DEVELOPMENT OF A TWO-DIMENSIONAL
HUMAN THERMAL MODEL
FOR EVA APPLICATIONS

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by

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ABSTRACT

The human thermoregulatory system, with its active and passive components, is
difficult to model due to nonlinearities, complex interactions, and a lack of understanding
of many of the active thermoregulatory mechanisms. Part of this thesis focuses on the
effect of passive system parametric uncertainties on two possible thermal comfort
predictors. The effect due to each of the system parameters is quantified using a
sensitivity analysis approach involving the equations of a human thermal model, the 41-
node man model. A simulation based sensitivity analysis, using the Wissler 1-D model,
is also performed to confirm the findings. Results show that both models display highest
sensitivity to many of the same parameters.

Another part of this thesis gives an overview for a 2-D human thermal model.
The human thermal model incorporates 2-dimensional (radial and angular) heat transfer
along with arterial and venous countercurrent blood flow. In addition, this thermal model
attempts to model the human digits in order to predict toe and fingertip temperatures that
are of special interest in regards to the possibility of controlling the thermal comfort of a
subject.
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Chapter 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

In 1964, NASA discovered that sufficient cooling of an astronaut could not be accomplished via air convection in the suit due to ventilation. Thus, NASA upgraded to the liquid cooling garment (LCG) to provide better thermal comfort. The astronaut controls the temperature of the water flowing through the LCG by manually adjusting the temperature control valve (TCV) located on the front of the space suit. However, manually manipulating the TCV setting can dramatically reduce the productivity of the astronaut, distracting them from the extra-vehicular activity (EVA) mission at hand. In general, humans are poor judges of their thermal state and since an astronaut’s attention is focused on other things during EVA, there are time lags in the application of temperature control. This can cause overheating or overcooling; placing unneeded thermal stress on the astronaut, and possibly degrading EVA performance. An attractive solution to this problem is the use of automatic control for thermal comfort. Before an automatic controller can be designed, human thermal models are needed to accurately describe the transient heat transfer processes and predict the thermal response within an acceptable band of accuracy. Such human thermal models can also be extended to handle
various applications involving fire fighters, combat pilots, hazardous waste workers, and other industries where comfort in a thermally stressful environment needs to be insured.

The development of mathematical models for human thermoregulation started in the early 20th century. Early models used simple representations for the human thermal system, as it was not known of how much detail was needed to insure accuracy. However, in the 1960s, more detailed models surfaced as researchers strived to incorporate the complexities of human thermoregulation, as these complexities became known, to improve accuracy. Still the human thermoregulatory system, with its active and passive components, is difficult to model. Many aspects of the human's active thermal system are still not understood at all. The passive thermal system has been modeled with more success, but still uncertainties are present. Such uncertainties can stem from, but is not limited to, model approximations and parametric uncertainty. The latter is due to unaccounted parameter variations between human subjects (inter-subject variations) and effects influencing the individual at different times (intra-subject variations). It is advantageous for a modeler to identify important parameters of the passive thermal system and quantify their effect on the model's response to gain a better understanding of modeling issues and limitations.

The 41-Node Metabolic Man model, developed by NASA, can be used for thermal comfort and parametric uncertainty studies. The model greatly simplifies the human thermal system by modeling only one temperature for the entire blood pool and assuming only 1-dimesional, radial heat flow within the body. The relative simplicity of the 41-Node Man makes it ideal for analytical parametric sensitivity studies. However,
these simplifications might limit the model’s applicability for advanced thermal comfort
control studies where accurate models are essential.

1.2 OBJECTIVES

The first goal of this study is to quantify the effects of parametric uncertainty and
identify the more sensitive parameters for a representative human thermal model. The
second goal is to develop a human thermal model that can be used for EVA comfort
control studies, but also for other applications where thermal comfort is an important
issue. In developing the mathematical model, an emphasis is placed on improving the
human system whose complexity elicits the most uncertainty. Specifically, the objectives
of this study are as follows:

1. Identify representative human thermal models to be used for parametric sensitivity
   analysis (Chapter 2).

2. Identify all pertinent parameters and equations used by a representative human
   thermal model, and determine the outputs for the study (Chapter 2).

3. Quantify the effects of parametric uncertainty using an analytical method with one
   model, and then use a simulation-based method to verify the results with another
   model (Chapter 2).

4. Rank model parameters based on sensitivity (Chapter 2).

5. Determine the needed additions to the 41-Node Man to further meet NASA
   requirements (Chapter 3).
6. Outline all assumptions and equations used to implement the active and passive components of the human thermoregulatory system. Implement the model using MATLAB/SIMULINK (Chapter 3).

7. Run simulations using the model, to verify the need for 2-D heat flow and compare these results with existing simulation and experimental data.

8. Provide an overview of the entire model, The 2-D MU Model Man, listing all the features and assumptions (Chapter 4 – The entire documentation for the 2-D MU Man Model appears in the appendix as a stand alone report).
Chapter 2

QUANTIFYING MODELING UNCERTAINTIES
FOR THE PASSIVE HUMAN THERMAL SYSTEM

2.1 INTRODUCTION

Researchers have achieved mixed success modeling the passive human thermally [1-9], due in large part to the complexities, such as non-homogeneities and inter-subject variations. As an example case study investigated by the authors [10-12], human thermal models are used to predict thermal responses of astronauts performing extra-vehicular activity (EVA). Astronauts presently regulate their thermal comfort manually during EVA by frequently adjusting the temperature control valve (TCV). This degrades EVA performance without achieving thermal comfort since it has been shown that humans are not good judges of their own thermal state. To alleviate this situation, NASA is keen on developing a good understanding of the complexities involved in human thermal modeling to investigate automatic control strategies for the TCV [10].

Before a human thermal model can be used for EVA control studies, its response characteristics and limitations must be understood. Differences between experimental and simulation responses are typically caused both by modeling limitations and by experimental errors. Modeling errors include unaccounted parameter variations between
human subjects (inter-subject variations) and effects influencing the same individual at different times (intra-subject variations). The purpose of this study is to identify and quantify the significant parameters in modeling the passive human thermal system so as to better understand modeling issues and limitations. Two representative models are used to address this issue, the 41-Node man model for analytical studies, and the Wissler model for simulation studies.

Specifically, this chapter investigates the effect of parametric uncertainty on human thermal model heat transfer mechanisms and responses. Section 2.2 presents a brief review of human thermal modeling. Section 2.3 lists the representative human thermal model equations used for the sensitivity analysis. Section 2.4 describes the sensitivity analysis procedure proposed. Section 2.5 lists the results of the study, and Section 2.6 discusses the findings highlighting the contributions and suggests future directions.

2.2 OVERVIEW OF HUMAN THERMAL MODELING

A complete model of thermal regulation would involve the representation of 1) the passive system - heat transfer within the body and between the body and its environment, and 2) the active system – the thermoregulatory mechanisms by which the body can control its exchanges to maintain its temperature within close limits. This chapter is concerned primarily with the passive human thermal system.

Numerous human thermal models have been developed and used in many practical applications for the past sixty years, starting with the development of a steady-
state model to analyze heat transfer in a resting human forearm by Pennes in 1948 [13]. This cylindrical model served as the basis for a more advanced model by Wissler [2] and is still widely used for prediction of temperature elevation during hyperthermia [14,15]. Subsequent advances in computing technology and increased experimental data on human physiology helped researchers in developing better and more sophisticated human thermal models. In the 1960s, early versions of the well-known Wissler [6], Stolwijk [4], and Gagge [16] models were being developed. All later human thermal models for the most part, are probably extensions of these three mathematical models.

However, due to the natural complexity of human thermoregulation, it has been difficult to study the issue of accuracy for such models. Quantitative comparisons among models have also been difficult due to the individual characteristics of each model under particular environmental conditions [2,17,18]. From a user point of view, it has not been clear which of the models would be best suited for a particular environment and application. Various research teams [10,19-21] have developed models in the past decade to be used in environments that range from uniformly steady state to extremely transient and non-uniform. Models such as the Kansas State University model [20,22], the Berkeley model [21], and the MU model [19] are in development to achieve such objectives. Even though these models incorporate more detail, they have their roots either in the Wissler [8] or the Stolwijk [4] models. All these models include heat transfer within the body as well as between the body and its environment, as well as sweating, shivering, and vasomotor capabilities. An understanding of the accuracy of
such models can be achieved by careful sensitivity analysis studies and finding the
dominant parameters, and the reported study is a step in that direction.

41-Node Man Model

This transient model, developed by NASA [23], a Stolwijk-based [4] model, has
ten cylindrical segments each with four tissue layers to approximate the human form as
seen in Figure 2.1. There is one thermal node per tissue layer and one blood temperature
node with thermal connections to each tissue layer totaling 41 nodes overall. This model
is used in the chapter to identify principal modes of heat transfer and for the analytical
sensitivity study to determine the dominant model parameters affecting two thermal
comfort predictors.

Wissler Model

Wissler’s transient thermal model [8] predates the 41-Node man model, but is
similar in structure. It utilizes a fifteen cylindrical element representation of the human
form each containing fifteen nodes distributed through the four layers. Compact nodal
spacing in the outer tissue layers is intended to accurately predict the temperature field in
an element due to the higher temperature gradient that typically exists in this area—an
effect that is heightened in harsh environments [7]. There is one arterial and one venous
temperature node per cylinder giving 30 nodes for the circulatory system alone and 255
nodes overall. Blood flow paths to the extremities and back are included explicitly along
with counter current heat exchange between large veins and arteries.
2.3 REPRESENTATIVE HUMAN THERMAL EQUATIONS

This section presents the human thermal model equations using the 41-Node man model as the basis and identifies the dominant mechanisms of heat transfer within the model. These equations are used as being representative of typical human thermal models for the parametric sensitivity analysis proposed in the chapter.

An energy balance is computed for the $i,j^{th}$ node ($i$ refers to the cylindrical segment while $j$ refers to tissue layer as shown in Figures 2.1 and 2.2; all symbols are listed in the Nomenclature section) of the 41-Node man model shown in Eqn. 2.1.

$$\dot{Q}_{\text{store}_{i,j}} = \dot{Q}_{\text{gen}_{i,j}} + \dot{Q}_{\text{cond}_{i,j}} + \dot{Q}_{\text{bi}_{i,j}} + \dot{Q}_{\text{resp}_{i,j}} + \dot{Q}_{\text{ext}_{i,j}}, \text{ where } \dot{Q} = d\mathcal{Q} / dt \quad (2.1)$$

Some of the heat transfer mechanisms of Eqn. 2.1 are zero depending on the tissue node for which the equation holds (e.g., respiratory heat in the foot core), with the individual terms defined in Eqns. 2.2 –2.19.

Heat storage

$$\dot{Q}_{\text{store}_{i,j}} = m_{i,j} c_{p_{i,j}} \frac{dT_{i,j}}{dt} \quad (2.2)$$

Generated body heat

$$\dot{Q}_{\text{gen}_{i,j}} = \dot{Q}_{\text{bas}_{i,j}} + (1 - \eta_m) (MR - \dot{Q}_{\text{bas}_{i,j}}) + \dot{Q}_{\text{shiv}_{i,j}} \quad (2.3)$$

The 41-Node man model considers shivering as heat generation in the muscle tissue and is a function of the thermal state of the simulated subject as shown in Eqn. 2.4.

$$\dot{Q}_{\text{shiv}_{i,j}} = \left[ \sum_{i=1}^{16} k_{\text{shiv}_{i,2}} (T_{\text{set}_{i,4}} - T_{i,4}) \right] * (T_{\text{set}_{i,1}} - T_{i,1}) d_{\text{shiv}_{i,2}} m_{m} / m_{m0} \quad (2.4)$$
where negative values of $\dot{Q}_{shv_{i,2}}$ are disallowed.

**Tissue conduction**

$$\dot{Q}_{cond_{i,j}} = G_{i,j-1}(T_{i,j-1} - T_{i,j}) + G_{i,j+1}(T_{i,j+1} - T_{i,j})$$  \hspace{1cm} (2.5)

where values of $j - 1 = 0$ and $j + 1 = 4$ are disallowed.

**Blood flow.** The heat flow from the central blood pool into tissue compartment $i,j$ is modeled as

$$\dot{Q}_{bi_{i,j}} = \dot{e}_{bi_{i,j}}(T_b - T_{i,j}), \quad \dot{e}_{bi_{i,j}} = \dot{m}_{bi_{i,j}}c_{p_b}$$  \hspace{1cm} (2.6)

It is known [1] that muscle blood flow increases with human activity. Additionally, vasodilation and vasoconstriction occurs in the skin as a mechanism to regulate the body’s temperature. This blood flow rate adjustment is modeled in the 41-Node man model as shown in Eqns. 2.7-2.10.

Muscle blood flow is modeled as

$$\dot{e}_{bi_{i,2}} = d_{bi_{i,2}}(MR + \dot{Q}_{shv_{i}})$$  \hspace{1cm} (2.7)

Skin blood flow is modeled as

$$\dot{e}_{bi_{i,j}} = (\dot{e}_{b,vas_{i,j}} + \dot{e}_{dil_{i,j}})/(1 + \Psi_{i})$$  \hspace{1cm} (2.8)

where

$$\dot{e}_{dil_{i,j}} = (T_{1,1} - T_{set_{i,1}})d_{dil_{i,j}}m_s/m_{s0}$$  \hspace{1cm} (2.9)

and

$$\Psi_{i} = \left( (T_{set_{i,1}} - T_{1,1}) + \sum_{l=1}^{10} k_{cons_{i}}(T_{set_{i,4}} - T_{i,4}) \right) * d_{cons_{i}}m_s/m_{s0}$$  \hspace{1cm} (2.10)

with $\dot{e}_{bi_{i,4}}$ set to zero if negative.
**Respiratory tract heat loss.** The respiratory tract in the 41-Node man model removes heat from the head and trunk segments. This is modeled as

\[
\dot{Q}_{\text{resp},i,j} = d_{\text{resp},i,j} (\dot{Q}_{\text{resp, lat}} + \dot{Q}_{\text{resp, sens}})
\]  

(2.11)

where \(\dot{Q}_{\text{resp},i,j}\) is only present at specific layers of the head and trunk as distributed by \(d_{\text{resp},i,j}\).

\[
\dot{Q}_{\text{resp, lat}} = MR \cdot k_{\text{resp, lat}} (P_{v,\text{air}} - P_{g,\text{resp}})/T_{\text{air, abs}}
\]  

(2.12)

\[
\dot{Q}_{\text{resp, sens}} = c_{p,\text{air}} P_{\text{air}} MR \cdot k_{\text{resp, sens}} (T_{\text{air}} - T_{\text{resp}})/T_{\text{air, abs}}
\]  

(2.13)

**External heat loss (skin only, \(i = 4\)).** The external heat loss term represents the sum of all sensible and latent heat exchange between the skin and the environment.

\[
\dot{Q}_{\text{ext}} = \dot{Q}_{\text{conv}, i} + \dot{Q}_{\text{rad}, i} + \dot{Q}_{\text{diff}, i} + \dot{Q}_{\text{sweat}, i}
\]  

(2.14)

\[
\dot{Q}_{\text{conv}, i} = hA_{\text{air}}(T_{\text{air}} - T_{i,4})
\]  

(2.15)

\[
\dot{Q}_{\text{rad}, i} = A_i \sigma_f(T_{\text{well, abs}}^4 - T_{\text{abs},i,4}^4)
\]  

(2.16)

\[
\dot{Q}_{\text{diff}, i} = A_i k_{\text{diff}} (P_{v,\text{air}} - P_{g,i})
\]  

(2.17)

\[
\dot{Q}_{\text{sweat}, i} = -S \cdot d_{\text{sweat}} i 2(T_{i,4} - T_{\text{set}, i})^{k_{\text{sweat},1}}
\]  

(2.18)

where the drive for sweating is computed as

\[
S = (T_{i,4} - T_{\text{set}, i}) \left( k_{\text{sweat}, 2} + \sum_{i=1}^{10} k_{\text{sweat}, 3,4} (T_{i,4} - T_{\text{set},i,4}) \right)
\]  

(2.19)

and positive values of \(\dot{Q}_{\text{sweat}, i}\) are disallowed. The heat balance of the central blood pool, which is structurally distinct from the solid tissue nodes, is shown in Eqn. 2.20.
\[ Q_{\text{store}} = \sum_{i=1}^{10} \sum_{j=1}^{4} \delta_{bi,j}(T_i - T_b) \]  

(2.20)

The assumption in the 41-Node man model is that blood is described by one central blood pool temperature, regardless of location in the body. One of the strengths of the Wissler model is that there are 30 blood temperature sites within the model, allowing explicit consideration of the fact that the temperature of blood in the extremities is typically lower than the body core.

Figure 2.2 presents data from simulations using the 41-Node man model runs at four metabolic rates to show various modes of heat generation and rejection at steady state using the environmental conditions in Table 2.1. Convection, conduction, sweating, respiration and radiation are the modes of conveying heat away from the skin. Heat generated is represented as positive values, with the basal metabolic rate being the same at all metabolic rates. Inefficient heat is the heat generated due to physical activity above the basal metabolic rate. For example, if mechanical efficiency were 10%, then the inefficient heat generated would be 90% of the difference between the total metabolic rate and basal metabolic rate. As expected, evaporative heat transfer via diffusion and active sweating becomes more important at the higher metabolic rates, while the heat generated by shivering becomes zero.

2.4 PARAMETRIC SENSITIVITY ANALYSIS

The methodology used in this chapter is as follows: (i) identify parameters in the representative human thermal equations in the previous section that affect only steady-
state temperatures; (ii) perform a sensitivity analysis to determine the effect of these parameters on two predictors of thermal comfort: average skin temperature, $T_{sk}$, and total body heat storage, $Q_{stot}$, with respect to the parameters identified in the first step; (iii) quantify the expected error in average skin temperature and body heat storage due to parameter value uncertainty and associated measurement uncertainty; (iv) perform a simulation sensitivity study using the Wissler model by running cases subject to the same parametric perturbations for comparison purposes; and (v) rank the magnitude of their effect on the two thermal comfort predictors used.

Only parameters affecting steady-state skin temperature and body heat storage were selected for study in this work; these were grouped into three loose categories. The measurable parameters include overall muscular efficiency, $\eta$; metabolic rate, $MR$; body area for each body cylinder, $A(i)$; radiant view factors for each body cylinder, $f(i)$ and body mass, $m$. The parameters that are somewhat difficult to determine are the tissue specific heat capacities, $c_p(i,j)$; thermal mass blood flowrates, $\dot{e}_b(i,j)$; and tissue thermal conductances, $G(i,j)$. The parameters representing hypothalamic temperature setpoint, $T_{set,core}$ and skin temperature setpoint $T_{set,skin}$ can only be deduced from exhaustive experimentation, but cannot be known absolutely.

The partial derivatives of average skin temperature and body heat storage, with respect to each of the eleven parameters listed above were calculated. Most of the resulting equations are too lengthy [19] to appear in the body of this chapter, but appear
in Appendix A. As an example, the partial derivative (Eqn. 2.21) of the energy balance in
the fat layer with respect to muscular efficiency is presented below.

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \eta} + G_{i,3} \frac{\partial T_{i,3}}{\partial \eta} + \epsilon_{b,bas,i,3} \frac{\partial T_b}{\partial \eta} - \frac{d_{rep,i,3} C_{p,air} \rho_{air} M R K_{rep,sea}}{T_{air,obs}} \frac{\partial T_{rep}}{\partial \eta} \right] - \left( G_{i,2} + G_{i,3} + \epsilon_{b,bas,i,3} \right) \frac{\partial T_{i,3}}{\partial \eta} \tag{2.21}
\]

The next step is to solve that equation for the partial derivative of skin
temperature, \( T_{i,4} \), with respect to each parameter, and evaluate it at different metabolic
rates. This resulted in 42 coupled partial differential equations in the 42 unknowns due to
the 40 solid tissue nodes, 1 blood pool node, and 1 respiratory temperature node. These
coupled equations are solved using Matlab, which provides a convenient automated
environment for such studies. Values for each of the partial derivatives were calculated at
four operating points: 100 to 400 Watts metabolic rate, in steps of 100W. Table 2.1
shows the environmental conditions for which the partial derivatives were calculated.
However, since partial derivatives do not have the same units, by themselves these values
offer little insight into which ones may have the greatest effect on the two thermal
comfort predictors average considered, skin temperature and body heat storage.
Estimation of the effects of parametric uncertainty or measurements on those predictors
accurate estimates of the uncertainty for each parameter and of the measurements is
needed. Once this is known, the effect of uncertainty \( \Delta \alpha_i \), of parameter or measurement
\( \alpha_i \), on average skin temperature, for example, is provided by Eqn. 2.22,

\[
\Delta T_{sk} = \sum_{i} \frac{\partial T_{sk}}{\partial \alpha_i} \Delta \alpha_i \tag{2.22}
\]
The reported study calculates both the partial derivatives and the individual contributions as described next, for four different metabolic rate (MR) levels.

2.5 RESULTS

A sensitivity analysis methodology is used to determine the contribution of each of the parametric errors to the two outputs of interest, average skin temperature $\overline{T}_{sk}$ and body heat storage $Q_{stor}$. The parameters are then ranked based on their importance in predicting the two outputs. Four different metabolic rate operating points are considered that span the typical range encountered in experiments to provide an indication of how the sensitivity values change with the operating points. As mentioned, this sensitivity analysis is performed analytically as well as using a simulation-based approach.

Analytical Observations

The results are presented in two forms. Table 2.2 lists the analytically estimated sensitivity values $\partial \overline{T}_{sk} / \partial \alpha_i$ and $\partial Q_{stor} / \partial \alpha_i$ with respect to the parameters considered. With a knowledge of the actual parametric uncertainties for each of the parameters, $\Delta \alpha_i$, an overall uncertainty bound on the output of interest (the two thermal comfort indicators, in our case) can be estimated using Eqn. 2.22.

Table 2.3 (a and b) lists the contributions of the various parameters to the two outputs assuming, for the analysis reported, uncertainty bounds of 0.5 °C for the temperature related parameters and 5% of nominal values for the other parameters, rather arbitrarily, for illustrating the methodology. As stated earlier, if more accurate estimates
of the uncertainty $\Delta \alpha$, are known, the partial derivative formulae [19] used to generate the values in Table 2.2 can be used to determine better estimates for the uncertainty bounds on the output. Such results are important for both theoretical and experimental researchers involved with human thermal modeling in general, and the methodology and results reported represents one step in the process of understanding the accuracy issues associated with such modeling efforts.

The first column in Table 2.3 lists the parameter and its assumed magnitude of uncertainty, for the analysis reported. The rows are grouped by ease of parameter determination with the first four rows listing parameters that are relatively easily determined, and progressing onto groups with higher levels of difficulty. A useful representation of the data is the ranking of normalized magnitudes of effects of parameter uncertainty on the outputs. The parameter that has the largest effect at each metabolic rate, i.e., the largest magnitude of the derivative, is normalized to 100. The most influential parameters are immediately identifiable, as is their quantified importance compared to the other parameters.

Considering the prediction of average skin temperature, the dominant parameters determined analytically (41-node man model) as shown in Table 2.3a. It should be noted that the important ones, across the operating points, are hypothalamic set point temperature, $T_{set,core}$; the metabolic rate, $MR$; body surface area, $A$; radiation view factor, $f$; body mass, $m$; and skin conductance, $G$. The remaining four parameters could be considered to be insignificant, in comparison. Among the important six, the analysis
shows that $T_{set,\text{core}}$ is twice as important as the other four. It should also be noted that uncertainties in the tissue specific heats alone do not have any effect on the average skin temperature at steady state. This makes sense since at steady state the heat storage rate of the body is zero. However, changes in specific heat capacity alter the body's time constants, thus affecting the dynamic response.

Considering body heat storage, the second output of interest, the hypothalamic set point temperature, muscular efficiency and metabolic rate are the dominant parameters. Again, the analysis shows that $T_{set,\text{core}}$ is about 3 to 4 times more important than the other parameters. Body area, specific heat capacity and radiation view factor have a relatively minor effect.

To validate these analytical results, as well as check for consistency of the observations, the sensitivity analysis predictions using the 41-node man model are checked using another model, the Wissler human thermal model [8]. The Wissler Model has numerous details and empirical constants and so does not lend itself to an analytical study as described above. So, the Wissler model is used for a simulation sensitivity study to compare with the analytical studies, as discussed in the next section.

**Simulation Observations**

The simulation based sensitivity study, using the Wissler model, considered the following parameters: hypothalamic set point temperature, metabolic rate, skin area, radiant view factor, muscular efficiency, body mass, tissue specific heat capacity, and skin temperature set point. The other two parameters could not be varied in the study since the Wissler model structure does not permit it easily; it should be noted that the
analytical study revealed those to be not important. The results of the simulation study are presented in Tables 2.4a and 2.4b.

Considering the effects of parameter uncertainty on average skin temperature $\bar{T}_{sk}$, the dominant parameters, at the average metabolic rate of 200 W are the hypothalamic set point temperature, muscular efficiency, body area and radiant view factor. The metabolic rate tends to be the dominant parameter at the 300 W operating point. The muscular efficiency is the dominant parameter at 400 W, while, at the other end, the importance of $T_{set,core}$ decreases at a metabolic rate of 400W. For the Wissler model, uncertainty in the skin temperature setpoint does not have a significant effect on the average skin temperature. Also, the effect of the most significant parameter on average skin temperature for large perturbations is about 0.78 °C. For the 41-Node model, it is about 0.4 °C. Also, it should be noted that uncertainties in the specific heat capacities within the Wissler model do not affect the steady state average skin temperature prediction. This finding is, again, consistent with the 41-Node man model predictions.

With body heat storage $Q_{stor}$ as the output of interest, the Wissler model shows that uncertainties in the hypothalamic set point temperature, body surface area, muscular efficiency, specific heat capacity, metabolic rate and radiant view factor are the important ones, in that order, at a metabolic rate of 200W. At that metabolic rate, the hypothalamic set point temperature is about 6 times more important than the others with the rest being approximately equally important numerically.
2.6 DISCUSSION AND CONCLUSION

The 41-Node man model, the Wissler model, and similar human thermal models are typically used to predict human thermal response to combinations of environmental conditions, clothing level, and exercise level. Accuracy of such thermal models in predicting variables of interest is an important topic that needs to be investigated. A methodology to identify and quantify the significant parameters in such models for the prediction of two comfort indicators has been reported, and results using two representative models are presented using analytical as well as simulation based sensitivity approaches. This study focuses only on the passive human thermal system assuming that the models represent other thermal physiology correctly. Other aspects of the thermal physiology will be considered separately in future research.

The reported study represents one step in a systematic study of the accuracy issues associated with such models. Specifically, the study attempts to answer the question – under the assumptions cited, what are the key parameters involved in the prediction of steady state average skin temperature and body heat storage, given a set of environmental conditions. Using an analytical sensitivity approach, the key parameters and their relative importance are quantified for various metabolic rates.

The findings of the analytical approach are confirmed using a simulation based approach using the Wissler model. Two different models reveal similar results, which strengthens the findings. The results can probably be best summarized by considering the observations for an average metabolic rate of 200W. For this metabolic rate, the
parameters and their ranked importance in predicting average skin temperature $T_{sk}$, are shown in Table 2.3a (analytical approach) as $T_{set, core}$, $m$, $MR$, $A$, $G$ and $f$, and in Table 2.4a (simulation based approach using the Wissler model) as almost the same, with interestingly, not significantly different normalized values. Considering the prediction of body heat storage $Q_{stor}$, the parameters and their ranked importance at $MR = 200W$, are shown in Table 2.3b (analytical approach) as $T_{set, core}$, $MR$, $\eta$, $A$, $f$ and $T_{set, skin}$, and in Table 2.4b (simulation based approach using the Wissler model) as $T_{set, core}$, $MR$, $A$, $f$ and $T_{set, skin}$, again with similar normalized values, except for $\eta$ and $c_p$. The $T_{set, core}$ is clearly ranked the highest, being about 5 times as important as the others, for both the outputs considered. The variation with metabolic rates is expected and this study provides the sensitivity values at different rates. The findings indicate that careful determination and/or measurement of hypothalamic setpoint, body area, radiant view factor, body mass, muscular efficiency, and metabolic rate will improve model predictions for both models. It should be noted that the importance of the parameters will dependent on the operating point, since the system is nonlinear.

