions of the body: head (10%), abdomen (70%), and feet (20%). Hagino developed a model specific to a limited set of test conditions in an automobile where six male subject were exposed to solar radiation on the arm and cold air jets to the face. This model used a weighted average of local comfort from the head, upper arm, thigh, and foot to predict overall thermal sensation (Hagino and Hara 1992).

Wang and Fiala proposed models for transients in spatially uniform conditions (Wang 1994; Fiala 1998). Wang's model uses a static term from Fanger's model and a transient term based on the rate of heat storage in the skin. Fiala's model uses skin temperature, skin temperature rate of change, and core temperature in a regression based on human subject data from the literature and from physiological model results. Recent work by Frank has shown that skin temperature and core temperature have equal weighting for predicting thermal sensation (as opposed to thermal regulation) in uniform conditions (Frank, Raja et al. 1999).

No model exists that can predict thermal sensation in non-uniform, transient conditions. The purpose of this project is to develop such a model.

Approach

We are performing human subject tests under a range of both steady state and transient thermal conditions to explore the relationship between local thermal conditions and perception of local and overall thermal comfort. The tests include collection of core and local skin temperatures as well as subjective thermal perception data obtained via a simple form. This data will then be used to develop a predictive model of thermal perception.

Development of a local skin segment heating and cooling system

Most experiments exploring non-uniform conditions have used horizontal or vertical thermal gradients without detailed segment specificity. Our approach is to carefully control the skin temperature of individual body segments by providing local heating or cooling as needed. It is necessary to be able to impose the same calibrated degree of asymmetry on many different subjects without restricting them too much. The local effects of air jets from diffusers and cold or hot panels close to the subject would be greatly altered by small postural changes and by body size, and therefore are not likely to provide the degree of control we desire.

The technique that we have chosen to control the skin temperature of the body segments is to use temperature controlled air sleeves. We have fabricated different air sleeves for each of the body segments, as shown in Figures 7 and 8. Our Controlled Environment Chamber has the capability to produce a secondary air flow (independent of the chamber temperature) at any temperature from 5°C to 50°C. This air is connected to the segment sleeve where the final delivered air temperature is controlled by an electric resistance reheat element. An inner soft fabric element prevents the subject from feeling the air flow against the skin, which could otherwise effect thermal sensation

<u>Human Subject Thermal Comfort Tests under Transient and Asymmetrical Conditions</u>

Experiment Set Up

The human subject testing is being carried out in the Controlled Environmental Chamber at UC Berkeley. The subject first stays in a temperature-controlled water bath for 10 minutes. The water bath decreases the time needed for the body to reach a stable initial condition. After drying, the subject puts on a special leotard, which has velcro sewed on to divide the body surface into multiple segments. A harness of skin surface temperature sensors is deployed under the leotard. In each test, we connect an air bag to an individual segment of the leotard and supply controlled temperature air through the air bag to provide local heating/cooling (Figure 9). The human subject votes his thermal sensation/comfort every minute. After 10 – 20 minutes, the local heating/cooling is removed. The same procedure is then repeated for different segments.

The skin temperature measurement harness has 28 very thin thermocouples to measure the skin temperatures at standardized locations on the body. Each thermocouple is soldered onto a small 8 mm copper disk. The thermocouples allow very fast response during temperature transients.

We use the ASHRAE 7-point thermal sensation scale. We also obtain thermal comfort votes at the same time (Figure 10), since people could feel 'warm' but also 'very comfortable' if the previous thermal sensation had been cold. The thermal sensation and comfort questionnaires are asked for both the local body and the whole body.

Preliminary Results

Figure 11 – 14 show a few examples of the local skin temperatures vs. whole body/local thermal sensation and thermal comfort votes. The main findings are described here.

(1). The local cooling of the back and chest has a strong influence on the whole body thermal sensation and comfort. In Figure 11 & 13 we can see that the overall thermal sensation and comfort votes are greatly dominated by the local cooling of these two segments.

(2). In contrast to chest and back cooling, the cooling of the leg and foot does not affect the whole body thermal sensation as much (Figure 12 & 14). An interesting thing can be seen after 5 – 8 minutes of leg and foot cooling. While the local thermal sensation and comfort continuously lowered (feel cooler), the whole body thermal sensation and comfort started to go up. This may indicate two things. One is that vasoconstriction in extremities is effective to keep body from continuously feeling cold. The second is that the cooling of leg and foot does not have that big impact on the whole body as the chest and back cooling.

(3). After the unpleasant local cooling was removed from chest, back, and leg, the whole body and local thermal sensation and comfort demonstrate overshooting characteristics Figure 11, 13 & 14). This may be related with the known overshooting behavior of thermal receptors.

(4). The figure temperature shows a fast falling during back cooling (Figure 11).

These are only preliminary results. After many tests, the measured skin and core results will be used to develop the model predicting whole body (and local) thermal sensation and comfort based on the skin and core temperatures, and the temperature change rates.

<u>Thermal sensation model development</u>

Once the subjective data is collected, we will develop a predictive model of thermal sensation. Current theory suggests that the model should be based on four variables:

T_{skin}	skin temperature
dT_{skin}/dt	
T_{core}	core temperature
dT_{core}/dt	

One likely direction for this model will be to simulate the firing of hot and cold thermal receptors based on temperature. Hensel (Hensel 1981; Hensel 1982) and others have mapped the distribution of thermal receptors in the body. de Dear has shown the differential response of hot and cold receptors in human subject tests and has proposed a skin model with cold receptors located more superficially than hot receptors (de Dear and Ring 1990). We may explore using de Dear's model to predict receptor temperature based on core and skin temperatures. We will compare the local segment weighting obtained from our human subject tests to the most recent data on thermal receptor distribution to determine whether there is a one-to-one mapping of sensor density to the psychological weighting factors.

Our model will allow individual differences in physiology to impact thermal sensation to the extent to which those differences affect skin and core temperatures. de Dear and others have suggested that physiological adaptation and psychological expectation also play a role in thermal sensation (de Dear and Brager 1998). Stevens has shown that thermal sensitivity changes with age (Stevens 1998). We will develop a bibliography of research that addresses such issues and incorporate them in the model as appropriate.

THERMAL COMFORT MANIKIN

Thermal manikins are currently available but they are used primarily for measuring the thermal insulation value of clothing. A few thermal manikins have been developed for thermal comfort research but they have very limited capabilities (Wyon 1989, Nilsson 1999, Meinander 1999, Madsen 1999). They utilize the same basic concept in that the heating power required to keep the manikin surface at a constant temperature is measured and used to correlate with thermal comfort. The problem with this approach is that the manikin does not respond to the environment like the human body. A human unconsciously varies the local skin temperature and local rate of heat transfer to control the physiological response, which couples to the sensory input system to affect the perception of thermal comfort. Most current manikins are primarily designed for steady state operation and possess long thermal response times. They also suffer from limited spatial resolution for sensing and response to the environment. The resolution is typically limited to a body segment such as the upper leg or lower leg, but this level is not adequate for highly non-uniform thermal fields, and to develop focused climate control systems to maximize energy efficiency. Most current manikins do not possess a sweating capability and hence only sense dry heat transfer. Evaporative cooling is a critical and often used component of the thermoregulatory system of the body. A thermal manikin should possess this capability in order to accurately simulate the response of the body in all thermal environments. A sweating system is desired that will generate a film of water on the skin surface, affecting the actual rate of evaporation to the environment, or transport into clothing.

A thermal manikin that possesses a high degree of sensory spatial resolution, local thermoregulatory responses including sweating, a fast time response, and a feedback loop to continuously react and adjust to a thermal environment like a human has never been developed. An advanced thermal manikin with these capabilities would help industry develop more effective and energy efficient climate control systems for transportation environments, or others where transient and extremely non-uniform thermal environments exist.

System Overview

National Renewable Energy Laboratory (NREL) is overseeing the development of a system of three tools to predict human thermal comfort in non-uniform transient thermal environments. These tools include a finite element model of human thermal physiology, a psychological model that predicts both local and global thermal comfort, and a high spatial resolution sweating thermal manikin for testing in actual vehicles.