Minimizing the effects of model uncertainty requires a combination of minimizing parameter uncertainty and maximizing measurement accuracy. The former is more elusive, since true parameter values must be determined in situ. The particular application that the model is intended to be used for will determine the characterization of uncertainty that will be required, for inter-subject and intra-subject. As cited, this study
represents one step in a larger effort to comprehend accuracy issues for a human thermal model for particular applications.

2.7 ACKNOWLEDGMENTS

This research was supported in part by NASA grant NAG 9-1210 from the Johnson Space Center, Houston.
2.8 NOMENCLATURE

\( \dot{Q} \)  heat flow
\( c_p \)  specific heat capacity
\( T \)  temperature
\( m \)  mass
\( d_i \)  percent distribution for variable \( i \)
\( G \)  thermal conductance
\( \dot{E}_b \)  thermal mass blood flow rate
\( \mathcal{R} \)  blood flow reduction via vasoconstriction
\( p_v \)  partial water vapor pressure
\( P_g \)  adiabatic saturation pressure of water
\( A \)  body surface area
\( \sigma \)  Stefan-Boltzmann constant
\( f \)  view factor
\( S \)  drive for sweating
\( h \)  convection coefficient
\( k \)  constants
\( \eta \)  muscular efficiency
\( MR \)  metabolic rate
\( ms/ms0 \)  ratio of skin mass to its nominal value
\( mm/mm0 \)  ratio of muscle mass to its nominal value
\( T_{set,\text{core}} \)  hypothalamic setpoint temperature
\( T_{set,\text{skin}} \)  setpoint temperature for \( i \)th skin node
\( \alpha \)  parameter
2.9 REFERENCES


2.10 TABLES

Table 2.1: Environmental conditions used for simulations.

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>23.9 °C</td>
</tr>
<tr>
<td>Dew Point</td>
<td>10 °C</td>
</tr>
<tr>
<td>Wall Temperature</td>
<td>23.9 °C</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>0 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>70 kg</td>
</tr>
<tr>
<td>Clothing Ensemble</td>
<td>Nude</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constant Activity Profile</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic Efficiency</td>
<td>25%</td>
</tr>
<tr>
<td>Metabolic Rate</td>
<td>100, 200, 300, 400 W</td>
</tr>
</tbody>
</table>
### Table 2.2: Sensitivity values for the two outputs at various metabolic rates.

#### 2.2a. Sensitivity of average skin temperature with respect to the parameters.

<table>
<thead>
<tr>
<th></th>
<th>(\frac{\partial T_{sk}}{\partial \alpha_i} )</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta \ [\degree C] )</td>
<td>-0.312</td>
<td>-1.930</td>
<td>-0.436</td>
<td>-0.718</td>
<td></td>
</tr>
<tr>
<td>(MR \ [\degree C/(J/min)])</td>
<td>0.001</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>(A \ [\degree C] ) **</td>
<td>-1.858</td>
<td>-2.518</td>
<td>-1.601</td>
<td>-1.367</td>
<td></td>
</tr>
<tr>
<td>(f \ [\degree C] )*</td>
<td>-2.429</td>
<td>-2.951</td>
<td>-2.171</td>
<td>-1.787</td>
<td></td>
</tr>
<tr>
<td>(m \ [\degree C/kg] )</td>
<td>-0.029</td>
<td>-0.043</td>
<td>-0.060</td>
<td>-0.060</td>
<td></td>
</tr>
<tr>
<td>(c_p \ [\degree C] )**</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>(G \ [\degree C] )**</td>
<td>1.840</td>
<td>2.386</td>
<td>3.063</td>
<td>2.676</td>
<td></td>
</tr>
<tr>
<td>(\dot{e}_b \ [\degree C] )**</td>
<td>1.350</td>
<td>1.130</td>
<td>1.600</td>
<td>3.210</td>
<td></td>
</tr>
<tr>
<td>(T_{set,core} \ [\degree C/\degree C] )</td>
<td>0.583</td>
<td>0.637</td>
<td>0.841</td>
<td>0.847</td>
<td></td>
</tr>
<tr>
<td>(T_{set,skin} \ [\degree C/\degree C] )</td>
<td>0.096</td>
<td>0.025</td>
<td>-0.083</td>
<td>-0.002</td>
<td></td>
</tr>
</tbody>
</table>

* parameter non-dimensional, so units are \(\degree C\)

** represents \(\sum_{all \ i} \frac{\partial T_{sk}}{\partial \alpha_i} \alpha_{i,\text{nom}}\) and so the units are \(\degree C\)

#### 2.2b. Sensitivity of body heat storage with respect to the parameters.

<table>
<thead>
<tr>
<th></th>
<th>(\frac{\partial Q_{stor}}{\partial \alpha_i} )</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta \ [kJ] )</td>
<td>-81.344</td>
<td>-487.218</td>
<td>-229.999</td>
<td>-322.842</td>
<td></td>
</tr>
<tr>
<td>(MR \ [kJ/(J/min)])</td>
<td>0.089</td>
<td>0.0471</td>
<td>0.014</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>(f \ [kJ] )*</td>
<td>-178.710</td>
<td>-252.604</td>
<td>-107.264</td>
<td>-87.885</td>
<td></td>
</tr>
<tr>
<td>(m \ [kJ/kg] )</td>
<td>-0.686</td>
<td>0.560</td>
<td>-2.486</td>
<td>-1.829</td>
<td></td>
</tr>
<tr>
<td>(c_p \ [kJ] )**</td>
<td>-154.001</td>
<td>-88.600</td>
<td>80.010</td>
<td>156.103</td>
<td></td>
</tr>
<tr>
<td>(G \ [kJ] )**</td>
<td>-133.499</td>
<td>-94.060</td>
<td>50.141</td>
<td>25.352</td>
<td></td>
</tr>
<tr>
<td>(\dot{e}_b \ [kJ] )**</td>
<td>44.206</td>
<td>-46.633</td>
<td>-24.055</td>
<td>0.469</td>
<td></td>
</tr>
<tr>
<td>(T_{set,core} \ [kJ/\degree C] )</td>
<td>163.426</td>
<td>173.765</td>
<td>211.641</td>
<td>206.682</td>
<td></td>
</tr>
<tr>
<td>(T_{set,skin} \ [kJ/\degree C] )</td>
<td>40.512</td>
<td>23.732</td>
<td>1.143</td>
<td>8.314</td>
<td></td>
</tr>
</tbody>
</table>

* parameter non-dimensional, so the units are \(kJ\)

** represents \(\sum_{all \ i} \frac{\partial Q_{stor}}{\partial \alpha_i} \alpha_{i,\text{nom}}\) and so the units are \(kJ\)
Table 2.3: Normalized effect of parametric uncertainty on two thermal comfort predictors for the 41-Node man model.

2.3a. Effect on $\bar{T}_{sk}$ for the 41-Node man model.

<table>
<thead>
<tr>
<th>$\Delta \bar{T}_{sk}$</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$, 5%</td>
<td>5</td>
<td>30</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>MR, 5%</td>
<td>53</td>
<td>46</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>A, 5%</td>
<td>37</td>
<td>42</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>$f$, 5%</td>
<td>32</td>
<td>35</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>m, 5%</td>
<td>32</td>
<td>47</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>$c_p$, 5%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G, 5%</td>
<td>32</td>
<td>37</td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>$\dot{\theta}_b$, 5%</td>
<td>26</td>
<td>17</td>
<td>19</td>
<td>39</td>
</tr>
<tr>
<td>$T_{set,core}$ 0.5 °C</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$T_{set,skin}$ 0.5 °C</td>
<td>16</td>
<td>4</td>
<td>10</td>
<td>0</td>
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</tbody>
</table>

2.3b. Effect on $Q_{stor}$ for the 41-Node man model.

<table>
<thead>
<tr>
<th>$\Delta Q_{stor}$</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$, 5%</td>
<td>5</td>
<td>28</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>MR, 5%</td>
<td>33</td>
<td>32</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>A, 5%</td>
<td>10</td>
<td>13</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>$f$, 5%</td>
<td>8</td>
<td>11</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>m, 5%</td>
<td>3</td>
<td>2</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>$c_p$, 5%</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>G, 5%</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$\dot{\theta}_b$, 5%</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$T_{set,core}$ 0.5 °C</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$T_{set,skin}$ 0.5 °C</td>
<td>25</td>
<td>14</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 2.4: Normalized effect of parametric uncertainty on two thermal comfort predictors for the Wissler model.

2.4a. Effect on $\bar{T}_{st}$ for the Wissler model.

<table>
<thead>
<tr>
<th>$\Delta \bar{T}_{st}$</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$, 5%</td>
<td>8</td>
<td>71</td>
<td>79</td>
<td>100</td>
</tr>
<tr>
<td>MR, 5%</td>
<td>83</td>
<td>39</td>
<td>100</td>
<td>94</td>
</tr>
<tr>
<td>$A$, 5%</td>
<td>100</td>
<td>46</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>$f$, 5%</td>
<td>92</td>
<td>39</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$m$, 5%</td>
<td>33</td>
<td>29</td>
<td>45</td>
<td>58</td>
</tr>
<tr>
<td>$c_p$, 5%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$T_{set, core}$ 0.5 °C</td>
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<td>100</td>
<td>76</td>
<td>13</td>
</tr>
<tr>
<td>$T_{set, skin}$ 0.5 °C</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

2.4b. Effect on $Q_{stor}$ for the Wissler model.

<table>
<thead>
<tr>
<th>$\Delta Q_{stor}$</th>
<th>MR=100W</th>
<th>200W</th>
<th>300 W</th>
<th>400 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$, 5%</td>
<td>24</td>
<td>11</td>
<td>34</td>
<td>100</td>
</tr>
<tr>
<td>MR, 5%</td>
<td>100</td>
<td>10</td>
<td>54</td>
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</tr>
<tr>
<td>$A$, 5%</td>
<td>68</td>
<td>16</td>
<td>26</td>
<td>77</td>
</tr>
<tr>
<td>$f$, 5%</td>
<td>58</td>
<td>10</td>
<td>17</td>
<td>46</td>
</tr>
<tr>
<td>$m$, 5%</td>
<td>53</td>
<td>11</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>$c_p$, 5%</td>
<td>25</td>
<td>21</td>
<td>28</td>
<td>19</td>
</tr>
<tr>
<td>$T_{set, core}$ 0.5 °C</td>
<td>19</td>
<td>100</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>$T_{set, skin}$ 0.5 °C</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
2.11 FIGURES

![Diagram of human thermal model](image)

**Figure 2.1:** Structure of the ten-cylinder 41-Node man human thermal model.
**Figure 2.2:** Modes of heat generation and rejection at steady state for the 41-node man model.
Chapter 3

THE DEVELOPMENT OF A 2-DIMENSIONAL HUMAN THERMAL MODEL

3.1 INTRODUCTION

Automatic thermal control for astronauts during extra-vehicular activity (EVA) has long been a considerable need. Before an automatic controller can be designed, human thermal models are needed to accurately describe the transient heat transfer processes that the astronaut will undergo. There have been several attempts to generate an accurate human thermal model [1, 6, 7, 14, 15]. The thermal model presented in this paper incorporates many aspects of past human thermal models, especially the 41-Node Man which is based on Stolwijk's six-segment, 25-node model. In a sense, this new thermal model improves on the 41-Node Man to more accurately predict the thermal comfort of an astronaut and further meet the criteria for NASA space suit design.

The new human thermal model approximately represents the human body using 14 cylindrical segments or elements. The major segments include the head, torso, arms, hands, fingers, legs, feet and toes. In this model, the five fingers on each hand are represented as one cylinder and the five toes on each foot are represented as one cylinder. Like the 41-Node man, each segment contains four concentric layers. These four layers
include the core, muscle, fat and skin regions. The 41-Node Man utilizes a radial
dependent temperature node for each layer. To reduce errors encountered when using
lumped capacitance methods, the new model employs finite difference methods to predict
the dynamics occurring within the body.

This human thermal model makes several additions to the 41-Node Man. The
current 41-Node Man model assumes that the temperatures vary only in the radial
direction. The new model incorporates two-dimensional (radial and angular) heat
conduction within the body. Each body element in the model contains six angular sectors
to account for these angular temperature variations. Also, the 41-Node Man assumes the
blood temperature is constant throughout the body at a given instant of time. The new
model incorporates heat exchange between tissues and arteries/veins where the arterial
and venous temperatures vary from element to element.

This chapter shows in detail the aspects needed for the development of a new
thermal model for extra-vehicular activity (EVA) applications in space. The paper
includes: (i) a review of human thermal modeling, (ii) model additions to the 41-Node
Man, (iii) dynamic equations for numerical solutions, and (iv) simulation results.

3.2 REVIEW OF HUMAN THERMAL MODELS

There have been several attempts to generate an accurate human thermal model.
Pennes (1948) was one of the first persons to use cylinders to represent a human's body in
thermal modeling [10]. In the 1960s, Wyndham and Atkins developed a human thermal
model that used one cylinder to represent the entire body of a human [16]. In 1970,
Stolwijk and Hardy went a step further using six cylindrical elements for human thermal modeling [13]. All these models paved the way for more current models such as the 41-Node Metabolic Man and Wissler model which utilize 10 and 15 cylindrical elements, respectively [1, 15]. All these models share a common characteristic. They are all one-dimensional in that they assume heat conduction within each cylindrical element depends on only the radial position.

Several models that employ two-dimensional heat conduction (radial and angular) have been developed. In 1979, Kuznetz expanded the 41-Node Metabolic Man to include two-dimensional heat conduction within each element [6]. Likewise, in 1989, Mungcharoen expanded the Wissler model to utilize two-dimensional heat flow within each cylindrical element [7]. In 1991, Smith went a step further and developed a three-dimensional model (radial, angular and axial conduction) called the K-State Model [12]. However, axial conduction can be neglected as long as the cylindrical elements in the model are accurate.

3.3 MODEL ADDITIONS TO THE 41-NODE

The new human thermal model makes some additions to the 41-Node Man to improve the prediction of thermal comfort for an astronaut in space. The following sections outline additions made for the new model.

3.3.1 Two-dimensional Conduction

One-dimensional models cannot account for cases where disparate environmental conditions exist on different sides of the body. A study by Hall and Klemm showed that
when the body was exposed to cold (-6.7°C) and hot (82°C and 93.3°C) radiative temperatures on different sides of the body, skin temperature differences between the anterior and posterior sides ranged between 9-10°C [4]. These experiments by Hall and Klemm were also validated through simulations of the two-dimensional model developed by Kuznetz where the environmental conditions of the experiments were duplicated for the simulations [6]. Kuznetz’s model also predicted different anterior and posterior temperatures for the same body element. For wall temperatures of -6.7°C and 82°C, temperature differences between Kuznetz’s model and Hall and Klemm’s experiment never exceed 1.5°C. A one-dimensional model where temperature does not vary with the angle cannot predict such temperature differences on different sides of the same body element.

In addition, one-dimensional models cannot account for cases where non-uniform heat generation within body causes temperatures to vary for different sides of an element. Non-uniform heat generation can occur due to non-homogeneity of organs within an element. Also, non-uniform heat generation can occur within muscles during exercise. For example, a particular exercise could work the hamstrings, but not the quadriceps. This would cause more heat generation in the back of the leg than in the front.

3.3.2 Modeling the Digits

For the development of a new human thermal model, it is necessary to incorporate the explicit modeling of digits (fingers and toes), which has been suggested by NASA also. Studies have shown [5] that the digits, especially the fingers, respond to changes in the thermal environment quicker than all other locations of the body. Thus, a change in a
digit temperature is a good indication of thermal imbalance in the body. Thus, a human thermal model that accurately predicts the digit thermal dynamics is important.

Accurate digit modeling is also important in extra-vehicular activity (EVA) applications. During EVA, astronauts encounter situations where they must handle objects with glove protected fingers and hands. If the object is at a different temperature than the glove, then heat transfer will occur between the glove and object. This will cause some kind of thermal imbalance that will be detected first by the fingers. Thus, thermal comfort must still be insured during such heat exchanges.

3.3.3 Detailed Cardiovascular Model

In the past, many different techniques have been used to thermally model blood [1, 3, 14, 15, 16]. One technique is to use a single blood pool, which assumes that the blood temperature is the same throughout the body. This assumption greatly simplifies the circulatory system. Since, the arterial blood flow is so fast, it is assumed the blood temperature is homogeneous all throughout the body. However, this blood modeling technique does not incorporate the fact that blood entering the tissue will exit the arteries approximately at the tissue temperature. In addition, it is known that the blood temperature varies at different locations in the body. Therefore, there is a need to incorporate a blood model that includes the explicit modeling of arteries and veins where blood temperature can vary at different areas in the body. In independently modeling arteries and veins, heat transfer occurs between the arteries and tissue, and between the veins and tissue. In addition, countercurrent heat exchange between arteries and veins approaches a realistic circulatory system. However, problems arise due to the difficulty
in determining parameters such as the heat transfer coefficients between the arteries and veins, between the arteries and tissue, and between the veins and tissue.

3.4 MATHEMATICAL ANALYSIS

This model features three different clothing ensembles, nude, liquid cooling garment (LCG), and liquid cooling and ventilation garment (LCVG) with suit. For this chapter, the nude case will be the focus in order to compare simulation results with existing experimental data. However, the complete documentation of the model can be obtained if the reader desires further insight (see Appendix)[18].

The human thermal system can be divided into two components. The first is the passive thermal system that includes non-decision making heat transfer processes. The second component is the active thermal system that includes all the decision-making processes such as sweating, shivering and vasomotor functions. These active systems attempt to update parameters or heat exchange rates on-line depending on the thermal state of the simulated subject.

3.4.1 Passive System

This human thermal model utilizes 14 cylindrical elements to represent the human body as shown in Figure 3.1a. Within each element are four concentric regions: the core, muscle, fat and skin layers as shown in Figure 3.1b. Each element contains radially and angularly varying temperature nodes. Each element contains six equally spaced angular sectors. Figure 3.1c shows the nodal spacing within each sector for the nude case. For
the nude case, there are a total of 686 temperature nodes. The heat equation for two-dimensional conduction and heat generation is shown below.

\[
C \frac{\partial T}{\partial t} = V k \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} \right] + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{resp}} \tag{3.1}
\]

The term on the left-hand side of Eq. 3.1 represents the heat storage, \( V \) represents the volume, \( C \) represents the thermal mass, the bracketed term on the right represents the conduction between tissues, \( \dot{Q}_{\text{blood}} \) represents the rate of heat addition due to blood, \( \dot{Q}_{\text{gen}} \) represents the rate of heat generation, and \( \dot{Q}_{\text{resp}} \) represents the rate of heat addition due to the respiratory system.

Eq. 3.1 is used for tissue nodes in the middle of a specific tissue region. However, there is a need for an equation for the temperature node at the interface between two distinct tissue regions. The following heat flux equality can be used for this purpose.

\[
-k_{in} \frac{\partial T}{\partial r} = -k_{out} \frac{\partial T}{\partial r} \tag{3.2}
\]

In Eq. 3.2, \( k_{in} \) represents the conductivity of the tissue layer on the inside of the interface and \( k_{out} \) represents the conductivity of the tissue layer on the outside of the interface.

In addition, at the edge of the skin layer, the following boundary condition must be imposed.

\[
-k \frac{\partial T}{\partial r} = \dot{Q}_{\text{ext}} \tag{3.3}
\]

For the nude case

\[
\dot{Q}_{\text{ext}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} + \frac{1}{6} \dot{Q}_{\text{lat}} \tag{3.4}
\]
where $\dot{Q}_{\text{conv}}$, $\dot{Q}_{\text{rad}}$, and $\dot{Q}_{\text{lat}}$ represent the rate of heat transfer due to convection, radiation and latent heat loss, respectively. It should be noted that $\dot{Q}_{\text{lat}}$ represents the latent heat loss for the entire body element. It is assumed this heat loss is distributed equally to each of the six sectors of the skin layer, thus explaining the 1/6 coefficient in Eq. 3.4.

**Convection** - The rate of heat transfer due to convection from the surrounding air to a skin temperature node is

$$\dot{Q}_{\text{conv}} = hA(T_{\text{air}} - T) \quad (3.5)$$

where $h$ is the convection coefficient, $A$ is the area of the skin surface and $T_{\text{air}}$ is the ambient air temperature.

**Radiation** - The rate of heat transfer due to radiation from the surroundings to the skin surface is

$$\dot{Q}_{\text{rad}} = A\sigma F[(T_r + 273.15)^4 - (T + 273.15)^4] \quad (3.6)$$

where $A$ is the skin surface area, $\sigma$ is the Stefan-Boltzmann constant, $F$ is the interchange factor and $T_r$ is the radiant temperature.

**Respiratory heat loss** - The rate of respiratory heat loss has two components: sensible and latent heat loss such that

$$\dot{Q}_{\text{resp}} = (\dot{Q}_{\text{resp,lat}} + \dot{Q}_{\text{resp,sens}})K_{\text{resp}} \quad (3.7)$$

where

$$\dot{Q}_{\text{resp,lat}} = MR\frac{G_i}{T_{\text{air,abs}}}(P_{v_{\text{air}}} - P_{g_{\text{resp}}}) \quad (3.8)$$
and

\[
\dot{Q}_{\text{res}_{\text{t, e}}_{\text{ns}}} = \frac{C_{\text{p, air}} \cdot P_{\text{air, abs}} \cdot M_{R} \cdot G_{2}}{T_{\text{air, abs}}} (T_{\text{air}} - T_{\text{resp}})
\]  

(3.9)

where \( K_{\text{resp}} \) is the percentage of the respiratory heat loss at a specific temperature node, \( M_{R} \) is the metabolic rate, \( T_{\text{air, abs}} \) is the absolute air temperature, \( P_{\text{vair}} \) is water vapor pressure of air, \( P_{G_{\text{resp}}} \) is the saturation pressure of water at the respiratory temperature, \( C_{\text{p, air}} \) is the specific heat of air, \( P_{\text{air, abs}} \) is the absolute air pressure, \( T_{\text{resp}} \) is the respiratory temperature, and \( G1 \) and \( G2 \) are empirical constants.

**Heat transfer due to blood** - The rate of heat transfer due to the blood to each tissue node is

\[
\dot{Q}_{\text{blood}} = \dot{h} A_{a} \left( T_{a} - T \right) + (\dot{e}_{b} + \dot{h} A_{v}) \left( T_{v} - T \right) \quad \text{where} \quad \dot{e}_{b} = \dot{m}_{b} C_{p_{b}}
\]  

(3.10)

where \( h A_{a} \) is the heat transfer coefficient between the tissue and artery, \( h A_{v} \) is the heat transfer coefficient between the tissue and vein, \( \dot{e}_{b} \) is the thermal mass blood flow rate, and \( T_{a} \) and \( T_{v} \) are the artery and vein temperatures, respectively. In this model, blood flow is assumed to originate at the heart flowing to tissue layers through the arteries, which flow into the capillary bed and then exits the tissue layer through the veins. In this model, it is assumed that the blood entering tissue will exit the arteries approximately at the tissue temperature. Thus, blood entering the capillaries will approximately be at the tissue temperature. Thus, the term in Eq. 3.10 that involves \( \dot{e}_{b} \) indicates perfect heat transfer within the capillary bed, or in other words that blood entering the capillary bed (at the tissue temperature) will exit at the vein temperature.
3.4.2 Active System

The active thermal system used in this thermal model utilizes the equations used for sweating, shivering and vasomotor actions from the 41-Node Man [1].

**Latent heat transfer** - The latent transfer of heat from the skin is comprised of two components: diffusion and active sweating such that

\[
\dot{Q}_{\text{lat}} = \dot{Q}_{\text{dif}} + \dot{Q}_{\text{sweat}} \tag{3.11}
\]

where

\[
\dot{Q}_{\text{dif}} = AG_3 \left(P_{v_{\text{air}}} - P_{v_{\text{skin}}} \right)^{or0} \tag{3.12}
\]

and

\[
\dot{Q}_{\text{sweat}} = -SK_{\text{sweat}} 2^{(T - T_{\text{set}})_{\text{set}}} G_4 \tag{3.13}
\]

where

\[
S = (T_{c} - T_{\text{set}})^{or0}_{\text{head}} \left( G_5 + \sum_{i=1}^{14} \gamma_{sw} (T_i - T_{\text{set}})^{or0}_{\text{skin}} \right) \tag{3.14}
\]

where \( A \) is the diffusion area, \( P_{v_{\text{air}}} \) is the water vapor pressure of the environment, \( P_{v_{\text{skin}}} \) is the saturated pressure of water at the skin temperature, \( K_{\text{sweat}} \) is the sweat distribution, \( T_{\text{set}} \) is the setpoint temperature, \( T_{c} \) is the core temperature, \( \gamma_{sw} \) is the skin mass distribution, and \( G_4, G_5 \) and \( G_6 \) are empirical constants.

In addition, active sweating is limited by the maximum evaporative capacity

\[
\dot{Q}_{\text{max}} = \left( 1 - \exp\left( - \frac{\dot{Q}_{\text{sweat}} G_7 T_{\text{air}} R_{w}}{H_{m} A h_{f_{b,\text{air}}} (P_{\text{v_{skin}}} - P_{v_{\text{air}}})} \right) \right) \frac{H_{m} A h_{f_{b,\text{air}}} (P_{\text{v_{skin}}} - P_{v_{\text{air}}})}{T_{\text{air}} R_{w}} \tag{3.15}
\]
where $H_{mass}$ is the mean mass transfer coefficient, $h_{fg,air}$ is the enthalpy of vaporization, $R_w$ is the universal gas constant, and $G_7$ is an empirical constant. As stated previously, $\dot{Q}_{lat}$ represents the latent heat loss from an entire body element.

**Shivering** - The rate of heat production due to shivering is distributed within the muscle region of each element and is given by

$$\dot{Q}_{shiver} = \left( \sum_{i=1}^{14} (T_{set,i} - T_{s,i}) \gamma_{sh,i} \right) (T_{set,c} - T_c) \gamma_{sh,c} G_{sh} K_{shiver} \frac{M_{m}}{M_{m0}}$$

(3.16)

where $T_{set,s}$ is the skin setpoint temperature, $T_s$ is the skin temperature, $\gamma_{sh}$ is the skin mass distribution, $T_{set,c}$ is the core setpoint temperature, $T_c$ is the core temperature, $K_{shiver}$ is the shiver distribution, $G_{sh}$ is an empirical constant and $M_{m}/M_{m0}$ is the muscle mass to nominal muscle mass ratio.

**Vasomotor functions** - In this model, the vasomotor actions work either to increase or decrease the blood flow rate to the skin. During vasodilation, the blood flow rate to the skin is increased to encourage heat loss to the environment. During vasoconstriction, the blood flow rate to the skin is decreased to inhibit heat transfer to the environment. Vasodilation occurs when the simulated subject is too warm. Vasoconstriction occurs when the simulated subject is cold. The skin thermal mass blood flow rate is updated on-line using the following equation:

$$\dot{e}_{b \rightarrow s} = \frac{\dot{e}_{b \rightarrow s, basal} + \dot{e}_{dl}}{1 + R}$$

(3.17)

where
\[ \dot{e}_{all} = (T_e - T_{sete})_{head} G_9 K_{dil} \frac{M_s}{M_{s0}} \]  

and

\[ \Re = \left( (T_{sete} - T_e)_{head} + \sum_{i=1}^{14} \gamma_{cons} (T_{seti} - T_i)_{skin} \right) G_{10} K_{cons} \frac{M_s}{M_{s0}} \]  

where \( K_{dil} \) is the vasodilation distribution, \( K_{cons} \) is the vasoconstriction distribution, \( M_s/M_{s0} \) is the skin mass to nominal skin mass ratio, and \( G_9 \) and \( G_{10} \) are empirical constants.

3.4.3 Numerical Solution

The heat transfer equations are solved numerically using MATLAB\textsuperscript{TM}/SIMULINK\textsuperscript{TM}. Eqs.3.1-3.3 can be approximated using the following equations.

\[ \frac{\partial^2 T}{\partial r^2} \bigg|_{r,\theta} \approx \frac{T_{r+1,\theta} + T_{r-1,\theta} - 2T_{r,\theta}}{(\Delta r)^2} \]  

(3.20)

\[ \frac{\partial T}{\partial r} \bigg|_{r,\theta} \approx \frac{T_{r+1,\theta} - T_{r-1,\theta}}{2\Delta r} \]  

(3.21)

\[ \frac{\partial^2 T}{\partial \theta^2} \bigg|_{r,\theta} \approx \frac{T_{r,\theta+1} + T_{r,\theta-1} - 2T_{r,\theta}}{(\Delta \theta)^2} \]  

(3.22)

\[ \frac{\partial T}{\partial t} \bigg|_{r,\theta} \approx \frac{T_{r,\theta}^{p+1} - T_{r,\theta}^p}{\Delta t} \]  

(3.23)

Thus, after substituting Eqs. 3.20–3.23, Eq. 3.1 has the following numerical approximation.

42
\[
\frac{T_{r,\theta}^{p+1} - T_{r,\theta}^p}{\Delta t} = \frac{k}{2\Delta r} \left( R_r + R_{r-1} \right) L \left( T_{r+1,\theta}^p - T_{r,\theta}^p \right) + \left( \frac{k}{2\Delta r} \left( R_r + R_{r-1} \right) L \right) \left( T_{r-1,\theta}^p - T_{r,\theta}^p \right) + \frac{k}{R_r \Delta \theta} \left( T_{r+1,\theta}^p + T_{r,\theta-1}^p - 2T_{r,\theta}^p \right) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{rep}}
\]  

(3.24)

In Eq. 3.24, \( R_r \) denotes the radius at the temperature node and \( L \) represents the length of the cylindrical segment.

Likewise, the heat flux equality at a tissue interface represented by Eq. 3.2 must also be numerically approximated. This approximation is shown below.

\[
k_{\text{in}} \frac{T_{r,\theta} - T_{r-1,\theta}}{\Delta r} = k_{\text{out}} \frac{T_{r+1,\theta} - T_{r,\theta}}{\Delta r}
\]  

(3.25)

The boundary condition at the skin edge represented by Eq. 3.3 can be numerically approximated using Eqs. 3.20 – 3.23. However, for this model, an energy balance equation at the skin surface was utilized to improve the accuracy [6]. Thus, the equation for the outer skin energy balance can also be numerically approximated as shown below.

\[
\frac{T_{r,\theta}^{p+1} - T_{r,\theta}^p}{\Delta t} = \frac{k}{2\Delta r} \left( R_r + R_{r-1} \right) L \left( T_{r-1,\theta}^p - T_{r,\theta}^p \right) + \frac{k}{2R_r \Delta \theta} \left( T_{r+1,\theta}^p + T_{r,\theta-1}^p - 2T_{r,\theta}^p \right) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{ext}}
\]  

(3.26)

As seen from inspection, Eq. 3.24 cannot be used to represent the central core temperature node. However, Osizik devised a finite-difference equation at the center of a cylindrical segment to be able to solve this particular problem [9]. Thus, an energy balance at the center of the core with radius \( \Delta r/2 \) can be formulated using Osizik's
scheme. The numerical approximation at the central core temperature then can be written as

\[
C \frac{T_0^{p+1} - T_0^p}{\Delta t} = \frac{k \Delta \theta L}{2} \left( T_1^p + T_2^p + \ldots + T_6^p - 6T_0^p \right) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gun}} + \dot{Q}_{\text{resp}}
\]  

(3.27)

where \( T_1, T_2, \ldots, T_6 \) represent six temperature nodes (since there are six angular sectors) radially spaced at distance of \( \Delta r \) from the central core temperature node. \( T_0 \) represents the temperature of the central core node.

3.5 RESULTS

The model was simulated using environmental conditions comparable to the experiments of Hall and Klemm [4]. For the simulation, the anterior and posterior sides of the body were exposed to 93.3 °C and −6.7 °C wall temperatures, respectively. The total simulation time was 30 minutes. The simulated subject was assumed to weigh about 70 kg with a 169 cm height. The subject was assumed to be resting, thus the metabolic rate was 81.4 W.

Figures 3.2–3.5 show results that justify modeling two-dimensional heat flow. The desired outputs were the anterior and posterior skin temperatures of the head, trunk, arm and leg. The results clearly show that the model can predict temperature variations on the same body element. As anticipated, the anterior side temperatures of each body element were greater than the posterior side temperatures. The largest temperature differences occur in the trunk. These findings are consistent with data from a two-dimensional human thermal model developed by Kuznetz [6].
Figure 3.6 shows a comparison of predicted anterior skin temperatures between a model developed by Kuznetz and the model proposed in this paper (MU Model). The transient results vary to some degree. However, the difference in output between the two models never exceeds 1.7 °C. At steady state, the difference in output is about 0.6 °C.

Figure 3.7 shows a comparison of predicted posterior skin temperatures with the experimental results of Hall and Klemm. The model tracks the experimental data fairly well with the difference in temperatures never exceeding 0.7 °C. In general, the model predicts cooler posterior skin temperatures than the experiment. This probably indicates that the model some what over-predicts the amount of heat loss due to active sweating.

Figure 3.8 shows the predicted and experimental body core temperature results. Again, there is a strong agreement between the model and experimental results. As expected, the core temperature remains relatively constant throughout the simulation. This is consistent with reality in that the body actively attempts to maintain a constant core temperature using vasomotor functions. If the vasomotor functions aren’t sufficient enough to maintain thermal comfort, then the body either sweats or shivers to insure a comfortable thermal state.

3.6 CONCLUSIONS

A new two-dimensional human thermal model was developed. The model included fingertip and toe temperature predictions along with countercurrent heat exchange involving arteries and veins. Arterial and venous countercurrent heat exchange
is an especially nice feature in that it approaches a realistic representation of the human cardiovascular system.

Results from simulations indicated that the model could also predict varying temperatures on a body segment due to disparate environmental conditions. This is especially important, because astronauts could be exposed to disparate environmental conditions during extra-vehicular activity (EVA) in space. Thermal comfort must be insured even in thermally disparate environments.

The model predicted slightly lower posterior skin temperatures than the experimental findings of Hall and Klemm. There are a few reasons that might possibly explain this finding. For one, the model assumes that latent heat loss for each body segment is evenly distributed to the front and back of the body. However, this assumption might be incorrect if the body is exposed to disparate radiant temperatures. In this particular case, where the back of the body is exposed to a cold radiant temperature, heat loss due to evaporation should occur more at the front of the body, which is exposed to a hot radiant temperature. In addition, the shivering and active sweating functions in the model are driven mainly by the difference in head core and hypothalamic setpoint temperatures. Thus, the model predicts either shivering or sweating at all times. In this case, the model predicted active sweating throughout the simulation. Thus, it is possible that the model predicted some low level of sweat production when in reality the body would not be actively sweating. In the future, both the sweat and shiver models would need to be modified, so that sweating or shivering does not always occur.
There are a few areas where further research is needed. For one, the heat transfer coefficients used in the cardiovascular model are not known with great certainty. More exact values for these parameters need to be determined in the future. In addition, the current cardiovascular model should be upgraded to include the physiological modeling of the arteriovenous anastomoses (AVAs), which are mainly located in the face, ears, hands and feet. AVAs are dense heat exchange vasculature and thus must be addressed in the future. Lastly, the model was created to describe the thermal state of an astronaut in space. Thus, the effects of microgravity on thermal physiology must also be incorporated into any future modeling efforts.
3.7 NOMENCLATURE

\( \dot{Q} \)     Heat flow
\( \rho \)     Density
\( \dot{V} \)     Volume
\( C_p \)     Specific heat capacity
\( T \)     Temperature
\( M \)     Mass
\( \dot{m} \)     Mass flow rate
\( G_{\text{empirical}} \)     Empirically derived gain
\( W \)     Work
\( \mathcal{R} \)     Blood flow reduction via vasoconstriction
\( \gamma \)     Weighting parameter
\( K \)     Various distribution value
\( P \)     Pressure
\( P_{\nu} \)     Partial water vapor pressure
\( P_g \)     Adiabatic saturation pressure of water
\( A \)     Area
\( \sigma \)     Stefan-Boltzmann constant
\( F \)     Interchange factor
\( S \)     Drive for sweating
\( R_w \)     Universal Gas constant for water
\( H_{\text{mass}} \)     Mass transfer coefficient
\( h_{fg} \)     Heat of vaporization for water
\( V_{\text{air}} \)     Velocity of air
\( H \)     Height
\( L \)     Segment length
\( R \)     Radius
\( h \)     Convection coefficient
\( k \)     Thermal conductivity
\( r \)     Denotes radial direction in 2-D conduction
\( \theta \)     Denotes angular direction in 2-D conduction
\( \dot{e}_b \)     Thermal mass blood flow rate
\( hA_a \)     Heat transfer coefficient between arteries and tissue
\( hA_v \)     Heat transfer coefficient between veins and tissue
3.8 REFERENCES


Figure 3.1a: Cylindrical representation of the human form with numbered elements.

Figure 3.1b: Concentric regions in each element
Figure 3.1c: Cross-sectional view of an element and nodal spacing for the nude case.

Figure 3.2: Head skin temperatures
Figure 3.3: Trunk skin temperatures

Figure 3.4: Arm skin temperatures
Figure 3.5: Leg skin temperatures

Figure 3.6: Comparison of predicted anterior skin temperatures between Kuznetz’s and MU Model.
Figure 3.7: Comparison of MU Model predictions and experimental results for posterior skin temperature.

Figure 3.8: Comparison of MU Model predictions and experimental results for body core temperature.
Chapter 4

OVERVIEW OF THE 2-D MU MAN MODEL

4.1 INTRODUCTION

A reliable human thermal model is used to predict the thermal response of subjects under specific conditions of thermal stress for various applications including astronauts performing extravehicular activity (EVA). A reliable model is key in developing strategies for controlling thermal comfort for these astronauts in space. A human thermal model has been developed in the Department of Mechanical and Aerospace Engineering at the University of Missouri-Columbia and is referred to as the MU Model. The model attempts to improve on the 41-Node Man, a model developed by NASA, by including two-dimensional (radial and angular) heat conduction, countercurrent heat exchange between arteries and veins, and digit modeling. For detailed documentation of the MU Model, refer to the technical report written in the appendix. This report discusses modeling issues such as passive and active thermal structure, circulatory system structure, and modeling assumptions. A comprehensive program listing with description, a discussion of the MU Model's various configurations and model usage is also included.
4.2 FEATURES

The MU Model was developed to provide useful results while being easy to use for EVA human thermal comfort evaluation. The modeling platform chosen is MATLAB/SIMULINK™ because of the following features:

- Transient modeling capabilities
- Intuitive graphical interface/User friendly
- Easy to edit or add on different components such as the liquid cooling and ventilation garment (LCVG) and space suit
- Feedback is inherent in the model, thus strategies to control thermal comfort can be implemented with relative ease
- Provides numerical solution without the use of complex, wordy coding.

4.2.1 Clothing Ensembles

The MU Model has the option to be run for three different clothing ensemble options:

1. Nude
2. Clothed
3. LCVG and suit (open loop)

**Ensemble 1** - This ensemble is selected when human thermal response comparisons with other models and experiments are required for the common nude case. This clothing ensemble can be used to study the influence that uncertainty of model parameters, inputs, and/or structural components has on human thermal model response by isolating the nude human from any garment dynamics and interactions.
**Ensemble 2** - This ensemble can be used to describe the human thermal response for a subject in a natural setting while wearing some type of clothing.

**Ensemble 3** - The responses of this model configuration can be verified directly by an LCVG experimental test bed. This ensemble is used to develop and evaluate control strategies that define inlet water and vent temperatures directly. It can also be used for EVA comfort studies.

### 4.2.2 Additional Features

- This model includes radial and angular conduction within each body element in order to handle situations where non-uniform heat generation or disparate environmental conditions exist.

- This model predicts finger and toe temperatures, which may be used in the future to design advanced thermal comfort strategies.

- The heat exchanges between major arteries/veins and tissues are modeled as well as countercurrent heat exchange between arteries and veins. Such modeling approaches a more realistic representation of the circulatory system.

### 4.3 MU MODEL ASSUMPTIONS

Numerous assumptions were made during the development of the human thermal model as with any elaborate modeling effort. They are outlined here.

1. The human form is thermally equivalent to a collection of 14 cylinders.

2. There are four solid tissue varieties in a given segment that can be approximated as concentric cylindrical layers.
3. The digits on each hand and foot can be lumped together as one cylinder.

4. Each layer has thermal properties that do not vary with time.

5. Heat flow is strictly radial and angular (two-dimensional), neglecting axial flow and conduction between adjacent body elements.

6. There are 28 unique blood temperature regions in the human body such that there exists one arterial and venous blood within each element.

7. Perfect heat transfer takes place in the capillary beds.

Work is required to investigate the significance of several of these modeling assumptions, particularly those involving blood dynamics.
Chapter 5

SUMMARY AND FUTURE RESEARCH

5.1 SUMMARY

Dominant parameters of the 41-Node Man model and the Wissler model were identified and ranked by order of importance. The quantitative effect on average skin temperature and body heat storage of nominal uncertainties in the parameters studied was reported. The methodology used was outlined. The value of the results is that researchers using either model can see which parameters, of the ones studied, are most important to evaluate accurately, and what affect the increased accuracy will have on the model being used. The findings indicate that careful determination and/or measurement of hypothalamic setpoint temperature, body area, radiant view factor, body mass, muscular efficiency, and metabolic rate will improve model predictions for both models.

A transient model of human thermoregulation, the 2-D MU Man Model, was developed. The model is an extension of the 41-Node Man model developed by NASA. To further meet NASA design specifications, the model includes two-dimensional heat flow, arterial and venous blood pools within each body element, and explicit digit modeling. The model incorporates the passive and active thermal systems of the human body. Simulation results show that the model is capable of predicting different temperature responses for varying locations on the same body segment, due to disparate
environmental conditions. The model was simulated and compared to data obtained from experiments involving disparate environmental conditions. The model performed fairly well, but there is still room for improvement. The accuracy of the model predictions can be improved by modifying the components of the active thermal system.

5.2 FUTURE RESEARCH

Suggestions for future research are presented below:

• Obtain more accurate heat transfer coefficients for the circulatory model.

• Understand and fully integrate the arteriovenous anastomoses (AVAs) into the model.

• Include the effects of microgravity on human thermal physiology into the model.

• Improve the model’s active control system (i.e. shivering, sweating and vasomotor functions).

• Include cold-induced vasodilation (CIVD) and heat-induced vasoconstriction (HIVC) into the model.

• Adapt the model to account for gender differences.

• Investigate thermal comfort control strategies for NASA, but also for other groups who could benefit i.e. pilots, divers, firefighters, etc.

Future Publications

• Monograph of Human Thermal Modeling

• Autonomic and Preferential Bias

• Advanced Control of Thermal Comfort
• Reduced Order Modeling – How many linearizations are needed to approximate the human body?
Appendix A

PARTIAL DERIVATIVES FOR PARAMETRIC

UNCERTAINTY
A1.0 INTRODUCTION

The partial derivatives of the average skin temperature and body heat storage, with respect to each parameter were calculated. The average skin temperature can be calculated as a surface area weighted sum of each skin temperature

\[ \overline{T}_{sk} = \sum_{i=1}^{10} \beta_i T_{i,4} \]  

(A.1)

where \( \beta_i \) represents the surface area weighting coefficient and \( T_{i,4} \) represents a skin temperature. The summation goes to 10, because there are 10 skin temperatures each corresponding to a body element. Thus, the partial derivative of the average skin temperature with respect to a parameter, \( \alpha \), can be calculated as

\[ \frac{\partial \overline{T}_{sk}}{\partial \alpha} = \sum_{i=1}^{10} \beta_i \frac{\partial T_{i,4}}{\partial \alpha} \]  

(A.2)

and this equation holds for all parameters. The body heat storage can be calculated as

\[ Q_{stor} = \sum_{i=1}^{10} \sum_{j=1}^{4} M_{i,j} C_{p_{i,j}} (T_{i,j} - T_{set_{i,j}}) \]  

(A.3)

where \( M_{i,j} \), \( C_{p_{i,j}} \), \( T_{i,j} \) and \( T_{set_{i,j}} \) represent the mass, specific heat, temperature and setpoint temperature, respectively of the tissue node at the \( i^{th} \) element and \( j^{th} \) tissue layer. For all parameters, except total body mass, specific heats and setpoint temperatures, the partial derivative of the body heat storage with respect to a parameter, \( \alpha \), can be calculated as

\[ \frac{\partial Q_{stor}}{\partial \alpha} = \sum_{i=1}^{10} \sum_{j=1}^{4} M_{i,j} C_{p_{i,j}} \frac{\partial T_{i,j}}{\partial \alpha} \]  

(A.4)

However, additional terms exist for the body mass, specific heats and setpoint temperatures. The partial derivative of body heat storage with respect to the total body mass, \( M_t \), can be calculated as
\[
\frac{\partial Q_{\text{stor}}}{\partial M} = \sum_{i=1}^{10} \sum_{j=1}^{4} \left( M_{i,j} C_{p_{i,j}} \frac{\partial T_{i,j}}{\partial M} + \frac{M_{i,j}}{M} C_{p_{i,j}} (T_{i,j} - T_{\text{set},i,j}) \right) \quad (A.5)
\]

The partial derivative of the body heat storage with respect to the specific heat of the tissue node at the \(k^{th}\) element and \(l^{th}\) tissue layer, \(C_{p_{k,l}}\), can be calculated as

\[
\frac{\partial Q_{\text{stor}}}{\partial C_{p_{k,l}}} = \left( \sum_{i=1}^{10} \sum_{j=1}^{4} M_{i,j} C_{p_{i,j}} \frac{\partial T_{i,j}}{\partial C_{p_{k,l}}} \right) + M_{k,l} (T_{k,l} - T_{\text{set},k,l}) \quad (A.6)
\]

In general, the partial derivative for the body heat storage with respect to any setpoint temperature, \(T_{\text{set},k,l}\), can computed as

\[
\frac{\partial Q_{\text{stor}}}{\partial T_{\text{set},k,l}} = \left( \sum_{i=1}^{10} \sum_{j=1}^{4} M_{i,j} C_{p_{i,j}} \frac{\partial T_{i,j}}{\partial T_{\text{set},k,l}} \right) - M_{k,l} C_{p_{k,l}} \quad (A.7)
\]

### A2.0 METHODOLOGY

As implied by the name of the model, the 41-Node Man has 41 solid temperature nodes comprised of 40 solid tissue nodes and 1 blood pool node. In addition, the respiratory temperature, \(T_{\text{resp}}\), is a function of specific tissue temperatures in the head and trunk, and can be calculated as

\[
T_{\text{resp}} = \sum_{i=1}^{2} \sum_{j} d_{\text{resp},i,j} T_{i,j} \quad (A.8)
\]

where \(d_{\text{resp}}\) represents some weighting coefficient. Thus, the partial derivative of \(T_{\text{resp}}\) with respect to any parameter, \(\alpha\), can be calculated as

\[
\frac{\partial T_{\text{resp}}}{\partial \alpha} = \sum_{i=1}^{2} \sum_{j} d_{\text{resp},i,j} \frac{\partial T_{i,j}}{\partial \alpha} \quad (A.9)
\]

With the inclusion of the \(T_{\text{resp}}\), there are 42 equations that must be simultaneously solved within the model. Thus, for each equation, the partial derivative with respect to
the parameter of interest was calculated. This resulted in 42 unknown partial derivatives of each temperature with respect to the parameter. These 42 partial derivatives where then solved using matrix inversion. Once these partial derivatives were obtained, they were substituted into Equations A.2, A.4 – A.7 to obtain the partial derivative of the average skin temperature and body heat storage, with respect to each parameter.

**A3.0 PARTIAL DERIVATIVE EQUATIONS**

This section shows the partial derivatives for the 40 tissue equations and 1 blood pool equation for each parameter. It would be tedious to write all 41 equations, so instead a representative equation was written for temperature nodes for the core, muscle, fat and skin layer in addition to the one equation for the blood. In each equation, the $i$ subscript represents the number corresponding to each cylindrical body element as shown in Figure A.1.

![Figure A.1: Corresponding numbers to the cylindrical elements in the 41-Node Man.](image)

In the equations, any value ranging between 1 and 10 (corresponding to the elements) can be substituted for $i$. The $j$ subscript ranges from 1-4, corresponding to the core, muscle, fat and skin layer, respectively.
\[ a = A_k \text{(Surface area at each element)} \]

**CORE**

\[ 0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b, bas \ ii,1} \frac{\partial T_b}{\partial \alpha} - d_{resp,1,1} \frac{C_{p,air} P_{air}}{T_{air,abs}} \frac{MR \times K_{resp,sens}}{\partial T_{resp}} \right] - \left( G_{i,1} + e_{b, bas \ ii,1} \right) \frac{\partial T_{i,1}}{\partial \alpha} \]

**MUSCLE**

\[ 0 = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} \]

\[ - \left[ Pow2Blood(T_b - T_{i,2}) + 1 \right] \left[ d_{shlv,1,2} \frac{M_m}{M_m} \left( T_{set,1,1} - T_{i,1} \right) \sum_{n=1}^{10} K_{shlv} \frac{\partial T_{n,4}}{\partial \alpha} \right] \]

\[ - \left[ Pow2Blood(T_b - T_{i,2}) + 1 \right] \left[ d_{shlv,1,2} \frac{M_m}{M_m} \sum_{n=1}^{10} K_{shlv} \left( T_{set,1,4} - T_{n,4} \right) \frac{\partial T_{1,1}}{\partial \alpha} \right] \]

\[ + \left( d_{w,1,2} (MR - Q_{BM}) \right) + \]

\[ + \left( \sum_{n=1}^{10} K_{shlv,2} (T_{set,1,4} - T_{n,4}) \right) d_{shlv,1,2} \frac{M_m}{M_m} \left( T_{set,1,1} - T_{i,1} \right) \]

\[ - d_{resp,1,2} \left( \frac{C_{p,air} P_{air}}{T_{air,abs}} \frac{MR \times K_{resp,sens}}{\partial T_{resp}} \right) \]

\[ - \left( G_{i,1} + G_{i,2} \right) \left[ d_{w,1,2} (MR - Q_{BM}) + \left( \sum_{n=1}^{10} K_{shlv,2} (T_{set,1,4} - T_{n,4}) \right) (T_{set,1,1} - T_{i,1}) \right] \]

\[ \left( d_{shlv,1,2} \frac{M_m}{M_m} \right) \left( Pow2Blood + e_{b, bas \ i,2} \right) \frac{\partial T_{i,2}}{\partial \alpha} \]

**FAT**

\[ 0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} + e_{b, bas \ i,3} \frac{\partial T_b}{\partial \alpha} - d_{resp,1,3} \frac{C_{p,air} P_{air}}{T_{air,abs}} \frac{MR \times K_{resp,sens}}{\partial T_{resp}} \right] \]

\[ - \left( G_{i,2} + G_{i,3} + e_{b, bas \ i,3} \right) \frac{\partial T_{i,3}}{\partial \alpha} \]
\[
- \sigma_f [T_{wall, abs}^4 - (T_k^{,4} + 273.15)^4] = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \\
+ (T_b - T_{i,4}) \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}} \frac{d_{di,i}}{M_{s,0}}}{\partial \alpha} \right) \\
+ \frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
\frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}} \\
\frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
\frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}} \\
\frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
\frac{(T_b - T_{i,4})}{\partial \alpha} \left( \frac{1 + \left( (T_{sel^{,1,1}} - T_{1,1}) + \sum_{n=1}^{10} K_{cons^{n}}(T_{sel^{n,4}} - T_{n,4}) \right) d_{cons^{i}} \frac{M_{s}}{M_{s,0}}}{\partial \alpha} \right) \\
- 4 \alpha \sigma_f (T_{i,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{1,1} - T_{sel^{,1,1}}) d_{sweat^{i}} \left( \frac{2 \cdot \left( \frac{T_{i,4} - T_{sel^{,1,4}}}{K_{sweat^{,1}}} \right) \left( \sum_{n=1}^{10} K_{sweat^{n,4}} \right)}{\partial \alpha} \right) \\
- \left( \frac{\ln(2 \cdot d_{sweat^{i}})}{K_{sweat^{,1}}} \right) \left( \frac{2 \cdot \left( \frac{T_{i,4} - T_{sel^{,1,4}}}{K_{sweat^{,1}}} \right)}{\partial \alpha} \right) \\
- d_{sweat^{i}} \left( \frac{\ln(2 \cdot d_{sweat^{i}})}{K_{sweat^{,1}}} \right) \left( \frac{2 \cdot \left( \frac{T_{i,4} - T_{sel^{,1,4}}}{K_{sweat^{,1}}} \right)}{\partial \alpha} \right)
\]
\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \cdot \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{4} \sum_{j=1}^{4} e_{b, i, j} \right) \frac{\partial T_1}{\partial \alpha} + \]

\[ + \left( \sum_{j=1}^{10} K_{cons} \cdot (T_{set, 1, i} - T_{1, i}) \right) \left( \sum_{j=1}^{10} K_{cons} \cdot \frac{M_s}{M_s^0} \cdot \frac{M_s}{M_s^0} \cdot \frac{d_{cons} i}{d_{div} i} \cdot \frac{M_s}{M_s^0} \right) \frac{\partial T_{1, i}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i, 1} - T_{1, 1}) \right) \left( e_{bat, i, 1} + \sum_{j=1}^{10} K_{cons} \cdot (T_{set, 1, i} - T_{1, i}) \right) \left( \sum_{i=1}^{10} K_{cons} \cdot \frac{M_s}{M_s^0} \cdot \frac{d_{cons} i}{d_{div} i} \cdot \frac{M_s}{M_s^0} \right) \frac{\partial T_{1, 1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i, 1} - T_{1, 1}) \right) \left( e_{bat, i, 1} + \sum_{j=1}^{10} K_{cons} \cdot (T_{set, 1, i} - T_{1, i}) \right) \left( \sum_{i=1}^{10} K_{cons} \cdot \frac{M_s}{M_s^0} \cdot \frac{d_{cons} i}{d_{div} i} \cdot \frac{M_s}{M_s^0} \right) \frac{\partial T_{1, 1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i, 2} - T_{1, 1}) \right) \frac{m_i}{m_0} \left( \sum_{j=1}^{10} K_{shiv, j, 1} \cdot (T_{set, 1, i} - T_{1, i}) \right) \frac{\partial T_{1, 1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i, 2} - T_{1, 1}) \right) \frac{m_i}{m_0} \left( T_{set, 1, i} - T_{1, i} \right) \sum_{j=1}^{10} K_{shiv, j, 1} \frac{\partial T_{1, 1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i, 2} - T_{1, 1}) \right) \left( e_{bat, i, 1} + \sum_{j=1}^{10} K_{cons} \cdot (T_{set, 1, i} - T_{1, i}) \right) \left( \sum_{i=1}^{10} K_{cons} \cdot \frac{M_s}{M_s^0} \cdot \frac{d_{cons} i}{d_{div} i} \cdot \frac{M_s}{M_s^0} \right) \frac{\partial T_{1, 1}}{\partial \alpha} \]

\[ * \text{ Equal to 0 if } T_{set, 1, i} - T_{1, i} \]

\[ ** \text{ Equal to 0 if } T_{1, i} - T_{set, 1, i} \]

\[ *** \text{ Equal to 0 if } T_{set, 1, i} - T_{1, i} \]

\[ **** \text{ Equal to 0 if } T_{1, i} - T_{set, 1, i} \]
\[ \alpha = C_{p,k,i} \text{ (Specific heat capacity at any tissue node)} \]