Each tool addresses an element of the total human comfort perception. The manikin provides a true form positioned in a vehicle to measure the transient thermal response with extremely high spatial density. The finite element model provides the manikin with a control algorithm closely mimicking true human response. The manikin communicates surface temperatures to the finite element model, which applies them as boundary conditions, and predicts the local heat generation and sweat rate. These rates are transmitted to the manikin which adjusts its heating and sweating system to match and the cycle repeats. This provides near true-human response characteristics from the manikin. The surface and core temperatures from this manikin/model system are input into a real-time psychological comfort model which outputs the end goal of the system – human perceptions of local and global thermal comfort.

Manikin System

The Thermal Manikin represents the physical hardware component in this comfort toolbox. It is being engineered to respond to a transient non-uniform thermal environment in the same manner as a human. The manikin acts as a heat transfer sensor that mimics a real three-dimensional body, sensing the local sweat evaporation, convection, and radiation processes that might not be correctly numerically modeled. The manikin can also be clothed so that an accurate depiction of a clothed human involving sweat transport and other clothing effects can be obtained. While the manikin is primarily designed as an integrated tool for use with the Physiological Response Model and Comfort Model, it can also operate autonomously as a stand-alone device to test clothing or environments following traditional control schemes.

The manikin, illustrated in Figure 15 below, is being designed to possess the following general capabilities:

- High spatial (est 150 zones) and rapid temporal control of surface heat output and sweating rate.
- Surface temperature response time constant mimicking human skin.
- Human like geometry and weight with prosthetic joints to simulate the human range of motion.
- Complete self-containment of manikin including battery power, wireless data transfer, and internal sweat reservoir for at least 2 hours of use with no external connections.
- Breathing with inflow of ambient air and outflow of warm humid air at realistic human respiration rates.
- Matching of manikin skin radiation absorptivity with human skin absorptivity
- Rugged and durable construction that requires minimal service

<u>Surface Segments</u> – This is the basis for the manikin, providing the skin surface with approximately 150 individual zones. Each surface segment is a stand-alone device with integrated heating, temperature sensing, sweat distribution and dispensing, and a Local Controller to manage the closed loop operation of the zone. The sweating surface is all-metal construction for thermal uniformity and response speed, with the thickness and composition optimized for thermal mass. Variable porosity within the metal surface provides lateral sweat distribution across the zone and flow regulation. Distributed resistance wire provides uniform heating, and is backed up by an insulative layer which also improves part rigidty. The single zone controller, including flow control valving is mounted directly to the rear of the zone.

<u>Power Management</u> – Component power efficiency is critical on this manikin system for two reasons. The requirement for two hours of untethered operation using an internal battery source necessitates no wasted energy. Additionally, since all heater amplifiers and related circuitry are within the manikin, the potential exists for operating errors due to waste heat in the body cavity. MTNW is using a custom pulse-width modulation scheme to drive the heaters with negligible heat generation on the amplifiers.

<u>Communication</u> – This manikin will be operable in a wireless mode, transfering data via 900 MHz spread spectrum transicevers. The high surface segment count results in large data throughput, since each of the 150 surface segments must communcate at an interval of 1-5 seconds to transfer surface temperature and receive new setpoint heat flux and sweat rates.

<u>Respiration</u> – The breathing system draws in ambient air and exhales warm, moist air to mimic the heating and moisture loads induced on climate control systems and de-fogging controls. This system will also be fitted within the manikin, further complicating internal manikin spaces

<u>Joints and Skeleton</u> – A full range of human motion is desired for realistic posing. Joints with one or two degrees of freedom will be located in the neck, shoulders, elbows, wrists, hips, knees, and ankles. All manikin surface segments will mount to a carbon fiber internal skeleton structure for maximum strength to weight ratio.

<u>Current Results</u>

At the time of this writing, prototype manikin surface segments have been developed and tested. A fully integrated sixteen segment sweating calf has been constructed and is undergoing functional testing. Images of the manikin calf are displayed in Figures 16 and 17.

Preliminary testing on the calf assembly and surface segments is underway. Experimental data from the system has been used primarily for design optimization at this time, but also quantifies the fundamental properties of the system. The method for backside heat loss compensation is still being optimized as part of this preliminary validation.

After assembly, the completed calf was evaluated in the manner of traditional manikins by operating unclothed in a uniform environment at a series of constant surface temperatures and measuring the steady state heat loss at each point. At steady state, the power input into the manikin heaters is presumably all lost through the skin surface, and can be used as a measure of the environment or clothing thermal resistance. The results obtained from operating the calf in this method indicated that there was a significant backwards heat transfer to the mechanical components inside the calf. Additionally, the top and bottom segments on the calf assembly had a higher heat loss due to edge losses, as they were located next to an unheated edge.

Based on the series of steady state tests, we chose to do the majority of our transient response testing on a single segment, allowing for better control of backside and edge heat loss conditions via insulation.

Single Zone Tests – Three modes of operation have been tested, with additional work to be done in each. The three tests are 1) time constant, 2) steady state heat loss, and 3) transient operation. These tests are described below and preliminary results provided for each.

Time Constant Test – The time constant of the surface segments is critical to the response of the manikin to transient environments. Additionally, it varies with the volume of water stored within the pores of the metal substrate. To measure the time constant of the segment, it is held in a stable environment, with the segment controlling to the same temperature as the ambient air. Once stable initial conditions are achieved, the heaters are turned to full power for a 10 minute period. The initial slope of the resulting temperature response curve is used to determine the thermal mass as shown in Figure 18. Testing for dry segment response is completed and testing for segments at various levels of water saturation is underway.

Steady State Heat Loss Test – The purpose of the steady state test is to quantify the backside heat loss component. A highly insulated segment will only lose heat from its skin surface. By varying the amount of insulation, the percentage of heat transfer from the back of the segment can be quantified, and used to validate the compensation sensor and algorithm. As of this writing, the baseline insulated tests were performed on a dry segment, insulated on the backside as shown in Figure 19. Future tests will vary the insulation thickness and introduce sweating on the surface.

Transient Operation Test – Transient tests are designed to create a transient event or series of events which cause the surface segment to pass through the same conditions as the Steady State Heat Loss test above. The first series of tests start at a higher ambient temperature, with a constant input heat flux into the surface segment. The segment is moved to the same ambient conditions as the Steady State Heat Loss test (lower temperature), and the resulting temperature decay is noted. The rate of change of segment temperature dT/dt is used to calculate the transient component of the heat loss. Adding input heater power with this transient component produces a real-time transient heat loss measurement as shown in Figure 20. Note that this correlates quite closely with the steady state heat loss measurement for the same skin temperature.

Manikin construction will be ongoing through 2002. The full system including manikin, physiological response model, and psychological comfort model is expected to be completed in 4th quarter of 2002 and undergoing long-term validation at that time.

CONCLUSIONS

The vehicle Thermal Comfort Project at NREL consists of three main components, which include the physiological model, a psychological comfort model, and a thermal manikin. All three components should be completed by January 2003. These tools will then be available for use by industry to develop more effective and efficient thermal comfort systems. The numerical thermal comfort models and thermal manikin will be the first thermal comfort tools that can accurately predict the human physiological and psychological response in both actual and simulated non-uniform transient thermal environments.