**CORE**

\[
0 = \left[ G_{l,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas,i,1} \frac{\partial T_{i,1}}{\partial \alpha} - d_{resp,i,1} \frac{C_{p,air} \rho_{air} MR * K_{resp,sens}}{T_{air,abs}} \frac{\partial T_{resp}}{\partial \alpha} \right] - (G_{l,1} + e_{b,bas,i,1}) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
(MR - Q_{bas}) d_{u,i,2} = G_{l,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{l,2} \frac{\partial T_{i,3}}{\partial \alpha} - [Pow2Blood(T_b - T_{i,1}) + 1][d_{shiv,i,2} \frac{M_{m}}{M_{m0}} (T_{set,i,1} - T_{i,1}) \sum_{n=1}^{10} K_{shiv,n} \frac{\partial T_{n,4}}{\partial \alpha}]**

\[
- [Pow2Blood(T_b - T_{i,1}) + 1][d_{shiv,i,2} \frac{M_{m}}{M_{m0}} \sum_{n=1}^{10} K_{shiv,n} (T_{set,n,4} - T_{n,4})] \frac{\partial T_{i,1}}{\partial \alpha} + \{[d_{u,i,2}(MR - \dot{Q}_{BMR}) + (\sum_{n=1}^{10} K_{shiv,n,2} (T_{set,n,4} - T_{n,4})) (T_{set,i,1} - T_{i,1}) d_{shiv,i,2} \frac{M_{m}}{M_{m0}}] Pow2Blood + e_{b,bas,i,2} \frac{\partial T_{b}}{\partial \alpha}
\]

\[
- d_{resp,i,2} \frac{C_{p,air} \rho_{air} MR * K_{resp,sens}}{T_{air,abs}} \frac{\partial T_{resp}}{\partial \alpha}
\]

\[
- [G_{l,1} + G_{l,2} + \{[d_{u,i,2}(MR - \dot{Q}_{BMR}) + (\sum_{n=1}^{10} K_{shiv,n,2} (T_{set,n,4} - T_{n,4})) (T_{set,i,1} - T_{i,1})
\]

\[
* d_{shiv,i,2} \frac{M_{m}}{M_{m0}}] Pow2Blood + e_{b,bas,i,2} \frac{\partial T_{i,2}}{\partial \alpha} \]

**FAT**

\[
0 = \left[ G_{l,2} \frac{\partial T_{i,3}}{\partial \alpha} + G_{l,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,bas,i,2} \frac{\partial T_{b}}{\partial \alpha} - d_{resp,i,3} \frac{C_{p,air} \rho_{air} MR * K_{resp,sens}}{T_{air,abs}} \frac{\partial T_{resp}}{\partial \alpha} \right]
\]

\[- (G_{l,2} + G_{l,3} + e_{b,bas,i,3}) \frac{\partial T_{i,3}}{\partial \alpha} \]

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\[ 0 = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]
\[ + (T_b - T_{i,4}) \left( \frac{1 + \left[ (T_{\text{set},1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const},n} T_{\text{set},n,4} T_{n,4} \right] \frac{M_s}{M_s^0} \frac{d_{\text{dil}}}{} \frac{M_s}{M_s^0} }{1 + \left[ (T_{\text{set},1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const},n} T_{\text{set},n,4} T_{n,4} \right] \frac{M_s}{M_s^0}^2 } \right) \frac{\partial T_{i,1}}{\partial \alpha} \]
\[ \cdot (T_b - T_{i,4}) \left[ \dot{E}_{b,\text{bas},i,4} + (T_{i,4} - T_{\text{set},1,1}) \frac{d_{\text{dil}}}{M_s^0} M_s \frac{M_s}{M_s^0} \frac{\partial T_{i,1}}{\partial \alpha} \right] \]
\[ + \left[ (T_{\text{set},1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const},n} T_{\text{set},n,4} T_{n,4} \right] \frac{M_s}{M_s^0} \frac{\partial T_{i,1}}{\partial \alpha} \]
\[ \cdot \left[ \dot{E}_{b,\text{bas},i,4} + (T_{i,4} - T_{\text{set},1,1}) \frac{d_{\text{dil}}}{M_s^0} M_s \frac{M_s}{M_s^0} \frac{\partial T_{i,1}}{\partial \alpha} \right] \]
\[ - \left[ (T_{\text{set},1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const},n} T_{\text{set},n,4} T_{n,4} \right] \frac{M_s}{M_s^0} \frac{\partial T_{i,1}}{\partial \alpha} \]
\[ - 4 A_i \sigma f_i (T_{i,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{\text{set},1,1}) d_{\text{sweat},i} \left[ 2^\gamma \left( \frac{T_{i,4} - T_{\text{set},1,1}}{K_{\text{sweat},i}} \right) \left( \sum_{n=1}^{10} K_{\text{sweat},n,4} \frac{\partial T_{n,4}}{\partial \alpha} \right) \right] \]
\[ - \left( \frac{\ln 2 \cdot d_{\text{sweat},i}}{K_{\text{sweat},i}} \right) \left[ 2^\gamma \left( \frac{T_{i,4} - T_{\text{set},1,1}}{K_{\text{sweat},i}} \right) (T_{i,1} - T_{\text{set},1,1}) \left( K_{\text{sweat},2} + \sum_{n=1}^{10} K_{\text{sweat},n,4} (T_{n,4} - T_{\text{set},1,1}) \right) \frac{\partial T_{i,1}}{\partial \alpha} \right] \]
\[ - d_{\text{sweat},i} \left( K_{\text{sweat},2} + \sum_{n=1}^{10} K_{\text{sweat},n,4} (T_{n,4} - T_{\text{set},1,1}) \right) \left( 2^\gamma \left( \frac{T_{i,4} - T_{\text{set},1,1}}{K_{\text{sweat},i}} \right) \right) \frac{\partial T_{i,1}}{\partial \alpha} \]
\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b_{i,j}} \frac{\partial T_{l_{i,j}}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b_{i,j}} \right) \frac{\partial T_{l_{1,1}}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \sum_{j=1}^{4} \frac{K_{const} \left(T_{set_{i,j}} - T_{l_{i,j}}\right)}{M_s_{i,j}} \frac{d_{cons} \cdot \frac{M_s_{i,j} - M_s_{i,j}^0}{M_s_{i,j}^0}}{d_{cons} \cdot \frac{M_s_{i,j}^0}{M_s_{i,j}^0}} \frac{\partial T_{l_{i,j}}}{\partial \alpha} \right) \]

\[ + \sum_{i=1}^{10} \left[ \left( T_{l_{i,4}} - T_b \right) \frac{e_{bas_{i,4}} + \left(T_{set_{i,4}} - T_{l_{i,4}}\right)}{d_{bas} \cdot \frac{M_s_{i,4}}{M_s_{i,4}^0}} \frac{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}}{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}} \frac{\partial T_{l_{i,1}}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} \left( T_{l_{i,2}} - T_b \right) \frac{pow2Blood \cdot \frac{d_{shv_{i,2}} \cdot \frac{M_m_{i,2}}{M_m_{i,2}^0}}{\sum_{j=1}^{10} K_{shv_{i,2}} \left(T_{set_{i,4}} - T_{l_{i,4}}\right)} \frac{\partial T_{l_{i,1}}}{\partial \alpha} \right) \}

\[ + \sum_{i=1}^{10} \left( T_{l_{i,4}} - T_b \right) \frac{e_{bas_{i,4}} + \left(T_{set_{i,4}} - T_{l_{i,4}}\right)}{d_{bas} \cdot \frac{M_s_{i,4}}{M_s_{i,4}^0}} \frac{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}}{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}} \frac{\partial T_{l_{i,4}}}{\partial \alpha} \]

\[ + \sum_{i=1}^{10} \left[ \left( T_{l_{i,4}} - T_b \right) \frac{e_{bas_{i,4}} + \left(T_{set_{i,4}} - T_{l_{i,4}}\right)}{d_{bas} \cdot \frac{M_s_{i,4}}{M_s_{i,4}^0}} \frac{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}}{d_{cons} \cdot \frac{M_s_{i,4}^0}{M_s_{i,4}^0}} \frac{\partial T_{l_{i,4}}}{\partial \alpha} \right) \}

* Equal to 0 if \( T_{set_{i,1}} - T_{l_{i,1}} \) 0

** Equal to 0 if \( T_{l_{i,1}} = T_{set_{i,1}} \) 0

*** Equal to 0 if \( T_{set_{i,4}} - T_{l_{i,4}} \) 0

**** Equal to 0 if \( T_{l_{i,4}} = T_{set_{i,4}} \) 0
\[ \alpha = e_{b,k} (\text{Thermal mass blood flow rate to the core of any element, } k) \]

**CORE**

\[
T_{k,1} - T_b^* = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas,1,3} \frac{\partial T_b}{\partial \alpha} - d_{resp,1} \frac{C_{p,air} \rho_{air} MR \ast K_{resp, sens}}{T_{air, abs}} \frac{\partial T_{resp}}{\partial \alpha} \right]
- \left( G_{i,1} + e_{b,bas,1,3} \right) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
0 = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha}
- \left[ \text{Pow2Blood} \left( T_b - T_{i,2} \right) + 1 \right] \left[ d_{shiv,1,2} \frac{M_m}{M_m 0} (T_{set,1,1} - T_{i,1}) \left( \sum_{n=1}^{10} K_{shiv,n} \frac{\partial T_{n,4}}{\partial \alpha} \right) \right]
- \left[ \text{Pow2Blood} \left( T_b - T_{i,2} \right) + 1 \right] \left[ d_{shiv,1,2} \frac{M_m}{M_m 0} \left( \sum_{n=1}^{10} K_{shiv,n} (T_{set,n,4} - T_{n,4}) \right) \frac{\partial T_{i,1}}{\partial \alpha} \right]
+ \left\{ \left[ d_{w,1,2} (MR - \dot{Q}_{BMR}) \right]
+ \left( \sum_{n=1}^{10} K_{shiv,n} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{i,1}) d_{shiv,1,2} \frac{M_m}{M_m 0} \right) \text{Pow2Blood} + e_{b,bas,1,3} \right\} \frac{\partial T_b}{\partial \alpha}
- d_{resp,1} \frac{C_{p,air} \rho_{air} MR \ast K_{resp, sens}}{T_{air, abs}} \frac{\partial T_{resp}}{\partial \alpha}
- \left[ G_{i,1} + G_{i,2} + \left\{ \left[ d_{w,1,2} (MR - \dot{Q}_{BMR}) \right] + \left( \sum_{n=1}^{10} K_{shiv,n} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{i,1}) \right) \right\} \left[ d_{shiv,1,2} \frac{M_m}{M_m 0} \right] \text{Pow2Blood} + e_{b,bas,1,3} \right\} \frac{\partial T_{i,2}}{\partial \alpha}
\]

**FAT**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,bas,1,3} \frac{\partial T_b}{\partial \alpha} - d_{resp,1} \frac{C_{p,air} \rho_{air} MR \ast K_{resp, sens}}{T_{air, abs}} \frac{\partial T_{resp}}{\partial \alpha} \right]
- \left( G_{i,2} + G_{i,3} + e_{b,bas,1,3} \right) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[ 0 = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ + (T_b - T_{i,4}) \left( \frac{1 + \left[ (T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{const} \sigma_n(T_{set,n,4} - T_{n,4}) \right] d_{const} \frac{M_s}{M_s^0} d_{diff} \frac{M_s}{M_s^0} \partial T_{1,1}}{1 + \left[ (T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{const} \sigma_n(T_{set,n,4} - T_{n,4}) \right] d_{const} \frac{M_s}{M_s^0} \partial T_{1,1}} \right) \]

\[ + (T_b - T_{i,4}) \left[ e_{b,bas} \frac{(T_{set,1,1} - T_{1,1}) d_{diff} \frac{M_s}{M_s^0} \partial T_{1,1}}{1 + \left[ (T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{const} \sigma_n(T_{set,n,4} - T_{n,4}) \right] d_{const} \frac{M_s}{M_s^0} \partial T_{1,1}} \right] \]

\[ + \left( T_b - T_{i,4} \right) \left[ e_{b,bas} \frac{(T_{set,1,1} - T_{1,1}) d_{diff} \frac{M_s}{M_s^0} \partial T_{1,1}}{1 + \left[ (T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{const} \sigma_n(T_{set,n,4} - T_{n,4}) \right] d_{const} \frac{M_s}{M_s^0} \partial T_{1,1}} \right] \]

\[ - 4 \cdot \sigma(T_{i,4} - 273.15) \frac{3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{1,1} - T_{set,1,1}) d_{sweat} \frac{2 \frac{T_{i,4} - T_{set,1,1}}{K_{sweat,1}^2}}{\sum_{n=1}^{10} K_{sweat,n,4} \frac{\partial T_{1,1}}{\partial \alpha}} \right) \]

\[ - \frac{\ln \frac{2}{d_{sweat}}} {K_{sweat,1}} \left[ 2 \frac{T_{i,4} - T_{set,1,1}}{K_{sweat,1}} \left( (T_{1,1} - T_{set,1,1}) \frac{2 \frac{\partial T_{1,1}}{\partial \alpha}}{\sum_{n=1}^{10} K_{sweat,n,4} (T_{n,4} - T_{set,n,4})} \right) \right] \]

\[ - d_{sweat} \left( K_{sweat,2} + \sum_{n=1}^{10} K_{sweat,3,n,4} (T_{n,4} - T_{set,n,4}) \right) \left[ 2 \frac{T_{i,4} - T_{set,1,1}}{K_{sweat,1}} \frac{\partial T_{1,1}}{\partial \alpha} \right] \]

\[ - d_{sweat} \left( K_{sweat,2} + \sum_{n=1}^{10} K_{sweat,3,n,4} (T_{n,4} - T_{set,n,4}) \right) \left[ 2 \frac{T_{i,4} - T_{set,1,1}}{K_{sweat,1}} \frac{\partial T_{1,1}}{\partial \alpha} \right] \]
\[ T_b - T_{k,1} = \sum_{i=1}^{10} \sum_{j=1}^{10} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \sum_{i=1}^{10} \sum_{j=1}^{10} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \{1 + [(T_{set,4} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j}(T_{set,4} - T_{1,1})]d_{cons, i} \frac{M_s}{M_s} \frac{M_s - d_{dir, i}}{M_s} \frac{M_s}{M_s} \frac{M_s}{M_s} \} \partial T_{i,1} \right)^{**} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \{e_{bas, i,4} + (T_{set,4} - T_{1,1}) d_{dir, i} \frac{M_s}{M_s} \frac{M_s}{M_s} \} \partial T_{i,1} \right)^{*} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_b) Pow2Blood \frac{d_{shv, i,2} M_m}{M_m^0} \frac{M_m^0}{M_m^0} \frac{M_m^0}{M_m^0} \right)^{**} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_b) Pow2Blood \frac{d_{shv, i,2} M_m}{M_m^0} \frac{M_m^0}{M_m^0} \frac{M_m^0}{M_m^0} \right)^{**} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \{e_{b, bas, i,4} + (T_{1,1} - T_{set,1,1}) d_{dir, i} \frac{M_s}{M_s} \frac{M_s}{M_s} \} \partial T_{i,4} \right)^{***} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \{e_{b, bas, i,4} + (T_{1,1} - T_{set,1,1}) d_{dir, i} \frac{M_s}{M_s} \frac{M_s}{M_s} \} \partial T_{i,4} \right)^{***} \]

* Equal to 0 if \( T_{set,1,1} - T_{1,1} \)
** Equal to 0 if \( T_{1,1} - T_{set,1,1} \)
*** Equal to 0 if \( T_{set,1,4} - T_{1,4} \)
**** Equal to 0 if \( T_{1,4} - T_{set,1,4} \)
+ Equal to 0 if \( k \neq i \)
\[ \alpha = e_{b,k,2} \text{(Thermal mass blood flow rate to the muscle for any element, } k) \]

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas, i,1} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp}, i,1} \frac{C_{p,air} \rho_{air} MR * K_{\text{resp},sens}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - \left( G_{i,1} + e_{b,bas, i,1} \right) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
T_{k,2} - T_{b}^+ = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} - \frac{d_{\text{shiv}, i,2}}{M_{m_0}} M_{m} \frac{T_{\text{set}, i,1} - T_{i,1}}{n} \sum_{n=1}^{10} K_{\text{shiv},n} \frac{\partial T_{n}}{\partial \alpha}
\]

\[
- \frac{d_{\text{shiv}, i,2}}{M_{m_0}} M_{m} \frac{T_{\text{set}, i,1} - T_{i,1}}{n} \sum_{n=1}^{10} K_{\text{shiv},n} \frac{\partial T_{n}}{\partial \alpha}
\]

\[
+ \{ [d_{w,i,2}(MR - \dot{Q}_{BM})] + \]

\[
+ \left( \sum_{n=1}^{10} K_{\text{shiv},n,i,2}(T_{\text{set},i,4} - T_{n,4})(T_{\text{set}, i,1} - T_{i,1}) \right) d_{\text{shiv}, i,2} \frac{M_{m}}{M_{m_0}} \frac{\partial T_{\text{blood}}}{\partial \alpha}
\]

\[- \frac{d_{\text{resp}, i,2}}{M_{m_0}} \frac{C_{p,air} \rho_{air} MR * K_{\text{resp},sens}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[- \left[ G_{i,1} + G_{i,2} + \{ [d_{w,i,3}(MR - \dot{Q}_{BM})] + \left( \sum_{n=1}^{10} K_{\text{shiv},n,i,3}(T_{\text{set},i,4} - T_{n,4})(T_{\text{set}, i,1} - T_{i,1}) \right) \right]^{*}
\]

\[* d_{\text{shiv}, i,2} \frac{M_{m}}{M_{m_0}} \frac{\partial T_{i,2}}{\partial \alpha} \]

**FAT**

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,bas, i,3} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp}, i,3} \frac{C_{p,air} \rho_{air} MR * K_{\text{resp},sens}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right]
\]

\[- \left( G_{i,2} + G_{i,3} + e_{b,bas, i,3} \right) \frac{\partial T_{i,3}}{\partial \alpha}
\]

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\[
0 = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha}
\]
\[
+ (T_b - T_{i,4})(\frac{1 + [(T_{set,1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons,n} (T_{set,n,4} - T_{n,4})] d_{dist}^{1} \frac{M_s}{M_{s,0}} d_{cons}^{1} \frac{M_s}{M_{s,0}}}{1 + [(T_{set,1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons,n} (T_{set,n,4} - T_{n,4})] d_{cons}^{1} \frac{M_s}{M_{s,0}}})^2 \frac{\partial T_{i,1,1}}{\partial \alpha}
\]
\[
+ \frac{(T_b - T_{i,4})[e_{b,bas,1,4} + (T_{i,1} - T_{set,1,1}) d_{dist}^{1} \frac{M_s}{M_{s,0}}]}{1 + [(T_{set,1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons,n} (T_{set,n,4} - T_{n,4})] d_{cons}^{1} \frac{M_s}{M_{s,0}}})^2 \frac{\partial T_{i,1,1}}{\partial \alpha}
\]
\[
+ \frac{\partial T_{i,4}}{M_{s,0}^2} \frac{\partial T_{n,4}}{\partial \alpha}
\]
\[
- 4 A t \sigma f(T_{i,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{set,1,1}) d_{sweat}^{1} \frac{M_s}{M_{s,0}} \frac{\partial T_{i,4}}{\partial \alpha}
\]
\[
- \frac{(ln 2 * d_{sweat}^{1})}{K_{sweat}} [2^\frac{(T_{i,4} - T_{set,1,4})}{K_{sweat}}] (T_{i,1} - T_{set,1,1}) [K_{sweat}^{2} + \sum_{n=1}^{10} K_{sweat,n,4} (T_{n,4} - T_{set,n,4})] \frac{\partial T_{i,4}}{\partial \alpha}
\]
\[
- d_{sweat}^{1} [K_{sweat}^{2} + \sum_{n=1}^{10} K_{sweat,n,4} (T_{n,4} - T_{set,n,4})] \frac{\partial T_{i,1,1}}{\partial \alpha}
\]
\[ T_{b} - T_{k,2} = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \right) \frac{\partial T_{1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_{b}) \left\{ 1 + \left[ (T_{\text{set},1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{\text{const},i}(T_{\text{set},j,4} - T_{j,4}) \right] d_{\text{const},i} \frac{M_{s}}{M_{s,0}} d_{\text{dil},i} \frac{M_{s}}{M_{s,0}} \right\} \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_{b}) \left\{ \hat{e}_{\text{bas}, i, 4} + (T_{\text{set},1,1} - T_{1,1}) d_{\text{dil},i} \frac{M_{s}}{M_{s,0}} \right\} \frac{d_{\text{const},i}}{M_{s,0}} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[- \left( \sum_{i=1}^{10} (T_{i,2} - T_{b}) \text{Pow2Blood} * d_{\text{shiv},i,2} \frac{M_{m}}{M_{m,0}} \left[ \sum_{j=1}^{10} K_{\text{shiv},i,2}(T_{\text{set},j,4} - T_{j,4}) \right] \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[- \left( \sum_{i=1}^{10} (T_{i,2} - T_{b}) \text{Pow2Blood} * d_{\text{shiv},i,2} \frac{M_{m}}{M_{m,0}} (T_{\text{set},1,1} - T_{1,1}) \sum_{j=1}^{10} K_{\text{shiv},i,2} \frac{\partial T_{j,4}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_{b}) \left\{ \hat{e}_{\text{bas}, i, 4} + (T_{1,1} - T_{\text{set},1,1}) d_{\text{dil},i} \frac{M_{s}}{M_{s,0}} \right\} \frac{d_{\text{const},i}}{M_{s,0}} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{j,4}}{\partial \alpha} \right) \]

\[ \sum_{j=1}^{10} K_{\text{const},j} \frac{\partial T_{j,4}}{\partial \alpha} \]

* Equal to 0 if $T_{\text{set},i,1} - T_{1,1} \leq 0$

** Equal to 0 if $T_{i,1} - T_{\text{set},1,1} \leq 0$

*** Equal to 0 if $T_{\text{set},i,4} - T_{i,4} \leq 0$

**** Equal to 0 if $T_{i,4} - T_{\text{set},i,4} \leq 0$

+ Equal to 0 if $k$
\[ \alpha = e_{b,k,3} \] (Thermal mass blood flow rate to the fat for any element, \( k \))

**CORE**

\[
0 = [G_{i,1} \frac{\partial T_{1,2}}{\partial \alpha} + e_{b,bas,1,1} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp},1,1} \frac{C_{p,air} \rho_{air} MR \ast K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}] - (G_{i,1} + e_{b,bas,1,1}) \frac{\partial T_{i,3}}{\partial \alpha}
\]

**MUSCLE**

\[
0 = G_{i,1} \frac{\partial T_{1,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{1,3}}{\partial \alpha}
\]

\[
- [\text{Pow2Blood}(T_b - T_{1,2}) + 1][d_{\text{shv},1,2} \frac{M_m}{M_m 0} (T_{\text{set},1,1} - T_{1,1}) \sum_{n=1}^{10} K_{\text{shv},n} \frac{\partial T_{n,4}}{\partial \alpha}]
\]

\[
- [\text{Pow2Blood}(T_b - T_{1,2}) + 1][d_{\text{shv},1,2} \frac{M_m}{M_m 0} \sum_{n=1}^{10} K_{\text{shv},n}(T_{\text{set},n,4} - T_{n,4})] \frac{\partial T_{1,1}}{\partial \alpha}
\]

\[ + \{[d_{w,1,2}(MR - \dot{Q}_{\text{BMR}}) +
\]

\[ + (\sum_{n=1}^{10} K_{\text{shv},n,2}(T_{\text{set},n,4} - T_{n,4}))(T_{\text{set},1,1} - T_{1,1})d_{\text{shv},1,2} \frac{M_m}{M_m 0} ]\text{Pow2Blood} + e_{b,bas,1,3} \frac{\partial T_b}{\partial \alpha}
\]

\[ - d_{\text{resp},1,2} \frac{C_{p,air} \rho_{air} MR \ast K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[- [G_{i,1} + G_{i,2} + \{[d_{w,1,2}(MR - \dot{Q}_{\text{BMR}}) + (\sum_{n=1}^{10} K_{\text{shv},n,2}(T_{\text{set},n,4} - T_{n,4}))(T_{\text{set},1,1} - T_{1,1})]
\]

\[ * d_{\text{shv},1,2} \frac{M_m}{M_m 0} ]\text{Pow2Blood} + e_{b,bas,1,3} \frac{\partial T_{1,2}}{\partial \alpha}
\]

**FAT**

\[ T_{k,3} - T^* = [G_{i,2} \frac{\partial T_{1,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{1,4}}{\partial \alpha} + e_{b,bas,1,3} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp},1,3} \frac{C_{p,air} \rho_{air} MR \ast K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}]
\]

\[- (G_{i,2} + G_{i,3} + e_{b,bas,1,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]

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\[ 0 = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} + \frac{(T_b - T_{i,4}) \left( \sum_{n=1}^{10} K_{\text{cons}} \left( T_{\text{set}}^{n,4} - T_{n,4} \right) d_{\text{cons}} \left( \frac{M_s}{M_{s,0}} \right) \frac{M_s}{M_{s,0}} \right)}{\left( 1 + \left( T_{\text{set}}^{1,1} - T_{1,1} \right) + \sum_{n=1}^{10} K_{\text{cons}} \left( T_{\text{set}}^{n,4} - T_{n,4} \right) d_{\text{cons}} \left( \frac{M_s}{M_{s,0}} \right) \frac{M_s}{M_{s,0}} \right)^2} \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \frac{(T_b - T_{i,4}) \left( E_{b,\text{bas}}^{i,4} + (T_{1,1} - T_{\text{set}}^{1,1}) d_{\text{dir}} \left( \frac{M_s}{M_{s,0}} \right) \frac{M_s}{M_{s,0}} \right) \frac{\partial T_{1,1}}{\partial \alpha}}{\left( 1 + \left( T_{\text{set}}^{1,1} - T_{1,1} \right) + \sum_{n=1}^{10} K_{\text{cons}} \left( T_{\text{set}}^{n,4} - T_{n,4} \right) d_{\text{cons}} \left( \frac{M_s}{M_{s,0}} \right) \frac{M_s}{M_{s,0}} \right)^2} \]
\[ T_b - T_{k,4} = \sum_{i=1}^{10} \sum_{j=1}^{4} \varepsilon_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} \varepsilon_{b, i, j} \right) \frac{\partial T_1}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ 1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j} (T_{set,1,4} - T_{j,4})] \frac{d_{cons, i} M_{i}}{M_{i,0}} \frac{d_{dist} M_{s}}{M_{s,0}} \right\}}{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j} (T_{set,1,4} - T_{j,4})] \frac{M_{s}}{M_{s,0}} \right)^2 \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ \varepsilon_{bas, i,4} + (T_{set,1,1} - T_{1,1}) d_{dist} M_{s} \right\}}{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j} (T_{set,1,4} - T_{j,4})] \frac{M_{s}}{M_{s,0}} \right)^2 \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} \frac{(T_{i,2} - T_b) \text{Pow2Blood} \ast d_{shiv,1,2} M_{m} \left\{ \sum_{j=1}^{10} K_{shiv, j,2} (T_{set,1,4} - T_{j,4}) \right\}}{M_{m,0}} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} \frac{(T_{i,2} - T_b) \text{Pow2Blood} \ast d_{shiv,1,2} M_{m} \left( T_{set,1,1} - T_{1,1} \right) \sum_{j=1}^{10} K_{shiv, j,2} \frac{\partial T_{j,4}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ \varepsilon_{bas, i,4} + (T_{1,1} - T_{set,1,1}) d_{dist} i \frac{M_{i}}{M_{i,0}} \right\}}{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j} (T_{set,1,4} - T_{j,4})] \frac{M_{s}}{M_{s,0}} \right)^2 \frac{\partial T_{j,4}}{\partial \alpha} \]

* Equal to 0 if \( T_{set,1,1} - T_{1,1} \)
** Equal to 0 if \( T_{1,1} - T_{set,1,1} \)
*** Equal to 0 if \( T_{set,1,4} - T_{1,4} \)
**** Equal to 0 if \( T_{1,4} - T_{set,1,4} \)
+ Equal to 0 if \( k \neq i \)

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\[ \alpha = e_{b,k,4} \] (Thermal mass blood flow rate to the skin layer for each element, \( k \))

**CORE**

\[
0 = [G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,\text{bas},i,1} \frac{\partial T_{i,b}}{\partial \alpha} - d_{\text{resp},i,1} \frac{C_{p,\text{air}} \rho_{\text{air}} M \cdot R \cdot \text{K}_{\text{resp, sens}}}{T_{\text{air, abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}] - (G_{i,1} + e_{b,\text{bas},i,1}) \frac{\partial T_{i,3}}{\partial \alpha}
\]

**MUSCLE**

\[
d_{w,i,2}(M - \dot{Q}_{\text{BMR}}) = G_{i,1} \frac{\partial T_{i,3}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,1}}{\partial \alpha}
\]

\[
-[\text{Pow2Blood}(T_{b} - T_{i,2}) + 1][d_{\text{shiv},i,2} \frac{M_{m}}{M_{m0}}(T_{\text{set},1,1} - T_{1,1}) \sum_{n=1}^{10} K_{\text{shiv},n} \frac{\partial T_{n,4}}{\partial \alpha}]
\]

\[
-[\text{Pow2Blood}(T_{b} - T_{i,2}) + 1][d_{\text{shiv},i,2} \frac{M_{m}}{M_{m0}} \sum_{n=1}^{10} K_{\text{shiv},n}(T_{\text{set},n,4} - T_{n,4}) \frac{\partial T_{i,1}}{\partial \alpha}]
\]

\[
+ \{[d_{w,i,2}(M - \dot{Q}_{\text{BMR}})]
\]

\[
+(\sum_{n=1}^{10} K_{\text{shiv},n,2}(T_{\text{set},n,4} - T_{n,4}))(T_{\text{set},1,1} - T_{1,1}) d_{\text{shiv},i,2} \frac{M_{m}}{M_{m0}} \text{Pow2Blood} + e_{b,\text{bas},i,2} \frac{\partial T_{b}}{\partial \alpha}
\]

\[
- d_{\text{resp},i,2}(C_{p,\text{air}} \rho_{\text{air}} M \cdot R \cdot \text{K}_{\text{resp, sens}}) \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
-G_{i,1} + G_{i,2} + \{[d_{w,i,2}(M - \dot{Q}_{\text{BMR}})] + (\sum_{n=1}^{10} K_{\text{shiv},n,2}(T_{\text{set},n,4} - T_{n,4}))(T_{\text{set},1,1} - T_{1,1})
\]

\[
* d_{\text{shiv},i,2} \frac{M_{m}}{M_{m0}} \text{Pow2Blood} + e_{b,\text{bas},i,2} \frac{\partial T_{i,2}}{\partial \alpha}
\]

**FAT**

\[
0 = [G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,\text{bas},i,1} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},i,3} \frac{C_{p,\text{air}} \rho_{\text{air}} M \cdot R \cdot \text{K}_{\text{resp, sens}}}{T_{\text{air, abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}]
\]

\[-(G_{i,2} + G_{i,3} + e_{b,\text{bas},i,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[ T_{s,4} - T_b^+ = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} + G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ + \frac{E_{b,\text{bas} i,4} + (T_{i,1} - T_{\text{set} 1,1}) d_{\text{diff} i} \frac{M_s}{M_s 0}}{1 + [(T_{\text{set} 1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const}, n}(T_{\text{set} n,4} - T_{n,4})] d_{\text{diff} i} \frac{M_s}{M_s 0}} \frac{\partial T_b}{\partial \alpha} \]

\[ - \frac{E_{b,\text{ons} i,4} + (T_{i,1} - T_{\text{set} 1,1}) d_{\text{diff} i} \frac{M_s}{M_s 0}}{1 + [(T_{\text{set} 1,1} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{const}, n}(T_{\text{set} n,4} - T_{n,4})] d_{\text{diff} i} \frac{M_s}{M_s 0}} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ - 4 A \sigma T^4 (T_{1,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{\text{set} 1,1}) d_{\text{sweat} i}^* 2^\star \left( \frac{T_{i,4} - T_{\text{set} 1,4}}{K_{\text{sweat} 1}} \right) (\sum_{n=1}^{10} K_{\text{sweat} n,4} \frac{\partial T_{n,4}}{\partial \alpha}) \]

\[ - \frac{\ln 2 \cdot d_{\text{sweat} i}^* (2^\star \left( \frac{T_{i,4} - T_{\text{set} 1,4}}{K_{\text{sweat} 1}} \right) (T_{i,1} - T_{\text{set} 1,1}) [K_{\text{sweat} 2} + \sum_{n=1}^{10} K_{\text{sweat} n,4} (T_{n,4} - T_{\text{set} n,4})] \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ - d_{\text{sweat} i} [K_{\text{sweat} 2} + \sum_{n=1}^{10} K_{\text{sweat} n,4} (T_{n,4} - T_{\text{set} n,4})] (2^\star \left( \frac{T_{i,4} - T_{\text{set} 1,4}}{K_{\text{sweat} 1}} \right) ) \frac{\partial T_{1,1}}{\partial \alpha} \]
BLOOD

\[ T_b - T_{k,4} = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b,i,j} \frac{\partial T_{i,j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b,i,j} \right) \frac{\partial T_1}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left[ 1 + (T_{set,i,1} - T_{i,1}) + \sum_{j=1}^{10} K_{cons,i} (T_{set,i,4} - T_{i,4}) \right] d_{cons,i} M_1 \frac{M_1}{M_0} - \frac{M_5}{M_0} \right) \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \right) \left( T_{i,4} - T_b \right) e_{bas,i,4} + (T_{set,i,1} - T_{i,1}) d_{dil,i} \frac{M_1}{M_0} d_{cons,i} M_5 \frac{M_5}{M_0} \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \right) \left( T_{i,4} - T_b \right) e_{bas,i,4} + (T_{i,1} - T_{set,i,1}) d_{dil,i} \frac{M_1}{M_0} d_{cons,i} M_5 \frac{M_5}{M_0} \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shiv,i,2} \frac{M_1}{M_0} \sum_{j=1}^{10} K_{shiv,i,2} (T_{set,j,4} - T_{j,4}) \right) \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shiv,i,2} \frac{M_1}{M_0} (T_{set,i,1} - T_{i,1}) \right) \sum_{j=1}^{10} K_{shiv,j,2} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \right) \left( T_{i,4} - T_b \right) e_{b,bas,i,4} + (T_{i,1} - T_{set,i,1}) d_{dil,i} \frac{M_1}{M_0} d_{cons,i} M_5 \frac{M_5}{M_0} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \right) \left( T_{i,4} - T_b \right) e_{b,bas,i,4} + (T_{i,1} - T_{set,i,1}) d_{dil,i} \frac{M_1}{M_0} d_{cons,i} M_5 \frac{M_5}{M_0} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ \text{\* Equal to 0 if } T_{set,i,1} - T_{i,1} = 0 \]

\[ \text{\** Equal to 0 if } T_{i,1} - T_{set,i,1} = 0 \]

\[ \text{\*** Equal to 0 if } T_{set,i,4} - T_{i,4} = 0 \]

\[ \text{\**** Equal to 0 if } T_{i,4} - T_{set,i,4} = 0 \]

\[ + \text{ Equal to 0 if } k = i \]
\( \alpha = \eta \) (mechanical efficiency)

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,\text{bas} \ i,1} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp} \ i,1} \frac{C_{p,\text{air}} \rho_{\text{air}} MR K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] \quad - \left( G_{i,1} + e_{b,\text{bas} \ i,1} \right) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
(MR - \dot{Q}_{\text{BMR}}) d_{w,i,2} = G_{i,2} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - [\text{Pow2Blood}(T_b - T_{i,2}) + 1][d_{\text{shv},i,2} \frac{M_n}{M_{n,0}} (T_{\text{set},i,1} - T_{i,1}) \sum_{n=1}^{10} K_{\text{shv},n} \frac{\partial T_{n,4}}{\partial \alpha}]^{***}
\]

\[
- [\text{Pow2Blood}(T_b - T_{i,3}) + 1][d_{\text{shv},i,2} \frac{M_n}{M_{n,0}} \sum_{n=1}^{10} K_{\text{shv},n}(T_{\text{set},n,4} - T_{n,4})] \frac{\partial T_{i,1}}{\partial \alpha}
\]

\[
+ \left\{ [d_{w,i,2}(MR - \dot{Q}_{\text{BMR}}) + \right.
\]

\[
+ \left( \sum_{n=1}^{10} K_{\text{shv},n,2}(T_{\text{set},n,4} - T_{n,4})(T_{\text{set},i,1} - T_{i,1}) \right] d_{\text{shv},i,2} \frac{M_n}{M_{n,0}} \text{Pow2Blood} + e_{b,\text{bas} \ i,2} \frac{\partial T_b}{\partial \alpha}
\]

\[
- d_{\text{resp},i,2} \frac{C_{p,\text{air}} \rho_{\text{air}} MR K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
- [G_{i,1} + G_{i,2} + \left\{ [d_{w,i,2}(MR - \dot{Q}_{\text{BMR}}) + \left( \sum_{n=1}^{10} K_{\text{shv},n,2}(T_{\text{set},n,4} - T_{n,4})(T_{\text{set},i,1} - T_{i,1}) \right]^* \right.
\]

\[
* d_{\text{shv},i,2} \frac{M_n}{M_{n,0}} \text{Pow2Blood} + e_{b,\text{bas} \ i,2} \frac{\partial T_{i,2}}{\partial \alpha}
\]

**FAT**

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,\text{bas} \ i,3} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},i,3} \frac{C_{p,\text{air}} \rho_{\text{air}} MR K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right]
\]

\[
- (G_{i,2} + G_{i,3} + e_{b,\text{bas} \ i,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[0 = G_{i,13} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} + (T_b - T_{i,4}) \frac{(1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} d_{div,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}} \]

\[+ (T_b - T_{i,4}) \frac{(1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}} \]

\[+ \frac{(T_b - T_{i,4}) \frac{(1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}} \]

\[-4 \alpha_i \sigma f(T_{i,4} - 273.15)^{3} \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{set,1,1}) d_{sweat,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha} \]

\[- \frac{\ln 2}{K_{sweat,1}} \frac{\partial T_{i,1,1}}{\partial \alpha} - d_{sweat,1} \frac{K_{sweat,2} + \sum_{n=1}^{10} K_{sweat,3}^{n,4}(T_{n,4} - T_{set,n,4}) \frac{\partial T_{i,1,1}}{\partial \alpha}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}} \]

\[-d_{sweat,1} \frac{K_{sweat,2} + \sum_{n=1}^{10} K_{sweat,3}^{n,4}(T_{n,4} - T_{set,n,4}) \frac{\partial T_{i,1,1}}{\partial \alpha}}{1 + [(T_{set,1,1} - T_{i,1,1}) + \sum_{n=1}^{10} K_{const}^n(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_s} \frac{\partial T_{i,1,1}}{\partial \alpha}} \]
\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \right) \frac{\partial T_{1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ 1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons, j} (T_{set,1,4} - T_{1,4})] d_{cons, i} M_s \right\} d_{dif, i} M_s}{M_s} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ \dot{e}_{b, i, 4} + (T_{set,1,1} - T_{1,1}) d_{dif, i} M_s \right\} d_{cons, i} M_s}{M_s} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{1,2} - T_b) P ow2Blood \cdot d_{shv, i, 2} M_m \left\{ \sum_{j=1}^{10} K_{shv, j, 2} (T_{set,1,4} - T_{1,4}) \right\} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{1,2} - T_b) P ow2Blood \cdot d_{shv, i, 2} M_m \left( T_{set,1,1} - T_{1,1} \right) \sum_{j=1}^{10} K_{shv, j, 2} \right) \frac{\partial T_{1,4}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \frac{(T_{i,4} - T_b) \left\{ \dot{e}_{b, i, 4} + (T_{1,1} - T_{set,1,1}) d_{dif, i} M_s \right\} d_{cons, i} M_s}{M_s} \right) \frac{\partial T_{1,4}}{\partial \alpha} \]

* Equal to 0 if \( T_{set,1,1} = T_{1,1} \)

** Equal to 0 if \( T_{1,1} = T_{set,1,1} \)

*** Equal to 0 if \( T_{1,4} = T_{set,1,4} \)

**** Equal to 0 if \( T_{1,4} = T_{set,1,4} \)
\( a = f_k \) (View factor at the element, \( k \))

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b, bas} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp},1,1} \frac{C_{p,\text{air}} \rho_{\text{air}} M R * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - (G_{i,1} + e_{b, bas}) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
0 = G_{i,2} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha}
\]

\[
- [\text{Pow2Blood}(T_b - T_{i,2}) + 1][d_{shiv,i,2}\frac{M_m}{M_{m_0}}(T_{\text{set},1,1} - T_{i,1})]^{10}K_{shiv,n}\frac{\partial T_{n,n,4}}{\partial \alpha}^{**}
\]

\[
- [\text{Pow2Blood}(T_b - T_{i,2}) + 1][d_{shiv,i,2}\frac{M_m}{M_{m_0}}\sum_{n=1}^{10}K_{shiv,n}(T_{\text{set},n,4} - T_{n,4})]\frac{\partial T_{1,1}}{\partial \alpha}^{**}
\]

\[
+ \left\{ d_{w,i,2}(MR - \dot{Q}_{\text{BMR}}) + \right. \]

\[
+ \left( \sum_{n=1}^{10}K_{shiv,n,3}(T_{\text{set},n,4} - T_{n,4}) \right) d_{shiv,i,2}\frac{M_m}{M_{m_0}} \text{Pow2Blood} + e_{b, bas}
\]

\[
- d_{\text{resp},1,2} \left( \frac{C_{p,\text{air}} \rho_{\text{air}} M R * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \right) \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
- [G_{i,1} + G_{i,2} + \left\{ d_{w,i,2}(MR - \dot{Q}_{\text{BMR}}) + \left( \sum_{n=1}^{10}K_{shiv,n,2}(T_{\text{set},n,4} - T_{n,4}) \right) \right. (T_{\text{set},1,1} - T_{1,1})^{*}
\]

\[
* d_{shiv,i,2}\frac{M_m}{M_{m_0}} \text{Pow2Blood} + e_{b, bas}
\]

**FAT**

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b, bas, i,3} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp},1,3} \frac{C_{p,\text{air}} \rho_{\text{air}} M R * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - (G_{i,2} + G_{i,3} + e_{b, bas, i,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[- A_k \sigma \left[ T_{\text{wall, abs}}^4 - (T_k + 273.15)^4 \right] = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[+ (T_b - T_{i,4}) \left( \frac{1}{\{1 + [(T_{\text{set,1,1}} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{cons}} n(T_{\text{set,1,1}}^n - T_{i,1})] d_{\text{cons}}^i M_z M_0}{(M_z M_0)^2} \right) \frac{\partial T_{i,4}}{\partial \alpha} \]

\[(T_b - T_{i,4}) \left[ \frac{e_{b, \text{bas}, i,4} + (T_{i,1} - T_{\text{set,1,1}}) d_{\text{di,1}} M_z M_0}{(M_z M_0)^2} \right] \frac{\partial T_{i,4}}{\partial \alpha} \]

\[+ \frac{\{1 + [(T_{\text{set,1,1}} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{cons}} n(T_{\text{set,1,1}}^n - T_{i,1})] d_{\text{cons}}^i M_z M_0}{(M_z M_0)^2} \sum_{n=1}^{10} K_{\text{cons}}^n \frac{\partial T_{n,4}}{\partial \alpha} \]

\[\frac{\{1 + [(T_{\text{set,1,1}} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{cons}} n(T_{\text{set,1,1}}^n - T_{i,1})] d_{\text{cons}}^i M_z M_0}{(M_z M_0)^2} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[\frac{\{1 + [(T_{\text{set,1,1}} - T_{i,1}) + \sum_{n=1}^{10} K_{\text{cons}} n(T_{\text{set,1,1}}^n - T_{i,1})] d_{\text{cons}}^i M_z M_0}{(M_z M_0)^2} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[- 4 A_s \sigma (T_{i,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{\text{set,1,1}}) d_{\text{sweat}}^i 2^\wedge (T_{i,4} - T_{\text{set,1,1}}) (\sum_{n=1}^{10} K_{\text{sweat,1}} n \frac{\partial T_{n,4}}{\partial \alpha} \]

\[- \left( \frac{\ln 2 * d_{\text{sweat}}}{K_{\text{sweat,1}}} \right) \times [2^\wedge \left( \frac{T_{i,4} - T_{\text{set,1,1}}}{K_{\text{sweat,1}}} \right) (T_{i,1} - T_{\text{set,1,1}}) K_{\text{sweat,2}} + \sum_{n=1}^{10} K_{\text{sweat,3,4}} n(T_{n,4} - T_{\text{set,1,1}}) \frac{\partial T_{i,4}}{\partial \alpha} \]

\[- d_{\text{sweat}}^i (K_{\text{sweat,2}} + \sum_{n=1}^{10} K_{\text{sweat,3,4}} n(T_{n,4} - T_{\text{set,1,1}})) * [2^\wedge \left( \frac{T_{i,4} - T_{\text{set,1,1}}}{K_{\text{sweat,1}}} \right) \frac{\partial T_{i,4}}{\partial \alpha} \]

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\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \left( \sum_{j=1}^{10} K_{\text{con} j} (T_{\text{set}, j, 4} - T_{j, 4}) \frac{d_{\text{cons} j}}{M_{s} M_{s}^0} \frac{M_{s}^0}{M_{s}^0} \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} \left( T_{i, 4} - T_{b} \right) \left[ e_{\text{bas} j, 4} + (T_{\text{set}, 1, 1} - T_{1, 1}) d_{\text{di} j} i \frac{M_{s}^0}{M_{s}^0} \frac{M_{s}^0}{M_{s}^0} \frac{\partial T_{1,1}}{\partial \alpha} \right) \right] \]

\[ - \left( \sum_{j=1}^{10} K_{\text{con} j} (T_{\text{set}, j, 4} - T_{j, 4}) \frac{d_{\text{cons} j}}{M_{s} M_{s}^0} \frac{M_{s}^0}{M_{s}^0} \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[ - \left( \sum_{j=1}^{10} \left( T_{i, 4} - T_{b} \right) \left[ e_{\text{bas} j, 4} + (T_{\text{set}, 1, 1} - T_{1, 1}) d_{\text{di} j} i \frac{M_{s}^0}{M_{s}^0} \frac{M_{s}^0}{M_{s}^0} \frac{\partial T_{1,1}}{\partial \alpha} \right) \right] \]

\[ + \left( \sum_{j=1}^{10} K_{\text{con} j} (T_{\text{set}, j, 4} - T_{j, 4}) \frac{d_{\text{cons} j}}{M_{s} M_{s}^0} \frac{M_{s}^0}{M_{s}^0} \frac{\partial T_{1,1}}{\partial \alpha} \right) \]

\[ * \text{ Equal to 0 if } T_{\text{set}, 1, 1} - T_{1, 1} \]

\[ ** \text{ Equal to 0 if } T_{1, 1} - T_{\text{set}, 1, 1} \]

\[ *** \text{ Equal to 0 if } T_{\text{set}, i, 4} - T_{i, 4} \]

\[ **** \text{ Equal to 0 if } T_{i, 4} - T_{\text{set}, i, 4} \]
\( \alpha = G_{b,1} \) (Thermal conductance between the core and muscle at element, \( k \))

**CORE**

\[
T_{k,1} - T_{k,2} = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas,1,1} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},1,1} \frac{C_{p,\text{air}} \rho_{\text{air}} MR \cdot K_{\text{resp,sens}}}{T_{\text{air},\text{abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] \\
\quad - (G_{i,1} + e_{b,bas,1,1}) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
T_{k,2} - T_{k,1} = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} \\
\quad - [\text{Pow2Blood} (T_{b} - T_{i,3}) + 1] \left[ d_{shiv,i,2} \frac{M_{m}}{M_{m0}} (T_{\text{set},1,1} - T_{1,1}) \sum_{n=1}^{10} K_{\text{shiv},n} \frac{\partial T_{n,4}}{\partial \alpha} \right] \\
\quad - [\text{Pow2Blood} (T_{b} - T_{i,2}) + 1] \left[ d_{shiv,i,2} \frac{M_{m}}{M_{m0}} \sum_{n=1}^{10} K_{\text{shiv},n} (T_{\text{set},n,4} - T_{n,4}) \right] \frac{\partial T_{i,1}}{\partial \alpha} \\
\quad + \left[ d_{w,i,2} (MR - \dot{Q}_{\text{BMR}}) \right] + \\
\quad + \left( \sum_{n=1}^{10} K_{\text{shiv},n,2} (T_{\text{set},n,4} - T_{n,4}) (T_{\text{set},1,1} - T_{1,1}) d_{shiv,i,2} \frac{M_{m}}{M_{m0}} \right] \text{Pow2Blood} + e_{b,bas,1,2} \frac{\partial T_{b}}{\partial \alpha} \\
\quad - d_{\text{resp},1,2} \left( \frac{C_{p,\text{air}} \rho_{\text{air}} MR \cdot K_{\text{resp,sens}}}{T_{\text{air},\text{abs}}} \right) \frac{\partial T_{\text{resp}}}{\partial \alpha} \\
\quad - [G_{i,1} + G_{i,2} + \left( d_{w,i,2} (MR - \dot{Q}_{\text{BMR}}) \right) + \left( \sum_{n=1}^{10} K_{\text{shiv},n,2} (T_{\text{set},n,4} - T_{n,4}) (T_{\text{set},1,1} - T_{1,1}) \right) * d_{shiv,i,2} \frac{M_{m}}{M_{m0}} \right] \text{Pow2Blood} + e_{b,bas,1,2} \frac{\partial T_{i,2}}{\partial \alpha}
\]

**FAT**

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,bas,1,3} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},1,3} \frac{C_{p,\text{air}} \rho_{\text{air}} MR \cdot K_{\text{resp,sens}}}{T_{\text{air},\text{abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] \\
\quad - (G_{i,2} + G_{i,3} + e_{b,bas,1,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[
0 = G_{i,n} \frac{\partial T_{i,n}}{\partial \alpha} - G_{i,n} \frac{\partial T_{i,n}}{\partial \alpha} - G_{i,n} \frac{\partial T_{i,n}}{\partial \alpha} \\
+ (T_b - T_{i,n})(1 + [(T_{text}^{1,1} - T_{i,n}) + \sum_{n=1}^{10} K_{cons}^n(T_{text}^{n,4} - T_{n,4})]d_{cons}^n \frac{M_s}{M_s^n} \frac{d_{di}^n}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ (T_b - T_{i,n})(e_{b,bas}^{i,4} + (T_{i,n} - T_{text}^{1,1})d_{di}^i \frac{M_s}{M_s^n} \frac{d_{cons}^i}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ \frac{\sum_{n=1}^{10} K_{cons}^n(T_{text}^{n,4} - T_{n,4})]d_{cons}^n \frac{M_s}{M_s^n} \frac{d_{di}^n}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ (T_b - T_{i,n})(e_{b,bas}^{i,4} + (T_{i,n} - T_{text}^{1,1})d_{di}^i \frac{M_s}{M_s^n} \frac{d_{cons}^i}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ \frac{\sum_{n=1}^{10} K_{cons}^n(T_{text}^{n,4} - T_{n,4})]d_{cons}^n \frac{M_s}{M_s^n} \frac{d_{di}^n}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ (T_b - T_{i,n})(e_{b,bas}^{i,4} + (T_{i,n} - T_{text}^{1,1})d_{di}^i \frac{M_s}{M_s^n} \frac{d_{cons}^i}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
+ \frac{\sum_{n=1}^{10} K_{cons}^n(T_{text}^{n,4} - T_{n,4})]d_{cons}^n \frac{M_s}{M_s^n} \frac{d_{di}^n}{M_s^n} \frac{M_s}{M_s^n}) \frac{\partial T_{i,n}}{\partial \alpha} \\
- 4A_i \gamma(T_{i,n}^{1,4} - 273.15) \frac{\partial T_{i,n}}{\partial \alpha} - (T_{i,n} - T_{text}^{1,1})d_{sweat}^{i,4} \frac{2^8(T_{i,n}^{1,4} - T_{text}^{1,1}) \sum_{n=1}^{10} K_{sweat}^n(T_{text}^{n,4} - T_{n,4}) \frac{\partial T_{i,n}}{\partial \alpha} \\
- \ln 2 \frac{d_{sweat}^{i,4}}{K_{sweat}^i} \frac{2^8(T_{i,n}^{1,4} - T_{text}^{1,1}) \sum_{n=1}^{10} K_{sweat}^n(T_{text}^{n,4} - T_{n,4}) \frac{\partial T_{i,n}}{\partial \alpha} \\
- d_{sweat}^{i,4}K_{sweat}^i \sum_{n=1}^{10} K_{sweat}^n(T_{text}^{n,4} - T_{n,4}) \frac{2^8(T_{i,n}^{1,4} - T_{text}^{1,1}) \frac{\partial T_{i,n}}{\partial \alpha}}{K_{sweat}^i} 
\]
\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b \ i \ j} \frac{\partial T_{i \ j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b \ i \ j} \right) \frac{\partial T_{i \ j}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \left[ (T_{i \ 4} - T_{b}) \left\{ 1 + \frac{\sum_{j=1}^{10} K_{\text{cons \ j}} (T_{\text{set}, j, 4} - T_{j, 4}) d_{\text{cons \ i}} \left( \frac{M_{s}}{M_{z, 0}} \right) d_{\text{dir \ i}} \left( \frac{M_{s}}{M_{z, 0}} \right) \right] \frac{\partial T_{i \ 1, 1}}{\partial \alpha} \right\} \right) \]

\[ + \left( \sum_{i=1}^{10} \left[ (T_{i \ 4} - T_{b}) \left\{ 1 + \frac{\sum_{j=1}^{10} K_{\text{cons \ j}} (T_{\text{set}, j, 4} - T_{j, 4}) d_{\text{cons \ i}} \left( \frac{M_{s}}{M_{z, 0}} \right) \right] \frac{\partial T_{i \ 1, 1}}{\partial \alpha} \right\} \right) \]

\[ - \left( \sum_{i=1}^{10} (T_{i \ 2} - T_{b}) \frac{d_{\text{shv \ i, 2}} \left( \frac{M_{m}}{M_{m, 0}} \right) \left( \sum_{j=1}^{10} K_{\text{shv \ j, 2}} (T_{\text{set}, j, 4} - T_{j, 4}) \right) \frac{\partial T_{i \ 1 \ 1}}{\partial \alpha} \right) \]

\[ - \left( \sum_{i=1}^{10} (T_{i \ 2} - T_{b}) \frac{d_{\text{shv \ i, 2}} \left( \frac{M_{m}}{M_{m, 0}} \right) (T_{\text{set}, i, 1} - T_{i, 1}) \sum_{j=1}^{10} K_{\text{shv \ j, 2}} \frac{\partial T_{i \ 4}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} \left[ (T_{i \ 4} - T_{b}) \left\{ 1 + \frac{\sum_{j=1}^{10} K_{\text{cons \ j}} (T_{\text{set}, j, 4} - T_{j, 4}) d_{\text{cons \ i}} \left( \frac{M_{s}}{M_{z, 0}} \right) \right] \frac{\partial T_{i \ 4}}{\partial \alpha} \right\} \right) \sum_{j=1}^{10} K_{\text{cons \ j}} \frac{\partial T_{i \ 4}}{\partial \alpha} \]

* Equal to 0 if $T_{\text{set}, i, 1} - T_{i, 1}$

** Equal to 0 if $T_{i, 4} - T_{\text{set}, i, 4}$

*** Equal to 0 if $T_{\text{set}, i, 4} - T_{i, 4}$

**** Equal to 0 if $T_{i, 4} - T_{\text{set}, i, 4}$
\[ a = G_{k,2} \] (Thermal conductance between the muscle and fat at element, \( k \))

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + e_{b, bas i,1} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp}, i,1} \frac{C_{p, \text{air}} \rho_{\text{air}} MR * K_{\text{resp, sens}}}{T_{\text{air, abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - (G_{i,1} + e_{b, bas i,1}) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
T_{k,3} - T_{k,3} = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha}
\]

\[
- \left[ \text{Pow2Blood} (T_b - T_{i,2}) + 1 \right] \left[ d_{\text{shiv}, i,2} \frac{M_m}{M_m 0} (T_{\text{set}, i,1} - T_{i,1}) \sum_{n=1}^{10} K_{\text{shiv}, n} \frac{\partial T_{n,4}}{\partial \alpha} \right] \]

\[
- \left[ \text{Pow2Blood} (T_b - T_{i,2}) + 1 \right] \left[ d_{\text{shiv}, i,2} \frac{M_m}{M_m 0} \sum_{n=1}^{10} K_{\text{shiv}, n} (T_{\text{set}, n,4} - T_{n,4}) \frac{\partial T_{i,1}}{\partial \alpha} \right]
\]

\[
+ \left[ (d_{w, i,2} (MR - \dot{Q}_{Bmr}) + \right]
\]

\[
+ \left( \sum_{n=1}^{10} K_{\text{shiv}, n} (T_{\text{set}, n,4} - T_{n,4}) (T_{\text{set}, i,1} - T_{i,1}) d_{\text{shiv}, i,2} \frac{M_m}{M_m 0} \right] \text{Pow2Blood} + e_{b, bas i,2} \frac{\partial T_b}{\partial \alpha}
\]

\[
- d_{\text{resp}, i,2} \left( \frac{C_{p, \text{air}} \rho_{\text{air}} MR * K_{\text{resp, sens}}}{T_{\text{air, abs}}} \right) \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
- \left[ G_{i,1} + G_{i,2} + \left( \sum_{n=1}^{10} K_{\text{shiv}, n} (T_{\text{set}, n,4} - T_{n,4}) (T_{\text{set}, i,1} - T_{i,1}) \right)
\]