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Human Thermal Comfort:
http://www.ott.doe.gov/coolcar/assessing.html

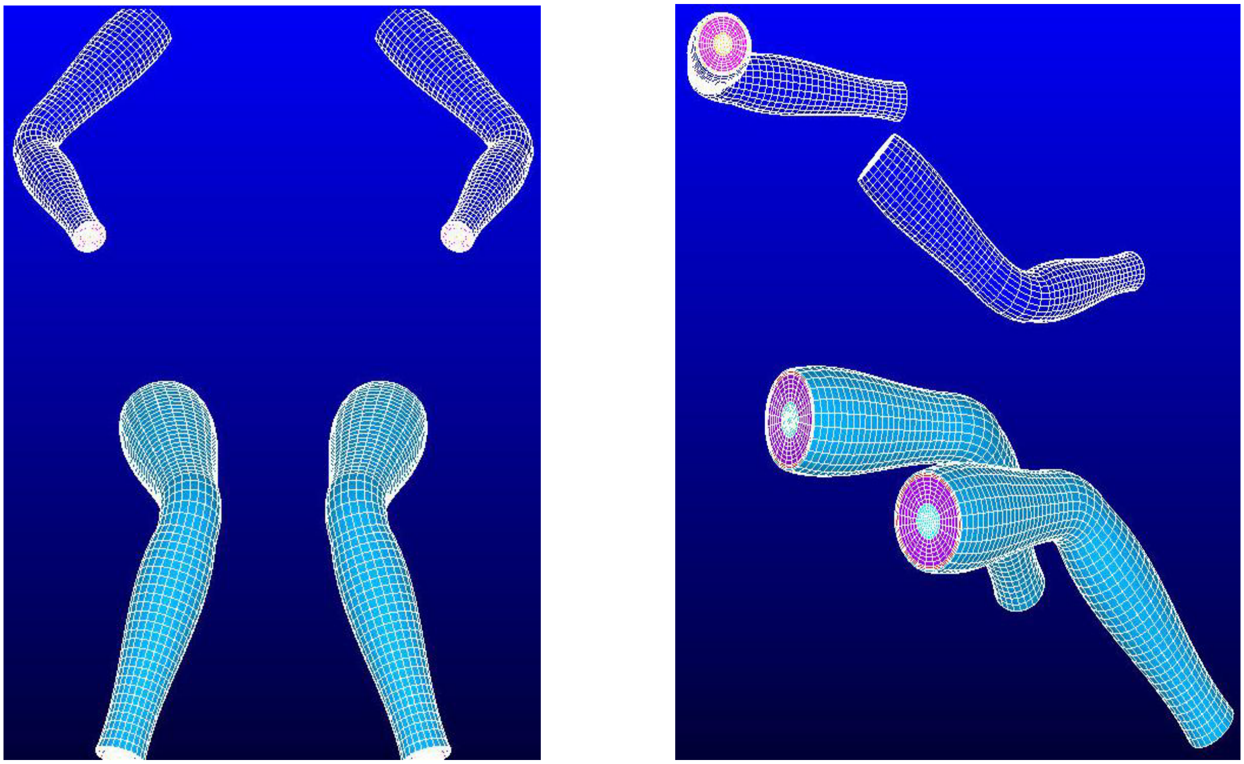

Figure 1: Human Body Limb Surface Shapes

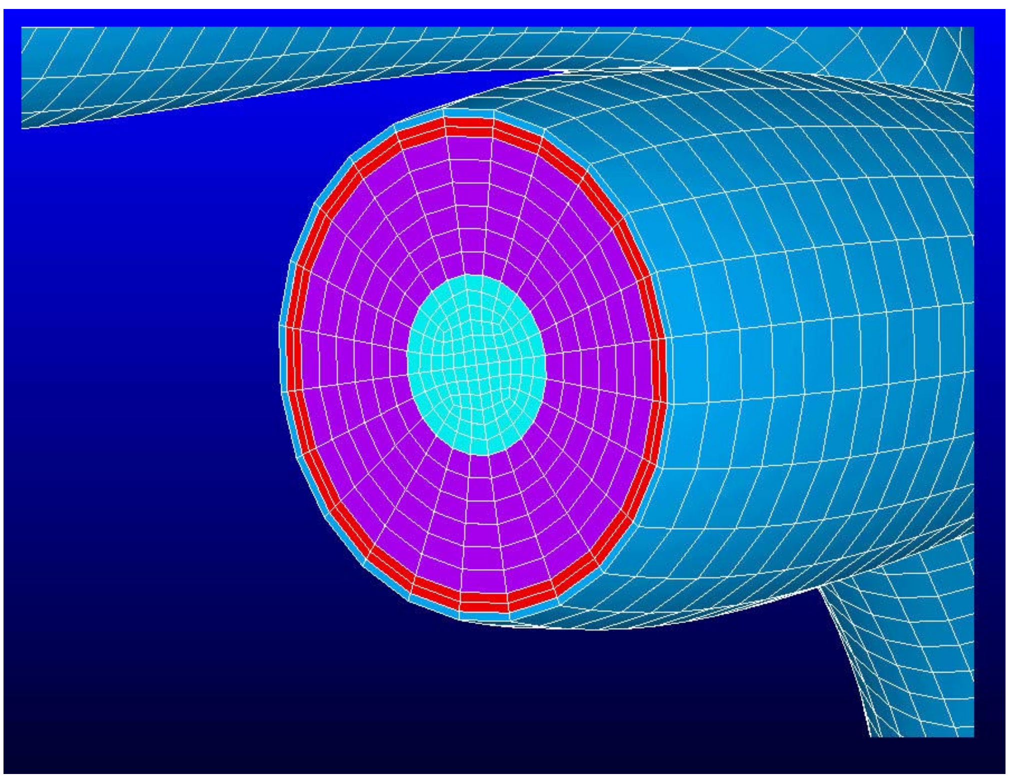

Figure 2: Limb Tissues and Finite Element Mesh

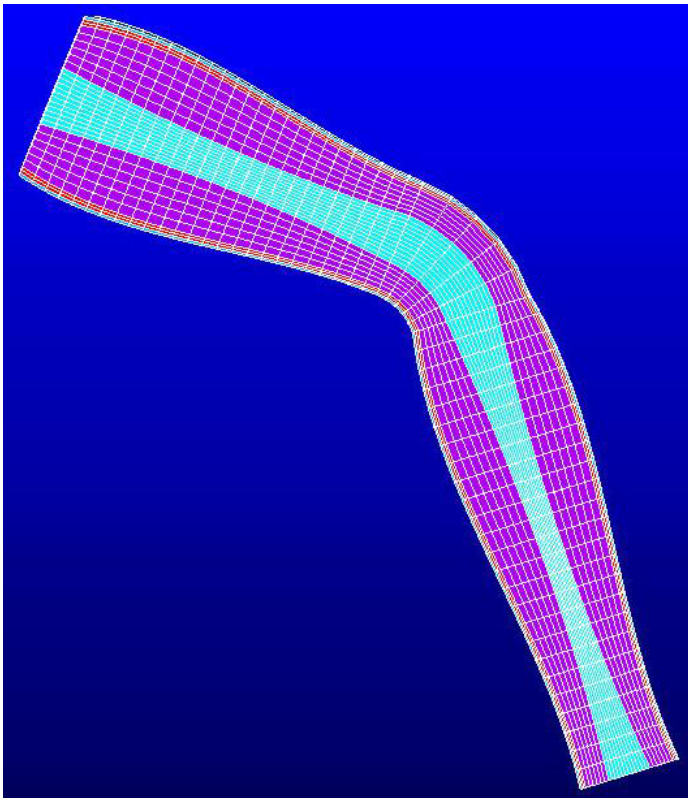

Figure 3: Cross-sectional View of Leg Tissues