\*
\]

**FAT**

\[
T_{k,3} - T_{k,2} = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b, bas i,3} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp}, i,3} \frac{C_{p, \text{air}} \rho_{\text{air}} MR * K_{\text{resp, sens}}}{T_{\text{air, abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right]
\]

\[
- (G_{i,2} + G_{i,3} + e_{b, bas i,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]
\[ 0 = G_{i,3} \frac{\partial T_{1.3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{1.4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{1.4}}{\partial \alpha} \]

\[ + \left( T_b - T_{1.4} \right) \left( \frac{1 + [(T_{set, l, 1} - T_{1, l}) + \sum_{n=1}^{10} K_{const}^n (T_{set, n, 4} - T_{n, 4})] d_{const} \frac{M_s}{M_{s, 0}} d_{diff} \frac{M_s}{M_{s, 0}}}{1 + [(T_{set, l, 1} - T_{1, l}) + \sum_{n=1}^{10} K_{const}^n (T_{set, n, 4} - T_{n, 4})] d_{const} \frac{M_s}{M_{s, 0}}^2} \right) \frac{\partial T_{1, l}}{\partial \alpha} \]

\[ + \left( T_b - T_{1.4} \right) \left[ \epsilon_{b, bas, i, 4} + (T_{1, l} - T_{set, l, 1}) d_{diff} \frac{M_s}{M_{s, 0}} \right] \frac{\partial T_{1, l}}{\partial \alpha} \]

\[ + \left( T_b - T_{1.4} \right) \left[ \epsilon_{b, bas, i, 4} + (T_{1, l} - T_{set, l, 1}) d_{diff} \frac{M_s}{M_{s, 0}} \right] \sum_{n=1}^{10} K_{const}^n \left( T_{set, n, 4} - T_{n, 4} \right) d_{const} \frac{M_s}{M_{s, 0}} \frac{\partial T_{1, l}}{\partial \alpha} \]

\[ - 4A_{\text{sweat}} \left( T_{1.4} - 273.15 \right) \frac{\partial T_{1.4}}{\partial \alpha} - (T_{1, l} - T_{set, l, 1}) d_{\text{sweat}} \left( \sum_{n=1}^{10} K_{sweat, n, 4} \left( T_{n, 4} - T_{set, n, 4} \right) \right) \frac{\partial T_{1, l}}{\partial \alpha} \]

\[ - \frac{2}{K_{\text{sweat}}} \left( \frac{T_{1.4} - T_{set, l, 4}}{K_{\text{sweat}}} \right) \left( \sum_{n=1}^{10} K_{sweat, n, 4} \left( T_{n, 4} - T_{set, n, 4} \right) \right) \frac{\partial T_{1, l}}{\partial \alpha} \]

\[ - d_{\text{sweat}} \left( K_{\text{sweat}} + \sum_{n=1}^{10} K_{sweat, n, 4} \left( T_{n, 4} - T_{set, n, 4} \right) \right) \frac{\partial T_{1, l}}{\partial \alpha} \]
\[
0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b \ i \ j} \frac{\partial T_{i \ j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b \ i \ j} \right) \frac{\partial T_{i}}{\partial \alpha} \\
+ \left( \sum_{i=1}^{10} \left( T_{i,4} - T_b^* \right) \left[ 1 + \left( T_{set,4} - T_{i,1} \right) + \sum_{j=1}^{10} K_{cons} \left( T_{set,4} - T_{i,4} \right) \right] \frac{d_{cons} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \right) \frac{\partial T_{i,1}}{\partial \alpha} \\
+ \left( \sum_{i=1}^{10} \left( T_{i,4} - T_b^* \right) \left[ e_{bas \ i,4} + \left( T_{set,4} - T_{i,1} \right) \right] \frac{d_{ill} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \right) \frac{\partial T_{i,1}}{\partial \alpha} \\
- \left( \sum_{i=1}^{10} \left( T_{i,2} - T_b \right) \text{Pow2Blood} \left[ d_{shv,2,2} \frac{M_m}{M_m} \left[ \sum_{j=1}^{10} K_{shv,2,2} \left( T_{set,4} - T_{i,4} \right) \right] \right] \frac{\partial T_{i,1}}{\partial \alpha} \\
- \left( \sum_{i=1}^{10} \left( T_{i,2} - T_b \right) \text{Pow2Blood} \left[ d_{shv,2,2} \frac{M_m}{M_m} \left( T_{set,1,1} - T_{i,1} \right) \right] \sum_{j=1}^{10} K_{shv,2,2} \frac{\partial T_{i,4}}{\partial \alpha} \\
+ \left( \sum_{i=1}^{10} \left( T_{i,4} - T_b \right) \left[ e_{b, bas \ i,4} + \left( T_{1,1} - T_{set,1,1} \right) \right] \frac{d_{ill} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \frac{d_{ill} M_s}{M_s} \right) \frac{\partial T_{i,4}}{\partial \alpha} \\
\right) \left[ 1 + \left( T_{set,1,1} - T_{i,1} \right) + \sum_{j=1}^{10} K_{cons} \left( T_{set,4} - T_{i,4} \right) \right] \frac{d_{cons} M_s}{M_s} \frac{d_{cons} M_s}{M_s} \frac{d_{cons} M_s}{M_s} \\
\]

* Equal to 0 if \( T_{set, i,1} - T_{i,1} \) 0
** Equal to 0 if \( T_{i,1} - T_{set, i,1} \) 0
*** Equal to 0 if \( T_{set, i,4} - T_{i,4} \) 0
**** Equal to 0 if \( T_{i,4} - T_{set, i,4} \) 0

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\[
\alpha = G_{k,3} \text{ (Thermal conductance between the fat and skin layer at element, } k) \]

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b, bas, i,1} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},i,1} \frac{C_{p,\text{air}} \rho_{\text{air}} \cdot MR \cdot K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - \left( G_{i,1} + e_{b, bas, i,1} \right) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
0 = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} - \left( [\text{Pow2Blood}(T_{b} - T_{i,2}) + 1] [d_{\text{shiv},i,2} \frac{M_m}{M_{m0}} (T_{\text{set},1,1} - T_{i,1}) \sum_{n=1}^{10} K_{\text{shiv},n} \frac{\partial T_{n,4}}{\partial \alpha}]^{**} \\
- [\text{Pow2Blood}(T_{b} - T_{i,3}) + 1] [d_{\text{shiv},i,2} \frac{M_m}{M_{m0}} \sum_{n=1}^{10} K_{\text{shiv},n}(T_{\text{set},n,4} - T_{n,4}) \frac{\partial T_{i,1}}{\partial \alpha}]
\]

\[
+ \left\{ [d_{w,1,2}(MR - \dot{Q}_{\text{BMR}}) + \\
+ \left( \sum_{n=1}^{10} K_{\text{shiv},n,2}(T_{\text{set},n,4} - T_{n,4})(T_{\text{set},1,1} - T_{i,1}) d_{\text{shiv},i,2} \frac{M_m}{M_{m0}} \right) \text{Pow2Blood} + e_{b, bas, i,2} \right\} \frac{\partial T_{b}}{\partial \alpha}
\]

\[
- d_{\text{resp},i,2} \frac{C_{p,\text{air}} \rho_{\text{air}} \cdot MR \cdot K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
- \left[ G_{i,1} + G_{i,2} + \left\{ [d_{w,1,2}(MR - \dot{Q}_{\text{BMR}}) + \left( \sum_{n=1}^{10} K_{\text{shiv},n,2}(T_{\text{set},n,4} - T_{n,4})(T_{\text{set},1,1} - T_{i,1}) \right] \\
* d_{\text{shiv},i,2} \frac{M_m}{M_{m0}} \right\} \text{Pow2Blood} + e_{b, bas, i,3} \right\} \frac{\partial T_{i,3}}{\partial \alpha}
\]

**FAT**

\[
T_{k,3} - T_{k,4} = \left[ G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b, bas, i,3} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},i,3} \frac{C_{p,\text{air}} \rho_{\text{air}} \cdot MR \cdot K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right]
\]

\[
- (G_{i,2} + G_{i,3} + e_{b, bas, i,3}) \frac{\partial T_{i,2}}{\partial \alpha}
\]

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\[ T_{k,4} - T_{k,3} = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ + \left( T_{b} - T_{i,4} \right) \frac{\left( 1 + \left[ (T_{set,4} - T_{i,4}) + \sum_{n=1}^{10} K_{cons \, n} \left( T_{set,4} - T_{n,4} \right) \right] d_{cons \, i} \frac{M_s}{M_s} d_{dil,4} \frac{M_s}{M_s} \right) \frac{\partial T_{b}}{\partial \alpha} \]

\[ + \left( T_{b} - T_{i,4} \right) \frac{\left( 1 + \left[ (T_{set,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons \, n} \left( T_{set,4} - T_{n,4} \right) \right] d_{cons \, i} \frac{M_s}{M_s} d_{dil,1} \frac{M_s}{M_s} \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \left( T_{b} - T_{i,4} \right) \frac{\left( 1 + \left[ (T_{set,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons \, n} \left( T_{set,4} - T_{n,4} \right) \right] d_{cons \, i} \frac{M_s}{M_s} d_{dil,1} \frac{M_s}{M_s} \right) \frac{\partial T_{n,4}}{\partial \alpha} \]

\[ + \left( T_{b} - T_{i,4} \right) \frac{\left( 1 + \left[ (T_{set,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons \, n} \left( T_{set,4} - T_{n,4} \right) \right] d_{cons \, i} \frac{M_s}{M_s} \right) \frac{\partial T_{b}}{\partial \alpha} \]

\[ + \left( T_{b} - T_{i,4} \right) \frac{\left( 1 + \left[ (T_{set,1} - T_{i,1}) + \sum_{n=1}^{10} K_{cons \, n} \left( T_{set,4} - T_{n,4} \right) \right] d_{cons \, i} \frac{M_s}{M_s} \right) \frac{\partial T_{i,4}}{\partial \alpha} \]

\[- 4 \pi \sigma f(T_{i,4} - 273.15)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{i,1} - T_{set,1}) d_{sweat} \]

\[ + 2 \left( \frac{M_s}{M_s} \right) \sum_{n=1}^{10} K_{sweat \, n} \frac{\partial T_{n,4}}{\partial \alpha} \]

\[- \left( \ln \frac{2}{K_{sweat \, 1}} \right) \frac{d_{sweat}}{K_{sweat \, 1}} \]

\[- d_{sweat} \left( K_{sweat \, 1} + \sum_{n=1}^{10} K_{sweat \, n} \right) \frac{\partial T_{i,1}}{\partial \alpha} \]
BLOOD

\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{10} \epsilon_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{10} \epsilon_{b, i, j} \right) \frac{\partial T_{i}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \left( T_{i,4} - T_{b} \right) \left( 1 + \left( T_{set,1,1} - T_{1,1} \right) + \sum_{j=1}^{10} K_{cons} \left( T_{set,1,4} - T_{1,4} \right) \right) \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} \left( (T_{i,4} - T_{b}) \left( e_{bas, i,4} + (T_{set,1,1} - T_{1,1}) d_{dil,i} \frac{M_s}{M_s^0} d_{cons,i} M_s \frac{M_s}{M_s^0} \right) \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_{b}) Pow2Blood \left( d_{shv,i,2} \frac{M_m}{M_m^0} \left( \sum_{j=1}^{10} K_{shv,j,2} \left( T_{set,1,4} - T_{1,4} \right) \right) \right) \frac{\partial T_{1,1}}{\partial \alpha} \]

\[ - \left( \sum_{i=1}^{10} (T_{i,2} - T_{b}) Pow2Blood \left( d_{shv,i,2} \frac{M_m}{M_m^0} \left( T_{set,1,1} - T_{1,1} \right) \right) \sum_{j=1}^{10} K_{shv,j,2} \frac{\partial T_{1,4}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} \left( (T_{i,4} - T_{b}) \left( e_{bas, i,4} + (T_{1,1} - T_{set,1,1}) d_{dil,i} \frac{M_s}{M_s^0} d_{cons,i} M_s \frac{M_s}{M_s^0} \right) \right) \frac{\partial T_{1,4}}{\partial \alpha} \]

\[ \left( \sum_{i=1}^{10} \left( (T_{i,4} - T_{b}) \left( T_{1,1} - T_{set,1,1} \right) + \sum_{j=1}^{10} K_{cons} \left( T_{set,1,4} - T_{1,4} \right) \right) \right) \frac{\partial T_{1,4}}{\partial \alpha} \]

* Equal to 0 if \( T_{set, l,1} - T_{1,1} \)

** Equal to 0 if \( T_{1,1} - T_{set, l,1} \)

*** Equal to 0 if \( T_{set, l,4} - T_{1,4} \)

**** Equal to 0 if \( T_{1,4} - T_{set, l,4} \)
\( a = G_{k,4} \) (Thermal conductance between the skin and air at element, \( k \))

**CORE**

\[
0 = \left[ G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas i,1} \frac{\partial T_{i,1}}{\partial \alpha} - d_{resp i,1} \frac{C_{p,air} \rho_{air} MR \ast K_{resp,sens}}{T_{air,abs}} \frac{\partial T_{resp}}{\partial \alpha} \right] - \left( G_{i,1} + e_{b,vas i,1} \right) \frac{\partial T_{i,3}}{\partial \alpha}
\]

**MUSCLE**

\[
0 = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha}
\]

\[
- [Pow2Blood(T_b - T_{i,2}) + 1] \left[ d_{shv i,2} \frac{M_m}{M_m0} (T_{set 1,1} - T_{i,1}) \sum_{n=1}^{10} K_{shv n} \frac{\partial T_{n,4}}{\partial \alpha} \right]^* + \frac{\partial T_{i,1}}{\partial \alpha}
\]

\[
+ \{[d_{w i,2}(MR - Q_{BMR}) +
\]

\[
+ \left( \sum_{n=1}^{10} K_{shv n,2}(T_{set n,4} - T_{n,4})(T_{set i,1} - T_{i,1}) d_{shv i,2} \frac{M_m}{M_m0} \right) Pow2Blood + e_{b,vas i,2} \} \frac{\partial T_{b}}{\partial \alpha}
\]

\[
- d_{resp i,2} \left( \frac{C_{p,air} \rho_{air} MR \ast K_{resp,sens}}{T_{air,abs}} \right) \frac{\partial T_{resp}}{\partial \alpha}
\]

\[
- \left[ G_{i,1} + G_{i,2} + \{[d_{w i,2}(MR - Q_{BMR}) + \left( \sum_{n=1}^{10} K_{shv n,2}(T_{set n,4} - T_{n,4})(T_{set i,1} - T_{i,1}) \right)^* \}ight.
\]

\[
\left. *d_{shv i,2} \frac{M_m}{M_m0} \right] Pow2Blood + e_{b,vas i,3} \frac{\partial T_{i,3}}{\partial \alpha}
\]

**FAT**

\[
0 = \left[ G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,vas i,3} \frac{\partial T_{i,1}}{\partial \alpha} - d_{resp i,3} \frac{C_{p,air} \rho_{air} MR \ast K_{resp,sens}}{T_{air,abs}} \frac{\partial T_{resp}}{\partial \alpha} \right]
\]

\[- (G_{i,2} + G_{i,3} + e_{b,vas i,3}) \frac{\partial T_{i,3}}{\partial \alpha} \]
\[ T_{k,4} - T_{d, dry} = G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[
(1 + [(T_{s,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{s, n,4} - T_{n,4})]d_{cons} \frac{M_{s}}{M_{s,0}} d_{dil} \frac{M_{s}}{M_{s,0}}) \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
(T_{b} - T_{i,4})[E_{b, bat} \frac{M_{s}}{M_{s,0}} d_{dil} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
1 + [(T_{s,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{s, n,4} - T_{n,4})]d_{cons} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
(T_{b} - T_{i,4})[E_{b, bat} \frac{M_{s}}{M_{s,0}} d_{dil} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
1 + [(T_{s,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{s, n,4} - T_{n,4})]d_{cons} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
\frac{\partial T_{b}}{\partial \alpha}^* \]

\[
1 + [(T_{s,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{s, n,4} - T_{n,4})]d_{cons} \frac{M_{s}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[
(\ln 2 * d_{sweat} [/K_{sweat}])(\frac{T_{i,4} - T_{s,1,4}}{K_{sweat}}) \frac{\partial T_{i,4}}{\partial \alpha}^* \]

\[-4 Ai_{\sigma f}(Ti,4 - 273.15) \frac{\partial T_{i,4}}{\partial \alpha}^* (T_{i,1} - T_{s,1,1})d_{sweat}^4 * 2^4 \frac{T_{i,4} - T_{s,1,4}}{K_{sweat}} (\sum_{n=1}^{10} K_{sweat,n,n}(T_{n,4} - T_{s, n,4})] \frac{\partial T_{1,1}}{\partial \alpha}^* \]

\[-d_{sweat}^4 (K_{sweat} 2 + \sum_{n=1}^{10} K_{sweat,n,n}(T_{n,4} - T_{s, n,4})] \frac{\partial T_{1,1}}{\partial \alpha}^* \]
\[ 0 = \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \right) \frac{\partial T_{i}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_b) \left[ 1 + \left( (T_{s,1,1} - T_{i,1}) + \sum_{j=1}^{10} K_{cons, i}(T_{s,1,1} - T_{i,1}) \right) d_{cons, i} \frac{M_s}{M_s} \right] d_{diff, i} \frac{M_s}{M_s} \right) \frac{\partial T_{i}}{\partial \alpha} \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_b) \left[ e_{b, i, 4} + (T_{s,1,1} - T_{i,1}) d_{diff, i} \frac{M_s}{M_s} \right] d_{cons, i} \frac{M_s}{M_s} \right) \frac{\partial T_{i}}{\partial \alpha} \]

\[ - \sum_{i=1}^{10} (T_{i,2} - T_b) Pow2Blood * d_{shv, i, 2} \frac{M_m}{M_m} \left( \sum_{j=1}^{10} K_{shv, i, 2}(T_{s,1,1} - T_{j,1}) \right) \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ - \sum_{i=1}^{10} (T_{i,2} - T_b) Pow2Blood * d_{shv, i, 2} \frac{M_m}{M_m} \left( (T_{s,1,1} - T_{i,1}) \sum_{j=1}^{10} K_{shv, i, 2} \frac{\partial T_{j,1}}{\partial \alpha} \right) \]

\[ + \left( \sum_{i=1}^{10} (T_{i,4} - T_b) \left[ e_{b, i, 4} + (T_{s,1,1} - T_{i,1}) d_{diff, i} \frac{M_s}{M_s} \right] d_{cons, i} \frac{M_s}{M_s} \right) \frac{\partial T_{j,4}}{\partial \alpha} \]

\[ + \sum_{i=1}^{10} K_{cons, i}(T_{s,1,1} - T_{j,4}) d_{cons, i} \frac{M_s}{M_s} \]

* Equal to 0 if \( T_{s,1,1} = T_{i,1} \)

** Equal to 0 if \( T_{i,1} = T_{s,1,1} \)

*** Equal to 0 if \( T_{s,1,1} = T_{j,4} \)

**** Equal to 0 if \( T_{j,4} = T_{s,1,1} \)
\[ a = M \text{ (Total body mass)} \]

**CORE**

\[ 0 = \left[ G_{i,1} \cdot \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,\text{bas} \ i,1} \cdot \frac{\partial T_b}{\partial \alpha} - d_{\text{resp} \ i,1} \cdot \frac{C_{\text{p,air}} \cdot \rho_{\text{air} \ MR} \cdot K_{\text{resp,sens}} \cdot \partial T_{\text{resp}}}{T_{\text{air,abs}}} \right] - \left( G_{i,1} + e_{b,\text{bas} \ i,1} \right) \cdot \frac{\partial T_{i,1}}{\partial \alpha} \]

**MUSCLE**

\[ - \frac{d_{\text{mass,m}}}{M_{m_0}} \left[ \text{Pow2Blood}(T_b - T_{i,2}) + 1 \right] \cdot d_{\text{shv} \ i,2} \cdot \frac{T_{\text{set} \ i,1} - T_{i,1}}{M_{m_0}} \cdot \left( \sum_{n=1}^{10} K_{\text{shv} \ n,2} \cdot (T_{\text{set} \ n,4} - T_{n,4}) \right) \]

\[ + \left( \sum_{n=1}^{10} K_{\text{shv} \ n,2} \cdot (T_{\text{set} \ n,4} - T_{n,4}) \right) \cdot d_{\text{shv} \ i,2} \cdot \frac{M_m}{M_{m_0}} \cdot \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ - \left[ \text{Pow2Blood}(T_b - T_{i,2}) + 1 \right] \cdot \left[ d_{\text{shv} \ i,2} \cdot \frac{M_m}{M_{m_0}} \cdot \left( \sum_{n=1}^{10} K_{\text{shv} \ n,2} \cdot (T_{\text{set} \ n,4} - T_{n,4}) \right) \cdot \frac{\partial T_{i,1}}{\partial \alpha} \right] \]

\[ - \left[ \text{Pow2Blood}(T_b - T_{i,2}) + 1 \right] \cdot \left[ d_{\text{shv} \ i,2} \cdot \frac{M_m}{M_{m_0}} \cdot \left( \sum_{n=1}^{10} K_{\text{shv} \ n,2} \cdot (T_{\text{set} \ n,4} - T_{n,4}) \right) \cdot \frac{\partial T_{i,1}}{\partial \alpha} \right] \]

**FAT**

\[ 0 = \left[ G_{i,2} \cdot \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \cdot \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,\text{bas} \ i,3} \cdot \frac{\partial T_b}{\partial \alpha} - d_{\text{resp} \ i,3} \cdot \frac{C_{\text{p,air}} \cdot \rho_{\text{air} \ MR} \cdot K_{\text{resp,sens}} \cdot \partial T_{\text{resp}}}{T_{\text{air,abs}}} \right] - \left( G_{i,2} + G_{i,3} + e_{b,\text{bas} \ i,3} \right) \cdot \frac{\partial T_{i,3}}{\partial \alpha} \]
\[
\frac{d_{\text{mass,t}}(T_b - T_i,4)(T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}}{M_{s,0} + \{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\}} \\
+ \frac{(T_b - T_i,4)[e_{1,1,4} + (T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}][(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{mass,t}}d_{\text{cons}}}{M_{s,0}^2} \\
= G_{1,3} \frac{\partial T_{1,3}}{\partial \alpha} - G_{1,3} \frac{\partial T_{1,4}}{\partial \alpha} - G_{1,4} \frac{\partial T_{1,4}}{\partial \alpha} \\
\{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\} \frac{\partial T_{1,1}}{\partial \alpha} \\
+ (T_b - T_i,4)\frac{[e_{1,1,4} + (T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}]\frac{M_s}{M_{s,0}}}{\frac{\partial T_{1,1}}{\partial \alpha}} \\
\{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\} \frac{\partial T_{1,1}}{\partial \alpha} \\
+ (T_b - T_i,4)\frac{[e_{1,1,4} + (T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}]\frac{M_s}{M_{s,0}}}{\frac{\partial T_{1,1}}{\partial \alpha}} \\
\{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\} \frac{\partial T_{1,1}}{\partial \alpha} \\
\frac{e_{1,1,4} + (T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial T_b} \\
\{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\} \frac{\partial T_{1,1}}{\partial \alpha} \\
\frac{e_{1,1,4} + (T_{\text{set},1,1} - T_{\text{set},1,1})d_{\text{dil}}}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha} \\
\{1 + [(T_{\text{set},1,1} - T_{\text{set},1,1}) + \sum_{n=1}^{10} K_{\text{cons}}(T_{\text{set},n,4} - T_{\text{n,4}})]d_{\text{cons}} \frac{M_s}{M_{s,0}}\} \frac{\partial T_{1,1}}{\partial \alpha} \\
- 4A_{\text{sf}}(T_{1,4} - 273.15) \frac{\partial T_{1,4}}{\partial \alpha} - (T_{1,1} - T_{\text{set},1,1})d_{\text{sweat}} \frac{2^\left(\frac{T_{1,4} - T_{\text{set},1,1}}{K_{\text{sweat,1}}}\right)\left(\sum_{n=1}^{10} K_{\text{sweat},n,4} \frac{\partial T_{1,4}}{\partial \alpha}\right)}{K_{\text{sweat},1}} \\
- \frac{\ln 2 \ast d_{\text{sweat}}}{K_{\text{sweat,1}}} \frac{2^\left(\frac{T_{1,4} - T_{\text{set},1,1}}{K_{\text{sweat,1}}}\right)}{K_{\text{sweat,1}}} \frac{\partial T_{1,1}}{\partial \alpha} \\
-d_{\text{sweat}} \frac{2^\left(\frac{T_{1,4} - T_{\text{set},1,1}}{K_{\text{sweat,1}}}\right)}{K_{\text{sweat,1}}} \frac{\partial T_{1,1}}{\partial \alpha} \\
\frac{2^\left(\frac{T_{1,4} - T_{\text{set},1,1}}{K_{\text{sweat,1}}}\right)}{K_{\text{sweat,1}}} \frac{\partial T_{1,1}}{\partial \alpha}
\]
$$- \sum_{i=1}^{10} \text{Pow2Blood}(T_{i,2} - T_b) d_{shv,1,2}(T_{set,1,1} - T_{1,1})(\sum_{n=1}^{10} k_{shv,n,2}(T_{set,n,4} - T_{n,4})) \frac{d_{mass,m}}{M_{m0}}$$

$$- \frac{d_{mass,t}}{M_{s0}} \sum_{i=1}^{10} \frac{(T_b - T_{i,4})(T_{i,1} - T_{set,1,1}) d_{di,l}^i}{\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{set,n,4} - T_{n,4})]d_{cons}^i \frac{M_s}{M_{s0}}\}^2}$$

$$+ \frac{d_{mass,t}}{M_{s0}} \sum_{i=1}^{10} \frac{(T_b - T_{i,4})(e_{b,bs, i,4} + (T_{set,1,1} - T_{i,1}) d_{di,l}^i \frac{M_s}{M_{s0}})(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{set,n,4} - T_{n,4})]d_{cons}^i \frac{M_s}{M_{s0}}\}^2}$$

$$= \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha} - \sum_{i=1}^{10} \sum_{j=1}^{4} e_{b, i, j} \frac{\partial T_{i, j}}{\partial \alpha}$$

$$+ \sum_{i=1}^{10} \frac{(T_{i,4} - T_b)(1 + [(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{set,n,4} - T_{n,4})]d_{cons}^i \frac{M_s}{M_{s0}}\}^2}$$

$$+ \sum_{i=1}^{10} \frac{(T_{i,4} - T_b)(e_{bs, i,4} + (T_{set,1,1} - T_{i,1}) d_{di,l}^i \frac{M_s}{M_{s0}})(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{set,n,4} - T_{n,4})]d_{cons}^i \frac{M_s}{M_{s0}}\}^2}$$

$$- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shv,1,2} \frac{M_m}{M_{m0}} \sum_{j=1}^{10} K_{shv,j,2}(T_{set,j,4} - T_{j,4}) \frac{\partial T_{1,1}}{\partial \alpha}$$

$$- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shv,1,2} \frac{M_m}{M_{m0}} (T_{set,1,1} - T_{1,1}) \sum_{j=1}^{10} K_{shv,j,2} \frac{\partial T_{j,4}}{\partial \alpha}$$

$$+ \sum_{i=1}^{10} (T_{i,4} - T_b)(e_{b,bs, i,4} + (T_{1,4} - T_{set,1,1}) d_{di,l}^i \frac{M_s}{M_{s0}})(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,n}(T_{set,n,4} - T_{n,4})]d_{cons}^i \frac{M_s}{M_{s0}}\}^2}$$

* Equal to 0 if $T_{set,1,1} - T_{1,1}$

** Equal to 0 if $T_{1,1} - T_{set,1,1}$

*** Equal to 0 if $T_{set,1,1} - T_{1,1}$

**** Equal to 0 if $T_{i,4} - T_{set,i,4}$

0
\[ \alpha = MR \text{ (Metabolic rate)} \]