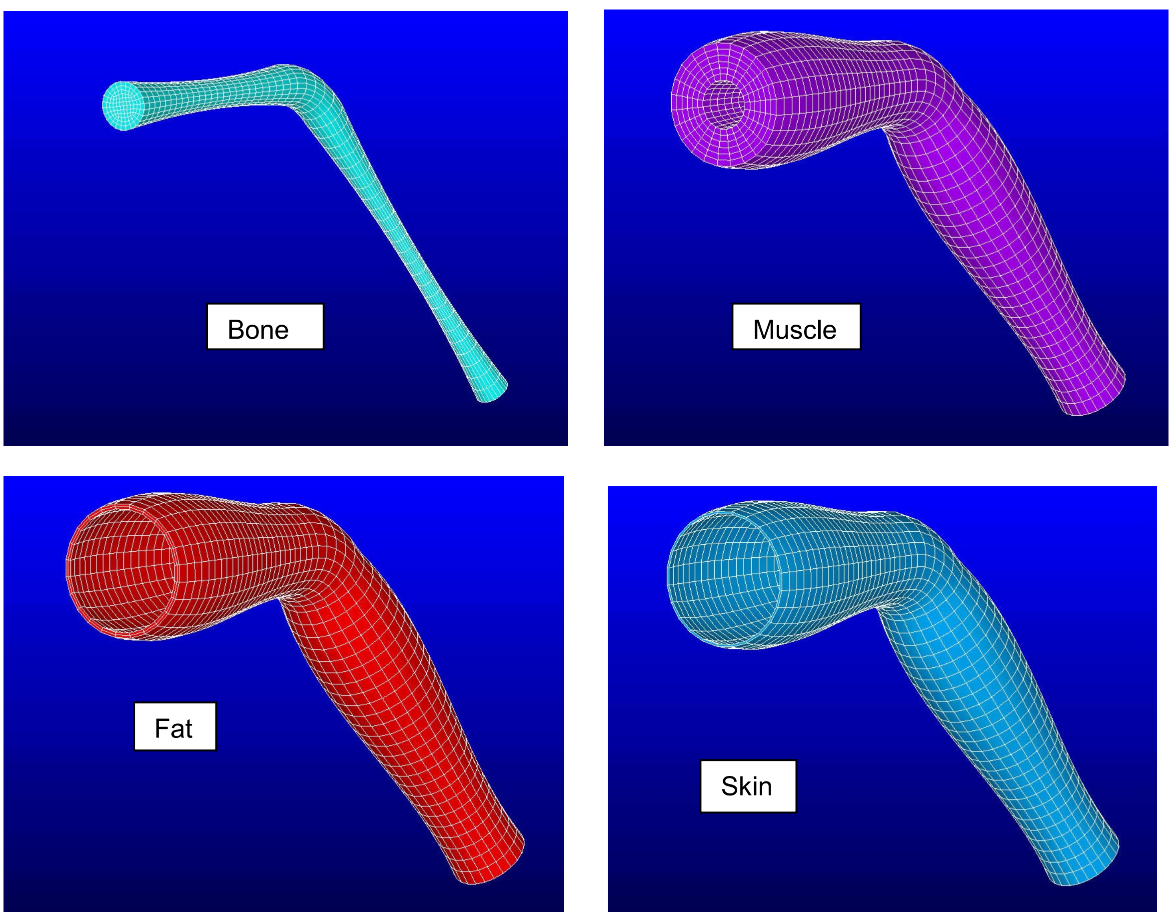

Figure 4: Three-dimensional View of Leg Tissues

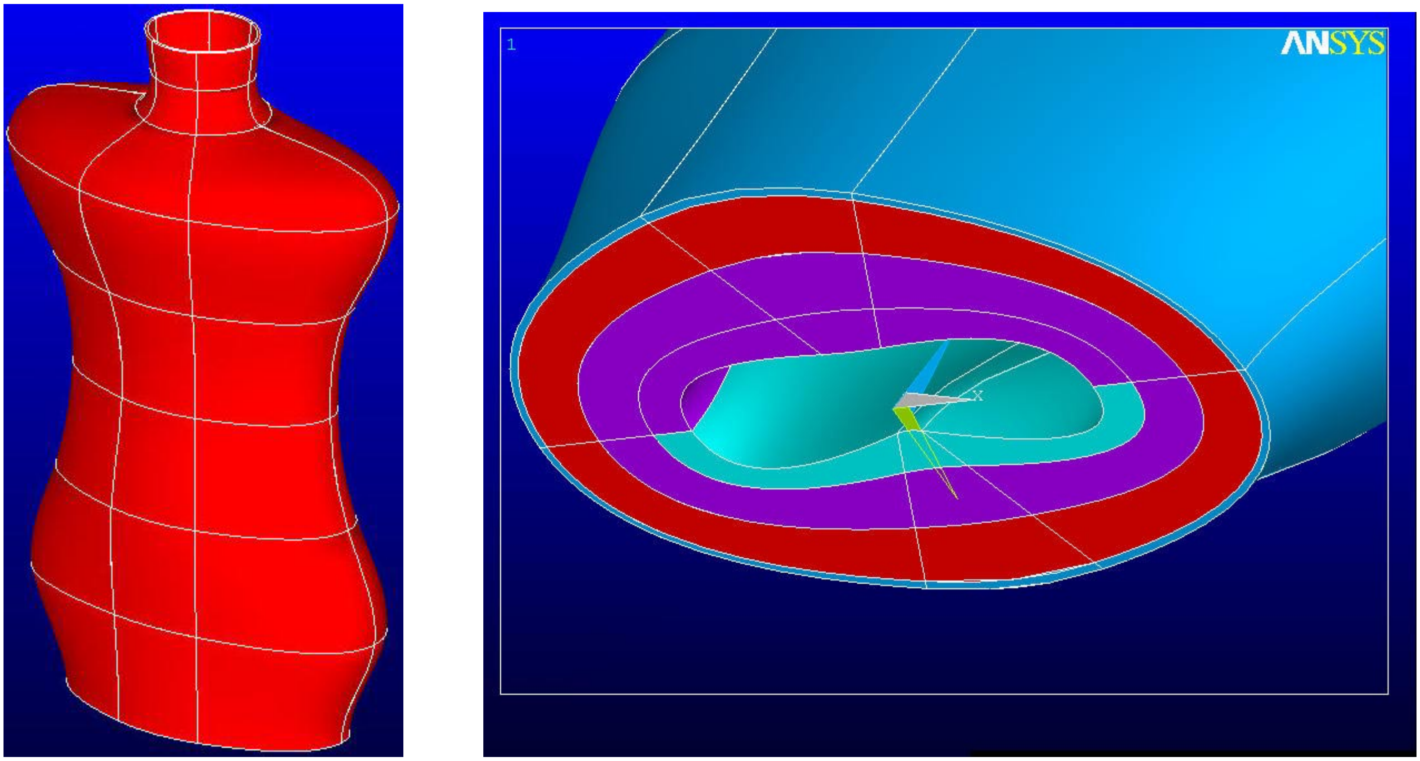

Figure 5: Torso Tissues and Mesh

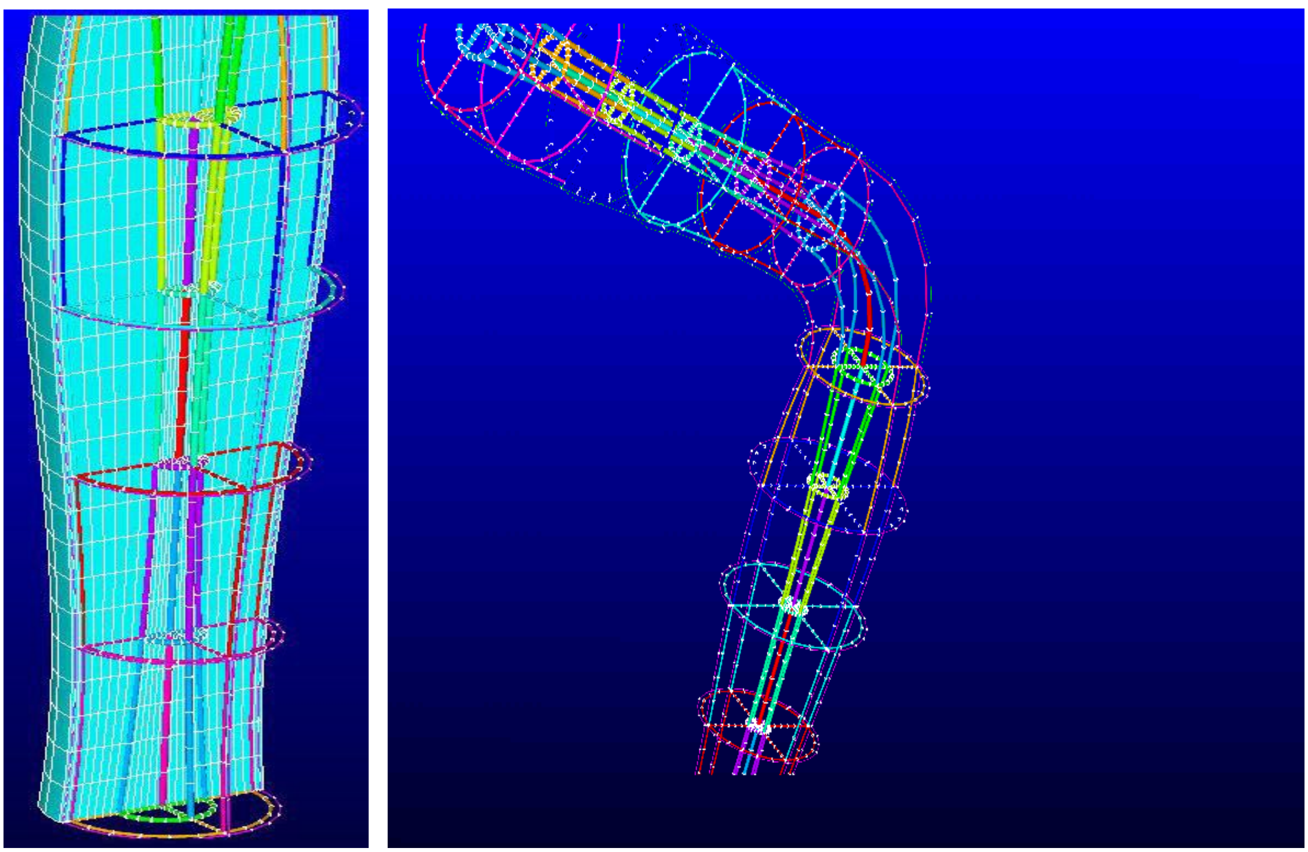

Figure 6: Limb Circulation System

Figure 7: Temperature Controlled Air Sleeve for the Arm

Figure 8: Leg Air Sleeve

Figure 9. Human subject test set up (this one is for back cooling)

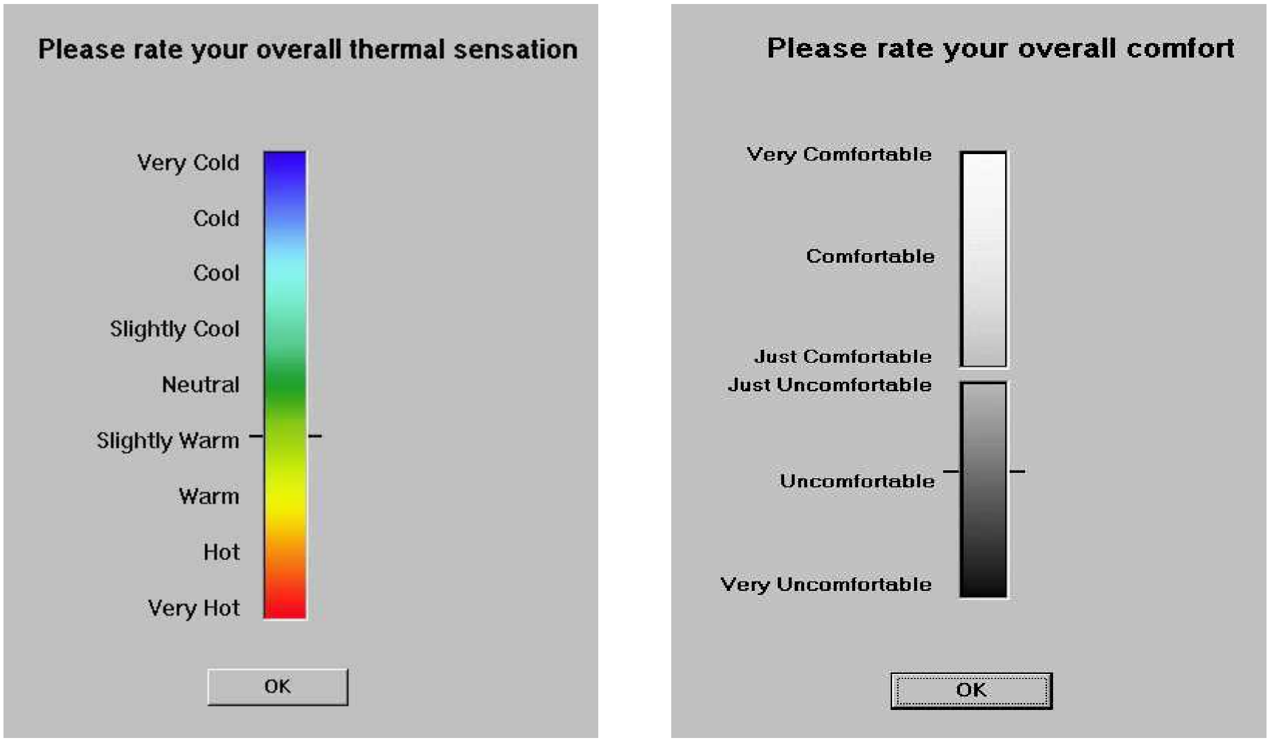

Figure10. Thermal sensation and comfort questionnaires

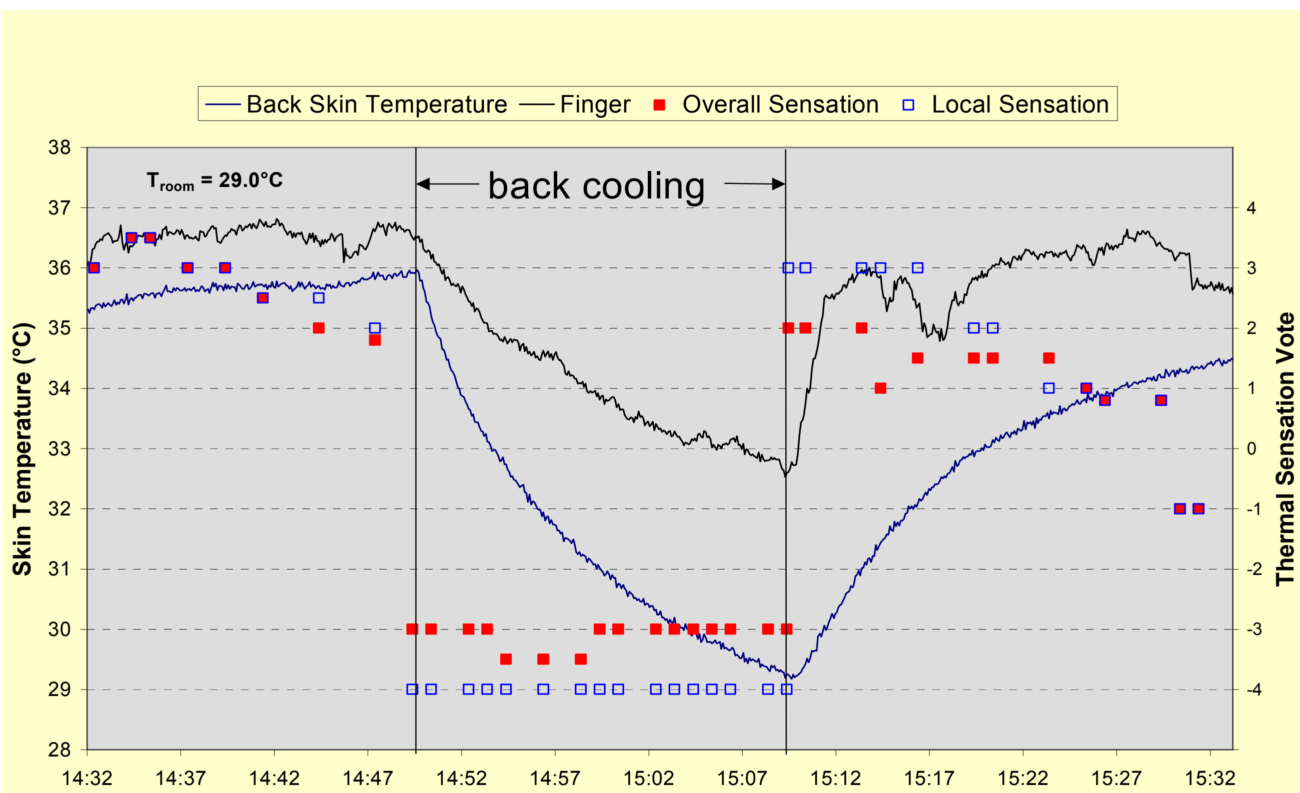

Figure 11. Back cooling and overall/local thermal sensation votes

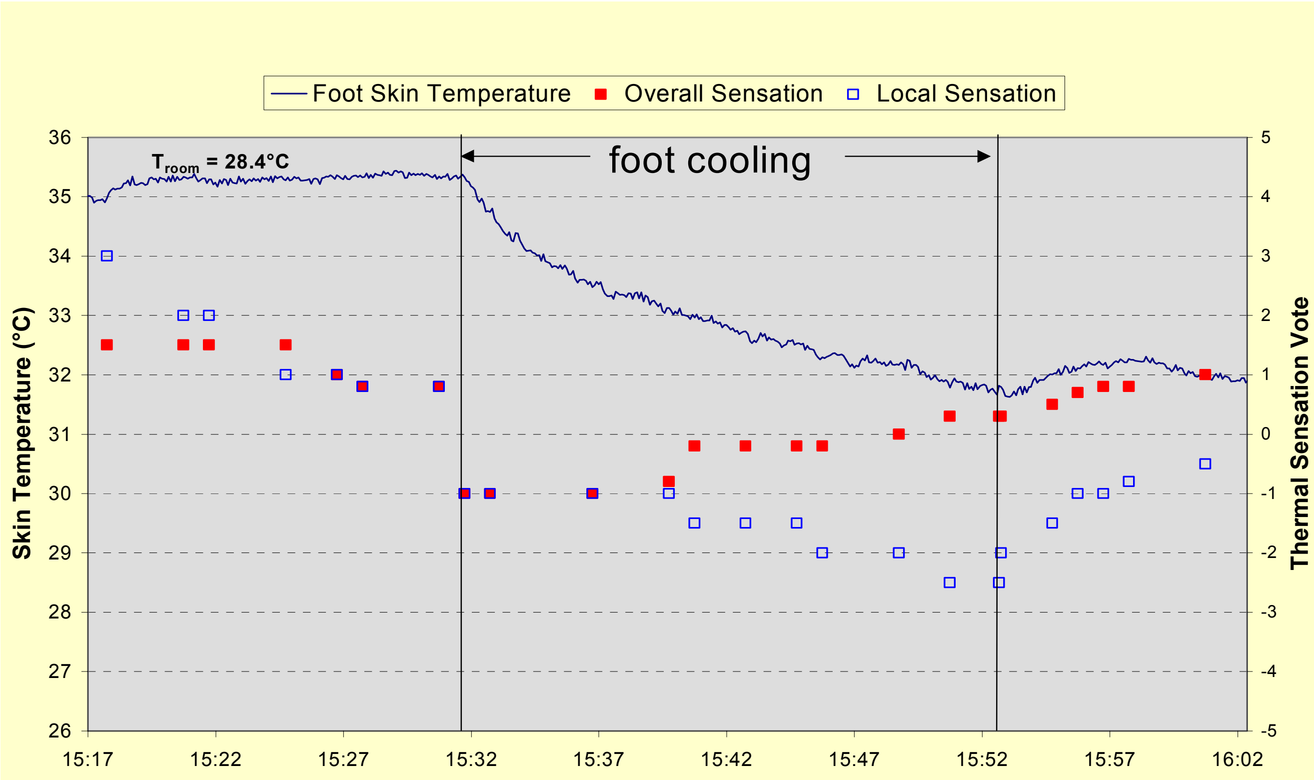