**CORE**

\[ -d_{\text{resp},1,2} \left[ \frac{K_{\text{resp},1,2} (P_{v,air} - P_{g,resp})}{T_{\text{air,abs}}} + \frac{c_{p,air} P_{air} K_{\text{resp,sens}} (T_{\text{air}} - T_{\text{resp}})}{T_{\text{air,abs}}} \right] = \]

\[ = [G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b,bas,1,1} \frac{\partial T_{i,2}}{\partial \alpha} - d_{\text{resp},1,2} \frac{C_{p,air} P_{air} MR * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}] - (G_{i,1} + e_{b,bas,1,1}) \frac{\partial T_{i,1}}{\partial \alpha} \]

**MUSCLE**

\[ -d_{w,1,2} [\text{Pow2Blood}(T_{b} - T_{i,2}) + (1 - \text{eff})] \]

\[ -d_{\text{resp},1,2} \left[ \frac{K_{\text{resp},1,2} (P_{v,air} - P_{g,resp})}{T_{\text{air,abs}}} + \frac{c_{p,air} P_{air} K_{\text{resp,sens}} (T_{\text{air}} - T_{\text{resp}})}{T_{\text{air,abs}}} \right] = \]

\[ = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha} \]

\[ -[\text{Pow2Blood}(T_{b} - T_{i,2}) + 1][d_{\text{shiv},1,2} \frac{M_{m}}{M_{m0}} (T_{set,1,1} - T_{i,1}) \sum_{n=1}^{10} K_{\text{shiv,n}} \frac{\partial T_{n,4}}{\partial \alpha}] \]

\[ -[\text{Pow2Blood}(T_{b} - T_{i,2}) + 1][d_{\text{shiv},1,2} \frac{M_{m}}{M_{m0}} \sum_{n=1}^{10} K_{\text{shiv,n}} (T_{set,n,4} - T_{n,4})] \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ + \left[ d_{w,1,2} (MR - \dot{Q}_{BMR}) + \sum_{n=1}^{10} K_{\text{shiv,n,2}} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{i,1}) \right] d_{\text{shiv},1,2} \frac{M_{m}}{M_{m0}} \text{Pow2Blood} + e_{b,bas,1,2} \frac{\partial T_{b}}{\partial \alpha} \]

\[ -d_{\text{resp},1,2} \frac{C_{p,air} P_{air} MR * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \]

\[ -[G_{i,1} + G_{i,2} + \left[ d_{w,1,2} (MR - \dot{Q}_{BMR}) + \sum_{n=1}^{10} K_{\text{shiv,n,2}} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{1,1}) \right] \]

\[ * d_{\text{shiv},1,2} \frac{M_{m}}{M_{m0}} \text{Pow2Blood} + e_{b,bas,1,2} \frac{\partial T_{i,2}}{\partial \alpha} ] \]

**FAT**

\[ -d_{\text{resp},1,3} \left[ \frac{K_{\text{resp},1,3} (P_{v,air} - P_{g,resp})}{T_{\text{air,abs}}} + \frac{c_{p,air} P_{air} K_{\text{resp,sens}} (T_{\text{air}} - T_{\text{resp}})}{T_{\text{air,abs}}} \right] = \]

\[ = G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b,bas,1,3} \frac{\partial T_{b}}{\partial \alpha} - d_{\text{resp},1,3} \frac{C_{p,air} P_{air} MR * K_{\text{resp,sens}}}{T_{\text{air,abs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \]

\[ - (G_{i,2} + G_{i,3} + e_{b,bas,1,3}) \frac{\partial T_{i,3}}{\partial \alpha} \]
\[ 0 = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} \]

\[ \{1 + [(T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{const}, n}(T_{\text{set},n,4} - T_{n,4})]d_{\text{cons}} i \frac{M_{s}}{M_{s,0}} \}d_{\text{dll}} i \frac{M_{s}}{M_{s,0}} \partial T_{1,1} \]

\[ + (T_{b} - T_{i,4}) \cdot \frac{(T_{b} - T_{i,4})[(e_{b,\text{bas}}, 1, 4 + (T_{1,1} - T_{\text{set},1,1})d_{\text{dll}} i \frac{M_{s}}{M_{s,0}}]d_{\text{cons}} i \frac{M_{s}}{M_{s,0}} \partial T_{1,1}}{1 + [(T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{const}, n}(T_{\text{set},n,4} - T_{n,4})]d_{\text{cons}} i \frac{M_{s}}{M_{s,0}} \}^2 \partial \alpha} \]

\[ + (T_{b} - T_{i,4}) \cdot \frac{(e_{b,\text{bas}}, 1, 4 + (T_{1,1} - T_{\text{set},1,1})d_{\text{dll}} i \frac{M_{s}}{M_{s,0}}]d_{\text{cons}} i \frac{M_{s}}{M_{s,0}} \partial T_{i,4}}{1 + [(T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{const}, n}(T_{\text{set},n,4} - T_{n,4})]d_{\text{cons}} i \frac{M_{s}}{M_{s,0}} \}^2 \partial \alpha} \]

\[ - 4 \lambda \sigma f (T_{i,4} - 273.15)^{3} \frac{\partial T_{1,4}}{\partial \alpha} - (T_{1,1} - T_{\text{set},1,1})d_{\text{sweat}} i^{*} 2^{*} \left( \frac{T_{i,4} - T_{\text{set},i,4}}{K_{\text{sweat}, 1}} \right) (\sum_{n=1}^{10} K_{\text{sweat}, n, 4} \partial T_{n,4}) \]

\[ - \frac{(\ln 2 * d_{\text{sweat}} i^{*})(T_{i,4} - T_{\text{set},i,4})(T_{1,1} - T_{\text{set},1,1})[K_{\text{sweat}}^{2} + \sum_{n=1}^{10} K_{\text{sweat}, n, 4}(T_{n,4} - T_{\text{set},n,4})] \partial T_{i,4}}{K_{\text{sweat}, 1}} \]

\[ - d_{\text{sweat}} i^{*} [K_{\text{sweat}}^{2} + \sum_{n=1}^{10} K_{\text{sweat}, n, 4}(T_{n,4} - T_{\text{set},n,4})] \left( \frac{T_{i,4} - T_{\text{set},i,4}}{K_{\text{sweat}, 1}} \right) \partial T_{i,1} \]

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- \sum_{i=1}^{10} d_{w,i,2} \text{Pow2Blood}(T_{i,2} - T_b) = \sum_{i=1}^{10} \sum_{j=1}^{4} e_b(i,j) \frac{\partial T_{i,j}}{\partial \alpha} - \left( \sum_{i=1}^{10} \sum_{j=1}^{4} e_b(i,j) \right) \frac{\partial T_i}{\partial \alpha} 

+ \left\{ (T_{i,4} - T_b) \left[ 1 + \left( (T_{set,1,1} - T_{i,1}) + \sum_{j=1}^{10} K_{cons} \frac{M_s}{M_s^0} \frac{1}{d_{cons}} \left[ \frac{M_s}{M_s^0} \right]^2 \frac{M_s}{M_s^0} \right) \frac{\partial T_{i,1}}{\partial \alpha} \right] 

+ \sum_{i=1}^{10} (T_{i,4} - T_b) \left[ e_{bas}(i,4) + (T_{set,1,1} - T_{i,1}) \frac{d_{cons} i}{M_s^0} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,1}}{\partial \alpha} \right\} 

- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shv,i,2} \left[ \frac{M_m}{M_m^0} \frac{1}{d_{shv} i} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,1}}{\partial \alpha} 

- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shv,i,2} \left[ \frac{M_m}{M_m^0} \frac{1}{d_{shv} i} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,1}}{\partial \alpha} 

+ \left\{ (T_{i,4} - T_b) \left[ e_{bas}(i,4) + (T_{i,1} - T_{set,1,1}) \frac{d_{cons} i}{M_s^0} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,4}}{\partial \alpha} \right\} 

\left\{ 1 + \left( (T_{set,1,1} - T_{i,1}) + \sum_{j=1}^{10} K_{cons} \frac{M_s}{M_s^0} \frac{1}{d_{cons}} \left[ \frac{M_s}{M_s^0} \right]^2 \frac{M_s}{M_s^0} \right) \frac{\partial T_{i,1}}{\partial \alpha} \right\} 

\sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} * d_{shv,i,2} \left[ \frac{M_m}{M_m^0} \frac{1}{d_{shv} i} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,1}}{\partial \alpha} 

\sum_{i=1}^{10} (T_{i,4} - T_b) \left[ e_{bas}(i,4) + (T_{i,1} - T_{set,1,1}) \frac{d_{cons} i}{M_s^0} \frac{M_s}{M_s^0} \right] \frac{\partial T_{i,4}}{\partial \alpha} 

* \text{Equal to 0 if } T_{set,1,1} - T_{i,1} = 0 

** \text{Equal to 0 if } T_{i,1} - T_{set,1,1} = 0 

*** \text{Equal to 0 if } T_{set,1,1} - T_{i,1} = 0 

**** \text{Equal to 0 if } T_{i,1} - T_{set,1,1} = 0
\[ \alpha = T_{set\,1,1} \] (Hypothalamic setpoint temperature)

**CORE**

\[
0 = [G_{i,1} \frac{\partial T_{i,2}}{\partial \alpha} + \epsilon_{b,\text{bas} i,1} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp}, i,1} \frac{C_{p,\text{air}} \rho_{\text{air}} MR \ast K_{\text{resp,sens}}}{T_{\text{air,obs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}] - (G_{i,1} + \epsilon_{b,\text{bas} i,1}) \frac{\partial T_{i,1}}{\partial \alpha}
\]

**MUSCLE**

\[
- [\text{Pow2Blood} (T_b - T_{i,2}) + 1] d_{\text{shiv}, i,2} \frac{M_m}{M_{m_0}} \sum_{n=1}^{10} k_{\text{shiv}, n, 2} (T_{set, n, 4} - T_{n, 4}) = G_{i,1} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2} \frac{\partial T_{i,3}}{\partial \alpha}
\]

\[
- [\text{Pow2Blood} (T_b - T_{i,3}) + 1] \left[ d_{\text{shiv}, i,2} \frac{M_m}{M_{m_0}} (T_{set, 1, 1} - T_{1,1}) \sum_{n=1}^{10} K_{\text{shiv}, n} \frac{\partial T_{n,4}}{\partial \alpha} \right]
\]

\[
- [\text{Pow2Blood} (T_b - T_{i,3}) + 1] \left[ d_{\text{shiv}, i,2} \frac{M_m}{M_{m_0}} \sum_{n=1}^{10} K_{\text{shiv}, n} (T_{set, n, 4} - T_{n, 4}) \right] \frac{\partial T_{i,1}}{\partial \alpha}
\]

\[
+ \left[ d_{w, i,2} (MR - \dot{Q}_{\text{BMR}}) + \sum_{n=1}^{10} k_{\text{shiv}, n, 2} (T_{set, n, 4} - T_{n, 4}) (T_{set, 1, 1} - T_{1,1}) d_{\text{shiv}, i,2} \frac{M_m}{M_{m_0}} \right] \text{Pow2Blood} + \epsilon_{b,\text{bas} i,2} \frac{\partial T_b}{\partial \alpha}
\]

\[
- d_{\text{resp}, i,2} \frac{C_{p,\text{air}} \rho_{\text{air}} MR \ast K_{\text{resp,sens}}}{T_{\text{air,obs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}
\]

\[
- [G_{i,1} + G_{i,2} + \left[ d_{w, i,2} (MR - \dot{Q}_{\text{BMR}}) + \sum_{n=1}^{10} k_{\text{shiv}, n, 2} (T_{set, n, 4} - T_{n, 4}) (T_{set, 1, 1} - T_{1,1}) \right]
\]

\[
* d_{\text{shiv}, i,2} \frac{M_m}{M_{m_0}} \right] \text{Pow2Blood} + \epsilon_{b,\text{bas} i,2} \frac{\partial T_{i,2}}{\partial \alpha}
\]

**FAT**

\[
0 = [G_{i,2} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + \epsilon_{b,\text{bas} i,3} \frac{\partial T_b}{\partial \alpha} - d_{\text{resp}, i,3} \frac{C_{p,\text{air}} \rho_{\text{air}} MR \ast K_{\text{resp,sens}}}{T_{\text{air,obs}}} \frac{\partial T_{\text{resp}}}{\partial \alpha}]
\]

\[- (G_{i,2} + G_{i,3} + \epsilon_{b,\text{bas} i,3}) \frac{\partial T_{i,3}}{\partial \alpha}
\]

**SKIN**

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\[\begin{align*}
(T_b - T_i,4)_{eb, bas} & = 4 + (T_{1,1} - T_{set,1,1})d_{diff} \frac{M_s}{M_s^0} d_{cons} \frac{M_s}{M_s^0} \\
\left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2
\end{align*}\]

\[\begin{align*}
(T_b - T_i,4) & \left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2
\end{align*}\]

\[\begin{align*}
- d_{sweat} (K_{sweat}^2 + \sum_{n=1}^{10} K_{sweat}^n (T_n - T_{sweat,n})) \left[2^\left(\frac{T_{sweat,n,4}}{T_{sweat}}\right)\right] & = G_i \frac{\partial T_{i,3}}{\partial \alpha} - G_i \frac{\partial T_{i,4}}{\partial \alpha}
\end{align*}\]

\[\begin{align*}
\frac{\partial T_{i,4}}{\partial \alpha} & + (T_b - T_{i,4}) \left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2 \\
\left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2 \\
\left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2
\end{align*}\]

\[\begin{align*}
(T_b - T_i,4)_{eb, bas} & = 4 + (T_{1,1} - T_{set,1,1})d_{diff} \frac{M_s}{M_s^0} d_{cons} \frac{M_s}{M_s^0} \\
\left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2
\end{align*}\]

\[\begin{align*}
(T_b - T_i,4)_{eb, bas} & = 4 + (T_{1,1} - T_{set,1,1})d_{diff} \frac{M_s}{M_s^0} d_{cons} \frac{M_s}{M_s^0} \\
\left\{1 + \left[\left(T_{set,1,1} - T_{1,1}\right) + \sum_{n=1}^{10} K_{cons}^n (T_{set,n,4} - T_{n,4})\right] d_{cons} \frac{M_s}{M_s^0} \right\}^2
\end{align*}\]

\[\begin{align*}
-4A \sigma_i (T_{i,4} + 27315)^3 \frac{\partial T_{i,4}}{\partial \alpha} - (T_{1,1} - T_{set,1,1})d_{sweat} \left(2^\left(\frac{T_{set,4}}{K_{sweat}}\right)\right) \left(\sum_{n=1}^{10} K_{sweat}^n (T_{n,4} - T_{sweat,n})\right)
\end{align*}\]
\[-\left(\frac{2 \cdot d_{\text{sweat}, i}}{K_{\text{sweat}, 1}}\right) \cdot \left[2^\left(\frac{T_{i, 4} - T_{\text{set}, i, 4}}{K_{\text{sweat}, 1}}\right)\right] \left(T_{i, 1} - T_{\text{set}, i, 1}\right) \left[K_{\text{sweat}, 2} + \sum_{n=1}^{10} K_{\text{sweat}, n, 4} (T_{n, 4} - T_{\text{set}, n, 4})\right] \frac{\partial T_{i, 4}}{\partial \alpha} \]
\[-d_{\text{sweat}, i} \left[K_{\text{sweat}, 2} + \sum_{n=1}^{10} K_{\text{sweat}, n, 4} (T_{n, 4} - T_{\text{set}, n, 4})\right] \left[2^\left(\frac{T_{i, 4} - T_{\text{set}, i, 4}}{K_{\text{sweat}, 1}}\right)\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{**} \]

**BLOOD**

\[
(T_b - T_{i, 4}) \left[\frac{e_{b, \text{bas}, i, 4} + (T_{1, 1} - T_{\text{set}, 1, 1}) d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right]}{1 + \left[\left(T_{\text{set}, 1, 1} - T_{1, 1}\right) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right]} \right]^* + \]
\[
\sum_{i=1}^{10} \left(T_{i, 4} - T_b\right) \left[\frac{(T_{\text{set}, 1, 1} - T_{1, 1}) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{**} \]
\[
\sum_{i=1}^{10} \left(T_{i, 4} - T_b\right) \left[\frac{(T_{\text{set}, 1, 1} - T_{1, 1}) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{*} \]
\[
\sum_{i=1}^{10} \left(T_{i, 4} - T_b\right) \left[\frac{(T_{\text{set}, 1, 1} - T_{1, 1}) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{***} \]
\[
\sum_{i=1}^{10} \left(T_{i, 4} - T_b\right) \left[\frac{(T_{\text{set}, 1, 1} - T_{1, 1}) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{****} \]
\[
\sum_{i=1}^{10} \left(T_{i, 4} - T_b\right) \left[\frac{(T_{\text{set}, 1, 1} - T_{1, 1}) + \sum_{j=1}^{10} K_{\text{cont}, j} (T_{\text{set}, j, 4} - T_{4, 4})\right] d_{\text{dil}, i} \left[\frac{M_s}{M_s 0}\right] d_{\text{cont}, i} \left[\frac{M_s}{M_s 0}\right] \frac{\partial T_{i, 1}}{\partial \alpha}^{*****} \]

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* Equal to 0 if \( T_{\text{set},1} - T_{i,1} \) 0
** Equal to 0 if \( T_{i,1} - T_{\text{set},1} \) 0
*** Equal to 0 if \( T_{\text{set},i,4} - T_{i,4} \) 0
**** Equal to 0 if \( T_{i,4} - T_{\text{set},i,4} \) 0
\[ \alpha = T_{set,k,4} \] (Skin setpoint temperature at element, \( k \))

**CORE**

\[ 0 = \left[ G_{i,1 \alpha} \frac{\partial T_{i,2}}{\partial \alpha} + e_{b, bas i,1} \frac{\partial T_{b,1}}{\partial \alpha} - d_{\text{resp},i,1} \frac{C_{p, air \varphi \text{air}} \text{MR} \ast K_{\text{resp.sens}}}{T_{\text{air, bas}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] - \left( G_{i,1 \alpha} + e_{b, bas i,1} \right) \frac{\partial T_{i,1}}{\partial \alpha} \]

**MUSCLE**

\[ - \left[ \text{Pow2Blood} (T_b - T_{i,2}) + 1 \right] d_{shv, i,2} \frac{M_m}{M_{m0}} \left( T_{set,1,1} - T_{i,1} \right) k_{shv,k,2} \]

\[ = G_{i,1 \alpha} \frac{\partial T_{i,1}}{\partial \alpha} + G_{i,2 \alpha} \frac{\partial T_{i,3}}{\partial \alpha} \]

\[ - \left[ \text{Pow2Blood} (T_b - T_{i,2}) + 1 \right] \left[ d_{shv, i,2} \frac{M_m}{M_{m0}} \left( T_{set,1,1} - T_{i,1} \right) \sum_{n=1}^{10} K_{shv,n} \frac{\partial T_{n,4}}{\partial \alpha} \right] \]

\[ - \left[ \text{Pow2Blood} (T_b - T_{i,2}) + 1 \right] \left[ d_{shv, i,2} \frac{M_m}{M_{m0}} \sum_{n=1}^{10} K_{shv,n} \left( T_{set,n,4} - T_{n,4} \right) \right] \frac{\partial T_{i,1}}{\partial \alpha} \]

\[ + \left\{ \left[ d_{w, i,2} (MR - \dot{Q}_{\text{BMR}}) \right] + \left( \sum_{n=1}^{10} K_{shv,n,2} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{i,1}) d_{shv, i,2} \frac{M_m}{M_{m0}} \right] \text{Pow2Blood} + e_{b, bas i,2} \right\} \frac{\partial T_{b,1}}{\partial \alpha} \]

\[- d_{\text{resp},i,2} \left( \frac{C_{p, air \varphi \text{air}} \text{MR} \ast K_{\text{resp.sens}}}{T_{\text{air, bas}}} \right) \frac{\partial T_{\text{resp}}}{\partial \alpha} \]

\[ - \left( G_{i,1} + G_{i,2} \right) \left\{ \left[ d_{w, i,2} (MR - \dot{Q}_{\text{BMR}}) \right] + \left( \sum_{n=1}^{10} K_{shv,n,2} (T_{set,n,4} - T_{n,4}) (T_{set,1,1} - T_{i,1}) \right) \right\} \]

\[ \left[ d_{shv, i,2} \frac{M_m}{M_{m0}} \right] \text{Pow2Blood} + e_{b, bas i,2} \frac{\partial T_{i,2}}{\partial \alpha} \]

**FAT**

\[ 0 = \left[ G_{i,2 \alpha} \frac{\partial T_{i,2}}{\partial \alpha} + G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} + e_{b, bas i,3} \frac{\partial T_{b,3}}{\partial \alpha} - d_{\text{resp},i,3} \frac{C_{p, air \varphi \text{air}} \text{MR} \ast K_{\text{resp.sens}}}{T_{\text{air, bas}}} \frac{\partial T_{\text{resp}}}{\partial \alpha} \right] \]

\[ - \left( G_{i,2} + G_{i,3} + e_{b, bas i,3} \right) \frac{\partial T_{i,3}}{\partial \alpha} \]
\[
\begin{aligned}
& (T_b - T_{i,4}) \left[ \dot{E}_{b,\text{bas},i,4} + (T_{1,1} - T_{\text{set},1,1}) d_{\text{dil},i} \frac{M_s}{M_z} d_{\text{cons},i} \frac{M_s}{M_z} k_{\text{cons},k} \right] \\
& \quad + \left\{ 1 + \left[ (T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{cons},n} (T_{\text{set},n,4} - T_{n,4}) \right] d_{\text{cons},i} \frac{M_s}{M_z} \right\}^2 \frac{\partial T_{i,4}}{\partial \alpha} \\
& \quad - (T_{1,1} - T_{\text{set},1,1}) d_{\text{sweat},i,2} \frac{K_{\text{sweat},i}}{k_{\text{sweat},i}} k_{\text{sweat},3} \frac{M_s}{M_z} \frac{4}{4} \\
& \quad - \left( \frac{\ln 2 \ast d_{\text{sweat},i}}{K_{\text{sweat},i}} \right) \ast \left[ 2^\wedge \left( \frac{T_{1,4} - T_{\text{set},1,4}}{K_{\text{sweat},i}} \right) \right] (T_{1,1} - T_{\text{set},1,1}) [K_{\text{sweat},2} + \sum_{n=1}^{10} K_{\text{sweat},3,n,4} (T_{n,4} - T_{\text{set},n,4})] \frac{\partial T_{i,4}}{\partial \alpha} \\
& \quad = G_{i,3} \frac{\partial T_{i,3}}{\partial \alpha} - G_{i,3} \frac{\partial T_{i,4}}{\partial \alpha} - G_{i,4} \frac{\partial T_{i,4}}{\partial \alpha} + \\
& \quad \left\{ 1 + \left[ (T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{cons},n} (T_{\text{set},n,4} - T_{n,4}) \right] d_{\text{cons},i} \frac{M_s}{M_z} \right\}^2 \frac{\partial T_{i,1,1}}{\partial \alpha} \\
& + (T_b - T_{i,4}) \left[ \dot{E}_{b,\text{bas},i,4} + (T_{1,1} - T_{\text{set},1,1}) d_{\text{dil},i} \frac{M_s}{M_z} d_{\text{cons},i} \frac{M_s}{M_z} \frac{\partial T_{i,1,1}}{\partial \alpha} \right] \\
& \quad + \left\{ 1 + \left[ (T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{cons},n} (T_{\text{set},n,4} - T_{n,4}) \right] d_{\text{cons},i} \frac{M_s}{M_z} \right\}^2 \frac{\partial T_{n,4}}{\partial \alpha} \\
& + (T_b - T_{i,4}) \left[ \dot{E}_{b,\text{bas},i,4} + (T_{1,1} - T_{\text{set},1,1}) d_{\text{dil},i} \frac{M_s}{M_z} d_{\text{cons},i} \frac{M_s}{M_z} \frac{\partial T_{b}}{\partial \alpha} \right] \\
& \quad + 1 + \left[ (T_{\text{set},1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{\text{cons},n} (T_{\text{set},n,4} - T_{n,4}) \right] d_{\text{cons},i} \frac{M_s}{M_z} \frac{\partial T_{i,4}}{\partial \alpha} \\
& - 4 A_{i} \sigma f(T_{i,4} - 273.15) \frac{3}{\partial \alpha} \left( \frac{\partial T_{i,4}}{\partial \alpha} \right) - (T_{1,1} - T_{\text{set},1,1}) d_{\text{sweat},i} \frac{2}{2} \left( \frac{T_{1,4} - T_{\text{set},1,4}}{K_{\text{sweat},i}} \right) \sum_{n=1}^{10} K_{\text{sweat},n,4} \frac{\partial T_{n,4}}{\partial \alpha} \\
& - \left( \frac{\ln 2 \ast d_{\text{sweat},i}}{K_{\text{sweat},i}} \right) \ast \left[ 2^\wedge \left( \frac{T_{1,4} - T_{\text{set},1,4}}{K_{\text{sweat},i}} \right) \right] (T_{1,1} - T_{\text{set},1,1}) [K_{\text{sweat},2} + \sum_{n=1}^{10} K_{\text{sweat},3,n,4} (T_{n,4} - T_{\text{set},n,4})] \frac{\partial T_{i,4}}{\partial \alpha} \\
& - d_{\text{sweat},i} [K_{\text{sweat},2} + \sum_{n=1}^{10} K_{\text{sweat},3,n,4} (T_{n,4} - T_{\text{set},n,4})] \ast \left[ 2^\wedge \left( \frac{T_{1,4} - T_{\text{set},1,4}}{K_{\text{sweat},i}} \right) \right] \frac{\partial T_{i,1,1}}{\partial \alpha}
\end{aligned}
\]
\[- \sum_{i=1}^{10} \text{Pow2Blood}(T_{i,1} - T_b) d_{shv,1,2} \frac{M_m}{M_{m,0}} (T_{set,1,1} - T_{1,1}) k_{shv,1,2}^* \]
\[+ \sum_{i=1}^{10} (T_{i,4} - T_b) [e_{b, bas, i,4} + (T_{1,1} - T_{set,1,1})] d_{di,1} \frac{M_s}{M_{s,0}} k_{cons,1} \]
\[\quad \times \sum_{n=1}^{10} \frac{[\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,1}(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}]^2}{\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{n=1}^{10} K_{cons,1}(T_{set,n,4} - T_{n,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}} \]
\[= \sum_{i=1}^{10} \sum_{j=1}^4 e_{b, i, j} \frac{\partial T_{i,j}}{\partial \alpha} - \sum_{i=1}^{10} \sum_{j=1}^4 e_{b, i, j} \frac{\partial T_{1,j}}{\partial \alpha} \]
\[+ \sum_{i=1}^{10} (T_{i,4} - T_b) \{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons,1}(T_{set,j,4} - T_{j,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \} d_{di,1} \frac{M_s}{M_{s,0}} \frac{\partial T_{1,1}}{\partial \alpha} \]
\[+ \sum_{i=1}^{10} [e_{set, i,4} + (T_{set,1,1} - T_{1,1})] d_{di,4} \frac{M_s}{M_{s,0}} k_{cons,1} \]
\[\quad \times \sum_{j=1}^{10} \frac{[\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons,1}(T_{set,j,4} - T_{j,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}]^2}{\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons,1}(T_{set,j,4} - T_{j,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}} \]
\[- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} \times d_{shv,1,2} \frac{M_m}{M_{m,0}} [\sum_{j=1}^{10} K_{shv,1,2}(T_{set,j,4} - T_{j,4})] \frac{\partial T_{1,1}}{\partial \alpha} \]
\[- \sum_{i=1}^{10} (T_{i,2} - T_b) \text{Pow2Blood} \times d_{shv,1,2} \frac{M_m}{M_{m,0}} (T_{set,1,1} - T_{1,1}) \frac{\partial T_{1,4}}{\partial \alpha} \]
\[+ \sum_{i=1}^{10} (T_{i,4} - T_b) [e_{b, bas, i,4} + (T_{1,1} - T_{set,1,1})] d_{di,4} \frac{M_s}{M_{s,0}} k_{cons,1} \]
\[\quad \times \sum_{j=1}^{10} \frac{[\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons,1}(T_{set,j,4} - T_{j,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}]^2}{\{1 + [(T_{set,1,1} - T_{1,1}) + \sum_{j=1}^{10} K_{cons,1}(T_{set,j,4} - T_{j,4})] d_{cons,1} \frac{M_s}{M_{s,0}} \}} \frac{\partial T_{1,4}}{\partial \alpha} \]

* Equal to 0 if $T_{set,1,1} - T_{1,1} = 0$
** Equal to 0 if $T_{1,1} - T_{set,1,1} = 0$
*** Equal to 0 if $T_{set,1,4} - T_{1,4} = 0$
**** Equal to 0 if $T_{1,4} - T_{set,1,4} = 0$
++++ Equal to 0 if $T_{set,k,4} - T_{k,4} = 0$
+++++ Equal to 0 if $k < i$
Appendix B

GRAPHICAL ATTACHMENTS TO CHAPTER 2

The figures in Appendix B supplement chapter 2 of this thesis. These figures show the actual change in average skin temperature and body heat storage due to parameter variations for the 41-Node Man and Wissler models. For these figures a 5% or 0.5 °C parameter deviation is assumed.
Figure B.1: Change in average skin temperature due to parametric uncertainty for the 41-Node Man.
Figure B.2: Change in body heat storage due to parametric uncertainty for the 41-Node Man.
Figure B.3: Change in average skin temperature due to parametric uncertainty for the Wissler model.
Figure B.4: Change in body heat storage due to parametric uncertainty for the Wissler model.
Appendix C

THE 2-D MU MAN MODEL

Appendix C is a stand-alone technical report that completely documents the 2-D MU Man Model. The report will be updated continuously as modifications to the model are implemented. The final goal is to create a monograph on human thermal modeling to be published as a book.
C1.0 INTRODUCTION

A reliable human thermal model is used to predict the thermal response of subjects under specific conditions of thermal stress for various applications including astronauts performing extravehicular activity (EVA). A reliable model is key in developing strategies for controlling thermal comfort for these astronauts in space. A human thermal model has been developed in the Department of Mechanical and Aerospace Engineering at the University of Missouri-Columbia and is referred to as the MU Model. The model attempts to improve on the 41-Node Man, a model developed by NASA, by including two-dimensional (radial and angular) heat conduction, countercurrent heat exchange between arteries and veins, and digit modeling. This report discusses modeling issues such as passive and active thermal structure, circulatory system structure, and modeling assumptions. A comprehensive program listing with description, a discussion of the MU Model's various configurations and model usage is also included.