Figure 12. Foot cooling and overall/local thermal sensation votes

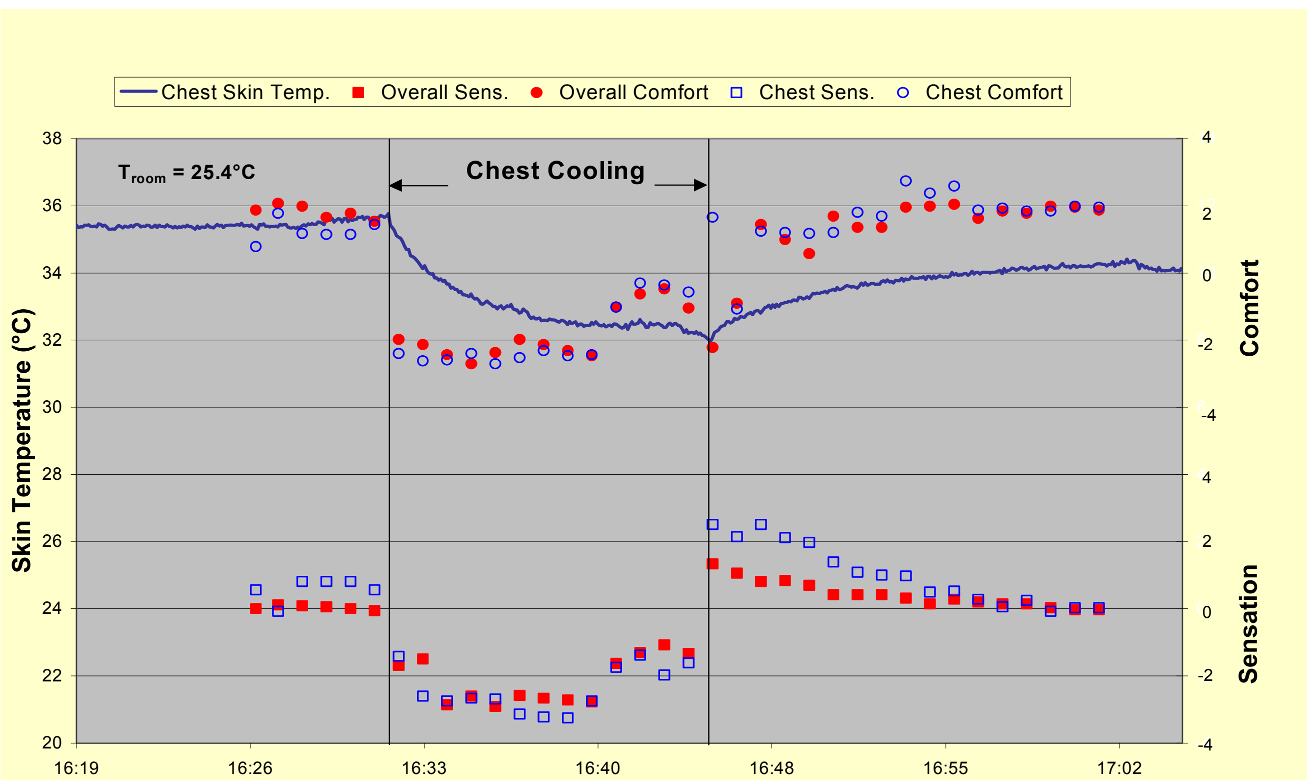

Figure 13. Chest cooling and overall/local thermal sensation/comfort votes

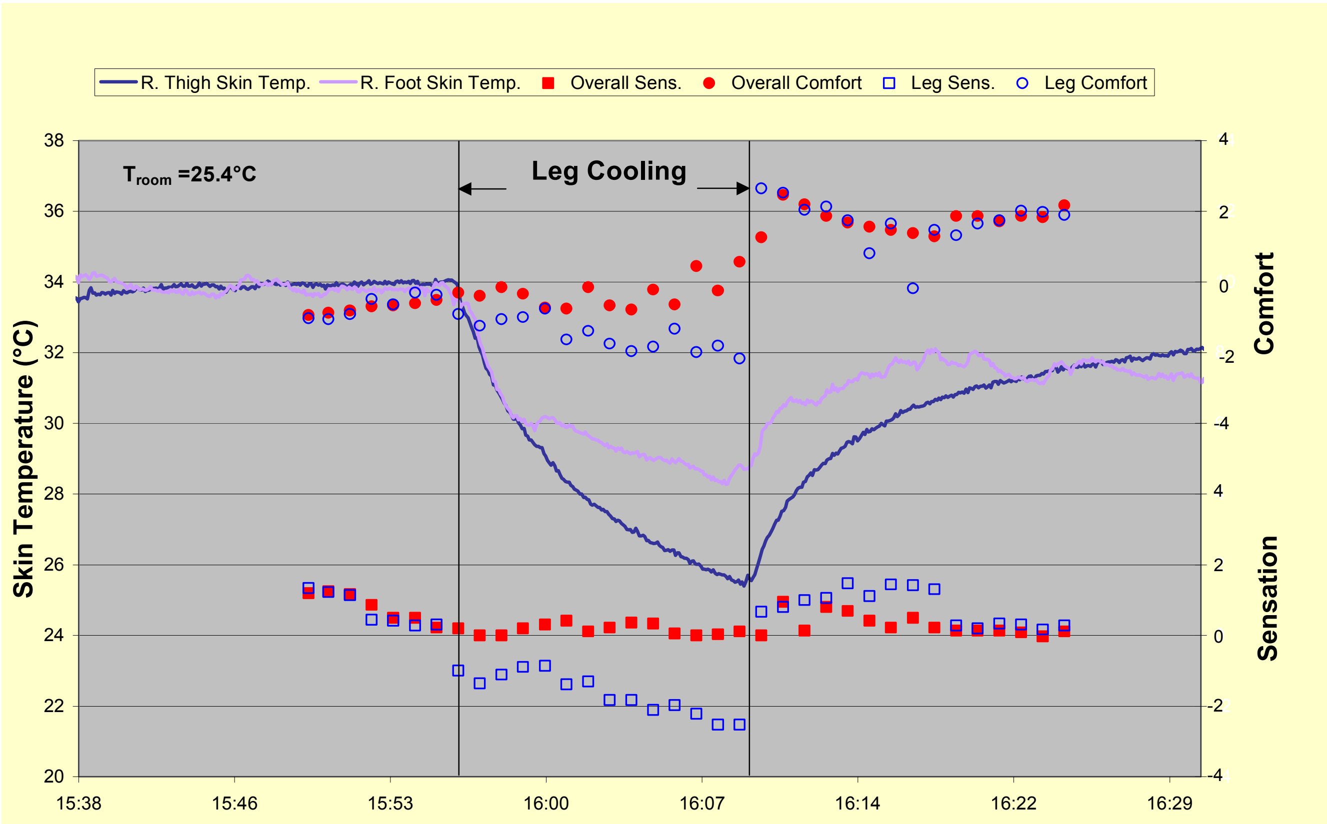

Figure 14. Leg cooling and overall/local thermal sensation/comfort votes

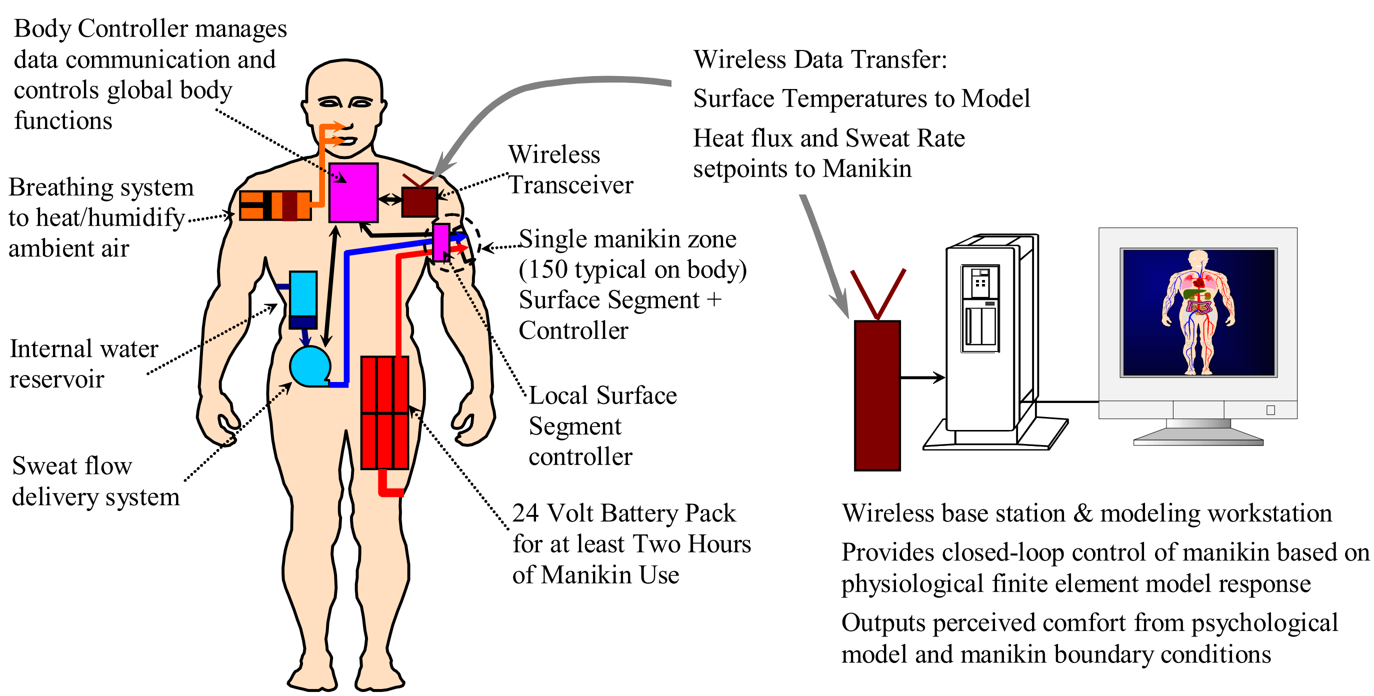

Figure 15: Thermal Manikin System Overview

Figure 16: Sixteen Segment Thermal Manikin Calf

Figure 17: Surface Segment Sweating

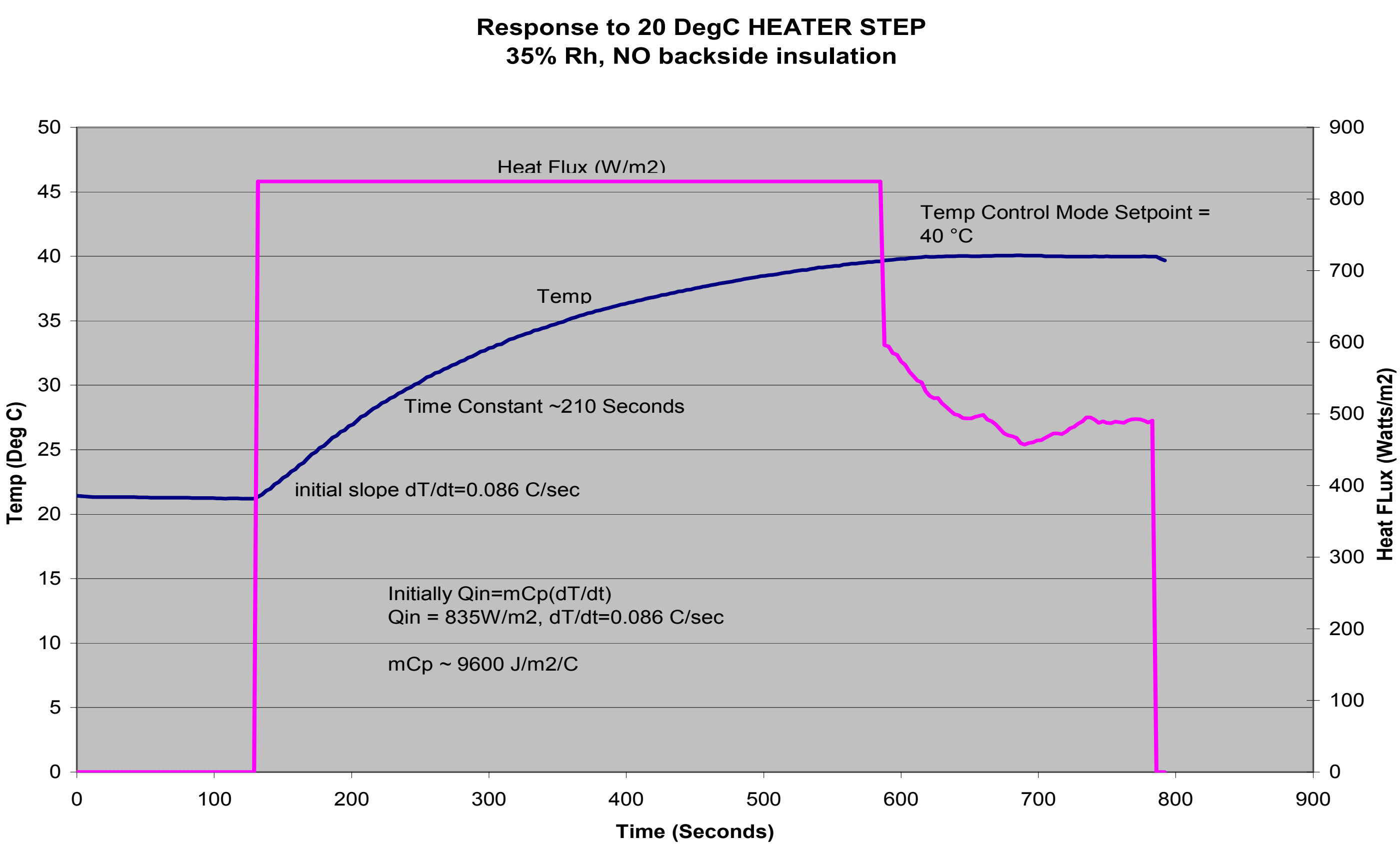

Figure 18: Time Constant Test on Dry Segment

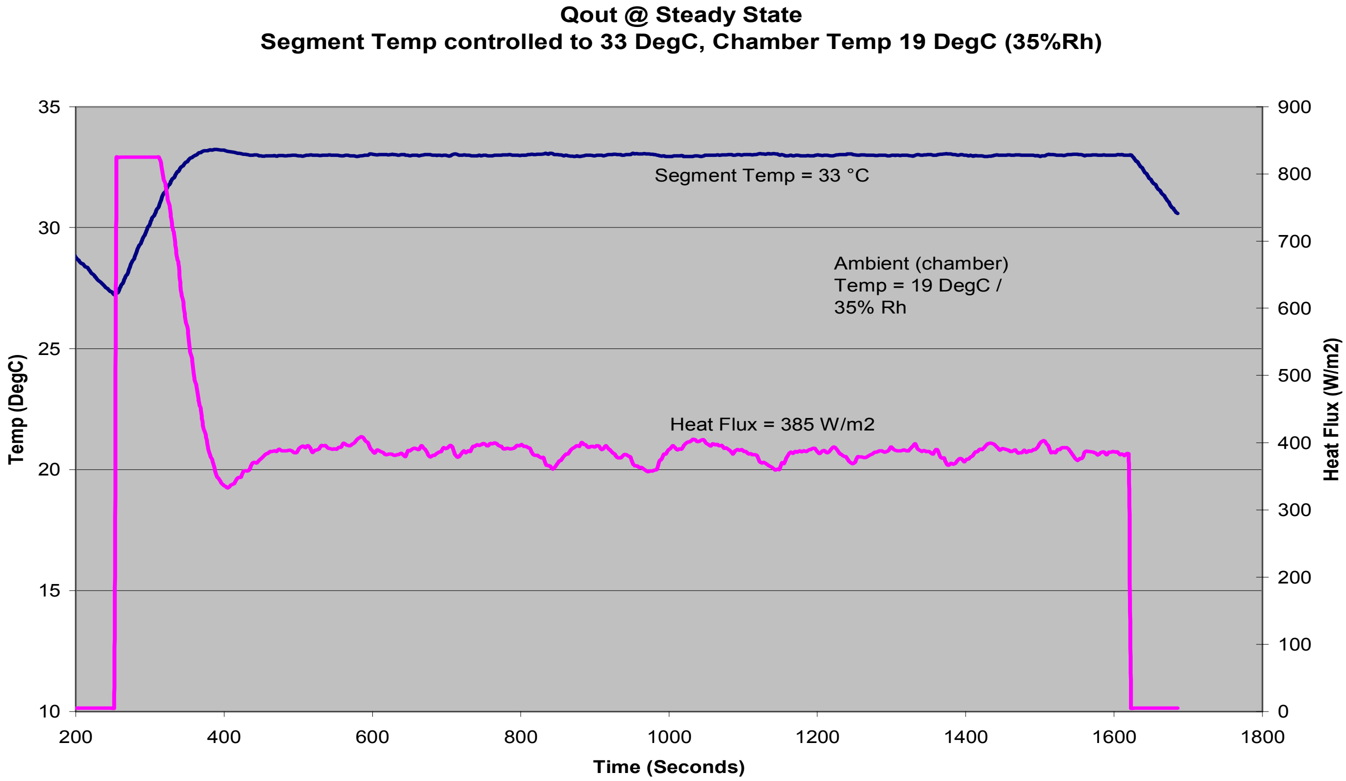

Figure 19: Steady State Heat Loss Test on Dry Segment

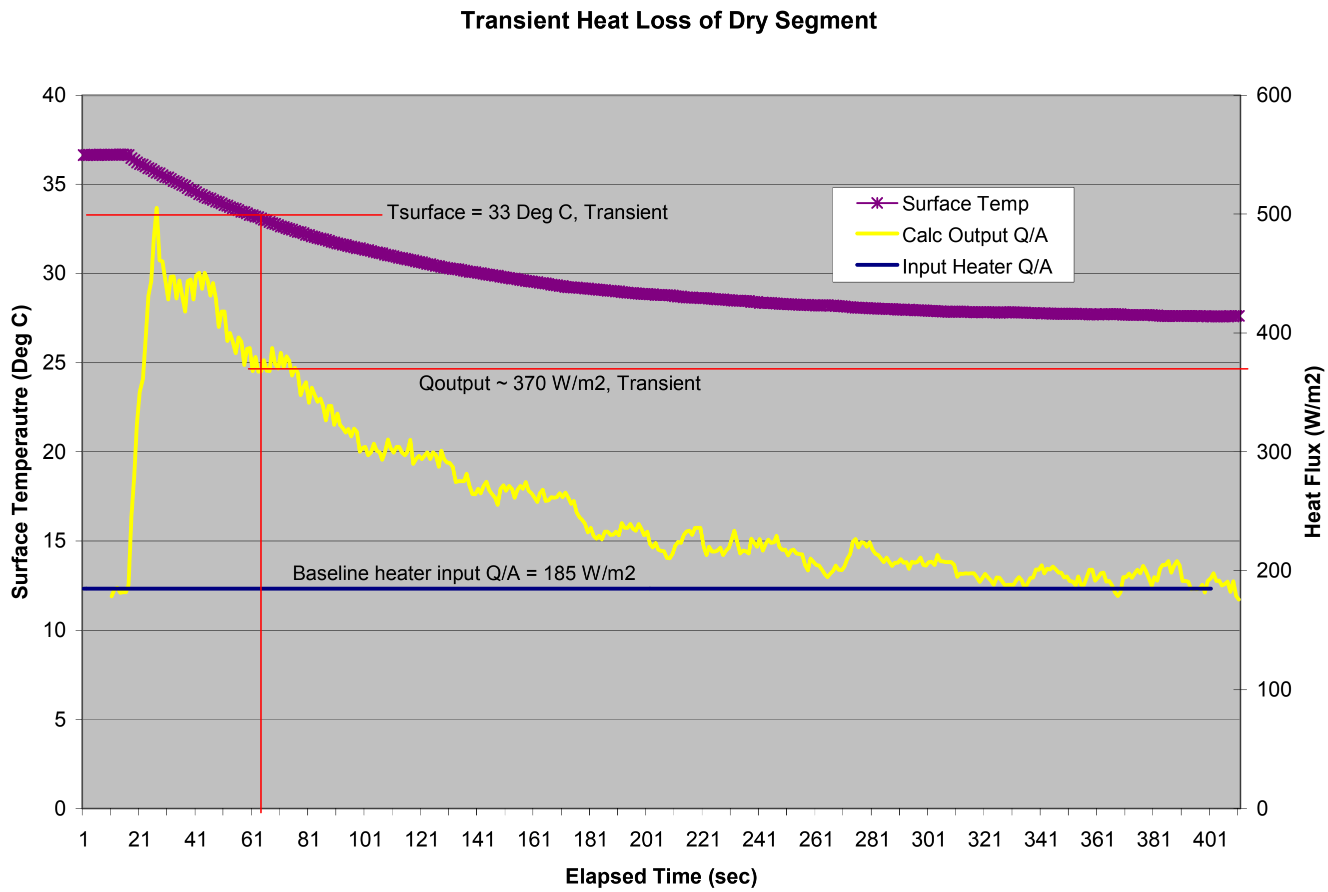

Figure 20: Transient Heat Loss Test