C2.0 FEATURES

The MU Model was developed to provide useful results while being easy to use for EVA human thermal comfort evaluation. The modeling platform chosen is MATLAB/SIMULINK™ because of the following features:

- Transient modeling capabilities
- Intuitive graphical interface/User friendly
- Easy to edit or add on different components such as the liquid cooling and ventilation garment (LCVG) and space suit
• Feedback is inherent in the model, thus strategies to control thermal comfort can be implemented with relative ease

• Provides numerical solution without the use of complex, wordy coding.

C2.1 Clothing Ensembles

The MU Model has the option to be run for three different clothing ensemble options:

1. Nude
2. Clothed
3. LCVG and suit (open loop)

**Ensemble 1** - This ensemble is selected when human thermal response comparisons with other models and experiments are required for the common nude case. This clothing ensemble can be used to study the influence that uncertainty of model parameters, inputs, and/or structural components has on human thermal model response by isolating the nude human from any garment dynamics and interactions.

**Ensemble 2** - This ensemble can be used to describe the human thermal response for a subject in a natural setting while wearing some type of clothing.

**Ensemble 3** - The responses of this model configuration can be verified directly by an LCVG experimental test bed. This ensemble is used to develop and evaluate control strategies that define inlet water and vent temperatures directly. It can also be used for EVA comfort studies.

C2.2 Additional Features
• This model includes radial and angular conduction within each body element in order to handle situations where non-uniform heat generation or disparate environmental conditions exist.

• This model predicts finger and toe temperatures, which may be used in the future to design advanced thermal comfort strategies.

• The heat exchanges between major arteries/veins and tissues are modeled as well as countercurrent heat exchange between arteries and veins. Such modeling approaches a more realistic representation of the circulatory system.

C3.0 DYNAMIC STRUCTURE

The MU Model has two main components. Component one is the passive thermal system including the solid tissue matrix and circulatory system. Component two is called the active thermal system due to its decision-making nature. It is a collection of thermoregulators that are used to quantify and update various parameters and heat flow on-line as dictated by the thermal state of the simulated subject. The equations used by the MU Model are described here, some of which come from Bue [1].

C3.1 Passive Thermal Structure

As with any elaborate modeling effort, numerous assumptions and engineering reductions are made with the MU Model beginning with the nodal structure. Structurally, the human aspect of the MU Model is a hybrid of the 41-Node Man and Wissler models [1,4] and the suit/LCVG portion uses aspects from the suit model developed by Campbell and the 41-Node Man [1,2].
C3.1.1 Solid Tissue Thermal Dynamics – This human thermal model utilizes 14 cylindrical elements to represent the human body as shown in Figure 1a. They represent the head, trunk, each arm, hand, fingers, leg, foot and toes. It should also be noted that each set of fingers and toes are lumped together as one cylinder. Within each element are four concentric tissue regions with constant properties: the core, muscle, fat and skin layers as shown in Figure 1b. The skin, fat, and muscle layers can be assumed to be homogeneous, but the core must consider the presence of skeletal tissue and multiple visceral tissue varieties. Each element contains radially and angularly varying temperature nodes. A cross-section view for each element is shown in Figure 2a. Each element contains six equally spaced angular sectors. Sectors 1-3 denote the front of the body while sectors 4-6 denote the back of the body. In Figure 3, the radially spaced temperature nodes are shown for sector 1. For the other five sectors, the temperature nodes are spaced similarly. There are a total of 686 temperature nodes representing the nude human body.

For temperature nodes that have mass, the heat equation for two-dimensional conduction and heat generation is used to describe the thermal dynamics.

\[
MCp \frac{\partial T}{\partial t} = \nabla \cdot \left[ \kappa \nabla T + \rho \theta \right] + Q_{\text{blood}} + Q_{\text{gen}} + Q_{\text{resp}}
\]  

(1)

The term on the left-hand side of Eq. 1 represents the rate of heat storage. The first term on the right-hand side of Eq. 1 represents the two-dimensional conduction. The last three terms on the right-hand side of Eq. 1 show the different modes of heat transfer (or heat addition) to the temperature node.

Equation 1 is used for tissue nodes in the middle of a specific tissue region. However, there is a need for an equation for the temperature node at the interface
between two distinct tissue regions. The following heat flux equality can be used for this purpose.

\[-k_{in} \frac{\partial T}{\partial r} = -k_{out} \frac{\partial T}{\partial r}\]  

(2)

In Eq. 2, \(k_{in}\) represents the conductivity of the inner tissue layer and \(k_{out}\) represents the conductivity of the outer tissue layer.

In addition, at the edge of the skin layer, the following boundary condition can be imposed.

\[-k \frac{\partial T}{\partial r} = \dot{Q}_{ext}\]  

(3)

where the term on the right hand side of the equation represents the external heat flux from the skin. However, for this model, an energy balance at the outer skin layer is utilized to improve the accuracy.

\[MCp \frac{\partial T}{\partial t} = \nabla k \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} \right] + \dot{Q}_{blood} + \dot{Q}_{gen} + \dot{Q}_{ext}\]  

(4)

For the nude case

\[\dot{Q}_{ext} = \dot{Q}_{conv} + \dot{Q}_{rad} + \frac{1}{6} \dot{Q}_{lat}\]  

(5)

where the three terms on the right-hand side of the equation represent the rate of heat transfer due to convection, radiation and latent heat loss, respectively. For the clothed case

\[\dot{Q}_{ext} = \dot{Q}_k + \frac{1}{6} \dot{Q}_{lat}\]  

(6)

where the first term on the right-hand side of the equation represents the rate of heat conduction to the skin due to contact with the clothing. For the LCVG and suit option
\[
\dot{Q}_{\text{ext}} = \frac{1}{6} \dot{Q}_{LCG} + \frac{1}{6} \dot{Q}_{VG} + \dot{Q}_{rad} + \frac{1}{6} \dot{Q}_{lat}
\] (7)

where the first two terms on the right-hand side of the equation represent the rate of heat exchange between the skin and LCG, and the rate of heat convection to the skin caused by the gas flowing through the VG, respectively. The third term on the right-hand side of the equation represents the rate of heat radiation to the skin from the inside of the suit.

In Eqs. 5-7, some of the terms contain a 1/6 coefficient. These heat rates are calculated for an entire segment. Since there are six sectors, these heat rates are distributed equally to each sector of the outer skin layer for each body element. Further explanation and detail about these modes of heat transfer occur in later sections.

**Heat Generation** – In this model, each solid tissue node generates at least some basal amount of heat. In addition, the muscle layer within each element generates heat due to a work rate that is above the basal metabolic rate, and shivering.

\[
\dot{Q}_{\text{gen}} = \dot{Q}_{bas} + \frac{1}{6} d_w (1 - \eta) (MR - BMR) + \frac{1}{6} \dot{Q}_{shiv}
\] (8)

In Eq. 8, the first term on the right-hand side denotes the basal metabolic rate. The second term represents the rate of heat production due to inefficient work where \(d_w\) denotes the heat distribution to a particular body element, \(\eta\) denotes the mechanical efficiency, \(MR\) denotes the total metabolic rate (including basal) and \(BMR\) represents the total basal metabolic rate. The third term represents the rate of heat produced due to shivering.

In Eq. 8, some of the terms contain a 1/6 coefficient. These heat rates are calculated for an entire segment, appearing only for energy balances at the muscle layer.
Since there are six sectors, these heat rates are distributed equally to each sector of the muscle layer in each element.

**Convection** – For the nude and clothed options, heat convection to (or from) the environment is modeled.

\[
\dot{Q}_{\text{conv}} = hA(T_{\text{air}} - T)
\]  

(9)

It should be noted that convection coefficient, \(h\), and surface area, \(A\), for the nude and clothed cases will be different.

**Radiation** – The rate of heat transfer due to radiation from the environment to the skin layer (clothing layer) is modeled for the nude (clothed) case.

\[
\dot{Q}_{\text{rad}} = A\sigma F\left(\left(T_{\text{rad}} + 273.15\right)^4 + (T + 273.15)^4\right)
\]  

(10)

In Eq. 10, \(A\) is the area exposed to radiation, \(\sigma\) is the Stefan-Boltzmann constant, and \(F\) is the interchange factor. It also should be noted that the temperatures must be in absolute units (i.e. Kelvin) when doing radiation calculations. This model features distinct frontal and back radiant temperatures to account for disparate environment conditions.

**Respiratory Tract** – The normal intake of air through the respiratory tract causes heat to be exchanged between the air and specific tissues in the head and trunk. The rate of respiratory heat loss has two components: sensible and latent heat loss such that

\[
\dot{Q}_{\text{resp}} = \left(\dot{Q}_{\text{resp, lat}} + \dot{Q}_{\text{resp, sens}}\right)K_{\text{resp}}
\]  

(11)

where

\[
\dot{Q}_{\text{resp, lat}} = MR\frac{G_{\text{empirical}}}{T_{\text{air, abs}}} (P_{\text{air}} - P_{\text{resp}})
\]  

(12)

and
\[ \dot{Q}_{\text{resp,sens}} = \frac{C_{p_{\text{air}}} P_{\text{air.abs}} M R \cdot G_{\text{empirical}}}{T_{\text{air.abs}}} (T_{\text{air}} - T_{\text{resp}}) \]  

(13)

In Eq. 11, \( K_{\text{resp}} \) represents the percentage of respiratory heat loss (or gain) to a specific tissue node. In Eqs. 12-13, \( G_{\text{empirical}} \) denotes an empirically derived constant [1].

**Heat Exchange due to Blood** – Solid tissue nodes exchange heat with neighboring arteries and veins due to blood flow.

\[ \dot{Q}_{\text{blood}} = h A_a (T_a - T) + (\dot{e}_b + h A_v)(T_v - T) \quad \text{where} \quad \dot{e}_b = \dot{m}_b C_{p_b} \]  

(14)

In Eq. 14, \( h A_a \) represents the heat transfer coefficient between the tissue and artery, \( h A_v \) represents the heat transfer coefficient between the tissue and vein, and \( \dot{e}_b \) represents the thermal mass blood flow rate, which equals the blood mass flow rate multiplied by the specific heat of blood. In this model, blood flow is assumed to originate at the heart flowing to tissue layers through the arteries, which flow into the capillary bed and then exits the tissue layer through the veins. In this model, it is assumed that the blood entering tissue will exit the arteries approximately at the tissue temperature. Thus, blood entering the capillaries will approximately be at the tissue temperature. Thus, the term in Eq. 14 that involves \( \dot{e}_b \) indicates perfect heat transfer within the capillary bed, or in other words that blood entering the capillary bed (at the tissue temperature) will exit at the vein temperature.

**C3.1.2 Circulatory System Thermal Dynamics** – As previously stated, each solid tissue node interacts with the circulatory system, thus heat flows in the presence of a temperature difference. The circulatory system model computes the temperature of the blood interacting with each tissue defining this temperature difference. Also computed is the local heat and mass perfusion rate through the capillaries. In this model, venous and
arterial temperatures are modeled independently such that there is an arterial and venous blood pool within each element. Thus, there are 28 blood temperature nodes since the model consists of 14 body elements. This circulatory system model explicitly preserves blood flow paths from the trunk to the extremities and vice versa. It also permits countercurrent heat exchange between deep tissue veins and arteries. Parameterizing this circulatory system model is difficult, however studies to achieve better parameter accuracy are on-going.

In this model, it is assumed that perfect heat transfer occurs for blood flowing from one blood pool into another. For example, blood entering the arterial blood pool of the arm will exit at the temperature of the arterial hand blood pool. In addition, all venous blood pools terminate at the trunk and all arterial blood pools originate at the trunk. It is assumed that perfect heat transfer occurs for blood flowing from the trunk venous blood pool into the trunk arterial blood pool. Eqs. 15-22 are used to determine arterial and venous temperatures for each body element.

- Head (i = 1), fingers (i = 7,8) and toes (i = 13,14) blood:

\[
M_{a,i}C_{p,a} \frac{dT_{a,i}}{dt} = \sum_{j=1}^{31} hA_{a,i,j}(T_{a,j} - T_{a,i}) + \left[ \sum_{j=1}^{31} \dot{e}_{b \rightarrow a,i,j} \right] (T_{b,j} - T_{a,i}) + hA_{a \rightarrow v,i} (T_{v,i} - T_{a,i})
\]  

(15)

\[
M_{v,i}C_{p,v} \frac{dT_{v,i}}{dt} = \sum_{j=1}^{31} (\dot{e}_{b \rightarrow a,i,j} + hA_{v,i,j})(T_{b,j} - T_{v,i}) + hA_{a \rightarrow v,i} (T_{a,i} - T_{v,i})
\]  

(16)

For the fingers and toes nodes, replace subscript 1 with 7, 8, 13, or 14 and 2 with 5, 6, 11 or 12.

- Trunk (i = 2) blood:
\[ M_{a,2} C_p \frac{dT_{a,2}}{dt} = \sum_{j=1}^{31} hA_{a,2,j} (T_{2,j} - T_{a,2}) + \left[ \sum_{j=1}^{14} \sum_{j=1}^{31} (\dot{e}_{b \rightarrow b, j} + hA_{a \rightarrow v,2}) T_{v,2} - T_{a,2} \right] \] (17)

\[ M_{v,2} C_p \frac{dT_{v,2}}{dt} = \sum_{j=1}^{31} (\dot{e}_{b \rightarrow b, j} + hA_{v,2,j}) (T_{2,j} - T_{v,2}) + \left[ \sum_{j=1}^{31} \dot{e}_{b \rightarrow b, j} \right] (T_{v,1} - T_{v,2}) + \sum_{i=3,4,9,10} \left[ \sum_{j=1}^{31} (\dot{e}_{b \rightarrow v, j} + \dot{e}_{b \rightarrow v, j} + \dot{e}_{b \rightarrow v, j}) \right] (T_{v,i} - T_{v,2}) + hA_{a \rightarrow v,2} (T_{a,2} - T_{v,2}) \] (18)

- Arm \((i = 3,4)\) and leg \((i = 9,10)\) blood:

\[ M_{a,3} C_p \frac{dT_{a,3}}{dt} = \sum_{j=1}^{31} hA_{a,3,j} (T_{3,j} - T_{a,3}) \] (19)

\[ M_{v,3} C_p \frac{dT_{v,3}}{dt} = \sum_{j=1}^{31} (\dot{e}_{b \rightarrow b, j} + hA_{v,3,j}) (T_{3,j} - T_{v,3}) + hA_{a \rightarrow v,3} (T_{v,3} - T_{a,3}) \] (20)

For left arm and leg nodes, replace subscript 3 with 4, 9, or 10.

- Hand \((i = 5,6)\) and foot \((i = 11,12)\) blood:

\[ M_{a,5} C_p \frac{dT_{a,5}}{dt} = \sum_{j=1}^{31} hA_{a,5,j} (T_{5,j} - T_{a,5}) \] (21)

\[ M_{v,5} C_p \frac{dT_{v,5}}{dt} = \sum_{j=1}^{31} (\dot{e}_{b \rightarrow b, j} + hA_{v,5,j}) (T_{5,j} - T_{v,5}) + hA_{a \rightarrow v,5} (T_{v,5} - T_{a,5}) \] (22)
For left hand and foot nodes, replace subscript 5 with 6, 11, or 12.

The cross-section view for each body element shows the different tissue regions and nodal spacing (Figure 2a). There are six sectors and in each sector there are five temperature nodes that have mass. These five solid tissue nodes correspond to the outer core, muscle, fat, inner skin and outer skin layer. In addition, there is one temperature node that corresponds to the center point of the core region (inner core). Thus, there are 31 solid tissue nodes within an element, explaining why summations are done 31 times in the above equations. As stated earlier, each solid tissue region exchanges heat with neighboring arterial and venous blood pools.

**C3.1.3 Clothing Layer Thermal Dynamics** – In this model, the clothing layer is treated as a concentric cylinder that encloses the skin layer (Figure 2b). The extra clothing layer exists for the trunk, arms, legs, feet and toe cylinders, which represent a shirt, pants and shoes. For each clothed element, there exists one clothing temperature node per sector that is located at the boundary of the clothing layer (Figure 2b). Thus, there are a total of 54 solid clothing nodes. The heat equation for two-dimensional conduction can be used to describe the energy balance at each clothing node.

\[
M_{cloth} \cdot C_{p_{cloth}} \frac{\partial T_{cl}}{\partial t} = V_{cloth} \cdot k_{cloth} \left[ \frac{\partial^2 T_{cl}}{\partial r^2} + \frac{1}{r} \frac{\partial T_{cl}}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T_{cl}}{\partial \theta^2} \right] + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{conv}} \tag{23}
\]

The clothing layer exchanges heat with the skin layer through radial conduction, and angular conduction with the clothing layer taken into account. Radiation and convection from the environment to the clothing layer also exists.

**C3.1.4 Suit and LCVG Thermal Dynamics** – The suit is the thermal and pressure barrier between the astronaut and the environment. The ventilation garment (VG) is the interior of the suit through which gas passes from the helmet over the
astronaut and into the ducts located at the wrists and ankles. The flow is split so that 75% and 25% of the flow goes over the arms and legs, respectively.

The dynamic equations used for the suit/LCVG model mostly come from model developed by Campbell [2], but also include portions of the 41-Node Man [1]. In Campbell's suit model, it is assumed that heat conducts only radially through the suit. However, in this model, two-dimensional (radial and angular) conduction within the suit is modeled to account for situations where disparate environmental conditions in space exist. As stated previously, each body element is divided into six angular sectors. Thus, the suit model consists of 84 interior suit temperature nodes \( T_{si} \), since there are 14 segments. The VG consists of 14 massless gas nodes \( T_g \) that correspond to the 14 cylinders of the human thermal model. The undergarment, which represents the liquid cooling garment (LCG) and thermal comfort undergarment (TCU), covers five body segments: the torso, each arm and each leg. The undergarment temperature \( T_{ug} \) varies angularly for each element, thus there are a total of 30 massless undergarment temperature nodes. The undergarment temperatures for the head, hands, finger, feet and toes are equal to the skin temperatures since the LCG does not cover these body segments.

A schematic of the suit thermal model can be seen in Figure 3. Conduction is modeled between the skin and the undergarment of the torso, arms and legs. Convection is modeled for the gas in the VG with the undergarment/skin and the inner suit surface. Radiation is modeled between the undergarment/skin and the inner suit surface. As previously stated, conduction is modeled through the suit between the inner and outer suit surfaces as well as angularly within the suit. In this model, there are two distinct outer
suit temperatures \(T_{so}\) for the front and back of the suit to account for disparate environmental conditions in space.

**Inner Suit Thermal Dynamics** — The heat equation for two-dimensional conduction can be used to write an energy balance at each inner suit temperature node

\[
\frac{1}{2} M_{suit} C_{p_{suit}} \frac{\partial T_{si}}{\partial t} = V_{suit} k_{suit} \left[ \frac{\partial^2 T_{si}}{\partial r^2} + \frac{1}{r} \frac{\partial T_{si}}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T_{si}}{\partial \Theta^2} \right] + \dot{Q}_{rad,ug} + \dot{Q}_{conv,si} \quad (24)
\]

where the radiation from the undergarment to the inner suit surface is

\[
\dot{Q}_{rad,ug} = A_{skin} \sigma F_{ug,ls} \left( (T_{ug} + 459.67)^4 - (T_{si} + 459.67)^4 \right) \quad (25)
\]

and the convection from the ventilation gas to the inner suit surface is

\[
\dot{Q}_{conv,si} = h A_{suit} (T_{g,avg} - T_{si}) \quad (26)
\]

In Eq. 24, \(M_{suit}\) represents the mass of the suit sector within each element. The inner suit node occupies one half of this mass, while the outer suit node occupies the other half. Thus, this explains why there is a \(\frac{1}{2}\) coefficient in front of the heat storage rate term. It should also be noted that Eq. 25 must be converted into SI units when used in energy balances at the skin layer, since the human part of model uses all SI units (J/min for heat rates) for calculations.

**Ventilation Garment** — As stated previously, gas flowing through the VG exchanges heat via convection with the undergarment/skin and inner suit surface. The average gas temperature for each element can be calculated using the following equation:

\[
T_{g,avg} = T_m + \frac{\dot{m}_{gas} C_{p,gas}}{h (A_{suit} + A_{skin})} (1 - e^{-h (A_{suit} + A_{skin})/\dot{m}_{gas} C_{p,gas}}) (T_{g,in} - T_m) \quad (27)
\]

where the weighted average temperature for the surfaces interacting with the gas is

\[
T_m = \frac{A_{suit} T_{si} + A_{skin} T_{ug}}{A_{suit} + A_{skin}} \quad (28)
\]
and the convection coefficient is

\[ h = 1.86 \frac{k_{\text{gas}}}{(D_o - D_i)} \left( \frac{4 \dot{m}_{\text{gas}} c_{p,\text{gas}}}{\pi (D_o + D_i) L k_{\text{gas}}} \right)^{1/3} \]  \hspace{1cm} (29)

where \( D_o, D_i \) and \( L \) represent the diameter at the skin boundary, the diameter at the inner suit surface and the length of the segment, respectively. It should be noted that Eqs. 27-29 are calculated for each body segment.

**Undergarment** – The undergarment temperature is derived assuming that the undergarment is a massless node

\[ T_{\text{ug}} = T_{\text{leg, out}} - \frac{CLO}{A_{\text{skin}}} (\dot{Q}_{\text{rad, ug}} + \dot{Q}_{\text{conv, skin}}) \]  \hspace{1cm} (30)

where the convection from the ventilation gas to the undergarment/skin is

\[ \dot{Q}_{\text{conv, skin}} = h A_{\text{skin}} (\overline{T}_{\text{ug}} - T_{g, \text{avg}}) \]  \hspace{1cm} (31)

In Eq. 31, \( \overline{T}_{\text{ug}} \) represents the average undergarment/skin temperature for each segment.

It should also be noted that \( \dot{Q}_{\text{VG}} \) in Eq. 7 is essentially the same as \( \dot{Q}_{\text{conv, skin}} \) in Eq. 31 except that the sign is reversed and the units are different.

\[ \dot{Q}_{\text{VG}} = -\text{CONV} \times \dot{Q}_{\text{conv, skin}} \]  \hspace{1cm} (32)

In general, calculations in the suit model are done in English units whereas calculations for the human part of model are done in SI units.

In addition, it should be noted that \( \dot{Q}_{\text{VG}} \) in Eq. 32 represents the total rate of convection to the undergarment/skin for the entire body element. It is assumed that this heat convects to each undergarment/skin node for each sector evenly for a given element.
Thus, the rate of convection to each undergarment/skin node is actually \( \dot{Q}_{vc} / 6 \), since there are six sectors within each element.

**Liquid Cooling Garment** - The LCG is responsible for primary heat removal from the body. It is a spandex mesh garment with small tubes woven into the mesh. The water cooling loop (WCL) liquid flows through these tubes and removes heat from the body. The LCG model is based on the 41-Node Man model’s representation of the LCG [1]. The model consists of a single massless node representing the water in the LCG. The model assumes that the only heat transfer with the LCG is between the skin and the LCG. The sensible heat transfer between the LCG and the suit gas is added directly to the undergarment/skin node heat balance. The LCG is modeled using the effectiveness-NTU method for heat exchanger analysis with the assumption that the heat capacitance of the skin is much larger than the heat capacitance of the LCG water. The heat transfer to the coolant of the LCG to each human body segment is calculated as

\[
\dot{Q}_{\text{lcg}} = f \dot{m}_{\text{lg}} c_p T_{\text{in,lg}} (T_{\text{out,lg}} - T_{\text{in,lg}})
\]

where \( f \) is the percent of flow of coolant in the LCG to each body segment. The outlet LCG temperature is calculated as

\[
T_{\text{out,lg}} = T_{\text{in,lg}} + \left(1 - e^{-\frac{U_A H_{\text{lg}} c_p}{f}}\right) \bar{T}_{\text{skin}} - T_{\text{in,lg}}
\]

where \( \bar{T}_{\text{skin}} \) is the weighted average skin temperature of the trunk, arms, and legs (i.e. the segments covered by the LCG). The overall heat transfer coefficient between the skin and LCG is calculated using the following empirical relationship

\[
U_A = K \cdot U_{A_0} \left[1 - 1.08 \exp(-0.0166 \dot{m}_{\text{lg}})\right]
\]

where
\[ UA_o = 75.5 - 1.1T_{in,leg} + 0.032T_{in,leg}^2 - 0.31 \times 10^{-3} T_{in,leg}^3 \]  

(36)

with \( UA_o > 27.55 \) for all \( T_{in,leg} \). In Eqs. 35-36, \( UA \) is in BTU/hr, \( F \), \( m_{kg} \) is in lbm/hr, \( T_{in,leg} \) is in F, and \( K \) is a model parameter to account for clothing under the LCG.

It should also be noted that \( \dot{Q}_{LCG} \) in Eq. 7 is essentially the same as \( \dot{Q}_{leg} \) in Eq. 33 except that the sign is reversed and the units are different.

\[ \dot{Q}_{LCG} = -CONV \times \dot{Q}_{leg} \]  

(37)

In general, calculations done in the suit model must be converted to SI units before they can be intermixed with the human model calculations.

In addition, it should be noted that \( \dot{Q}_{LCG} \) in Eq. 37 represents the total rate of heat transfer from the coolant to the skin for an entire element. It is assumed that the heat is transferred due to the LCG to each outer skin node of a sector evenly for a given segment. Thus, the rate of heat transferred due to the LCG to each outer skin node is actually \( \frac{\dot{Q}_{LCG}}{6} \), since there are six sectors within each element.

**C3.2 Active Thermal Structure**

The thermoregulators calculate several model parameters and system inputs online based on the computed thermal state of the subject, thus comprising the active thermal system. Specifically, there are four thermoregulators included in the human model.

1. Sweating
2. Shivering
3. Vasodilation
4. Vasoconstriction
Both sweating and shivering are heat terms (system inputs) that drive system response and are included in the skin and muscle layer energy balances, respectively. Vasodilation and vasoconstriction affect how quickly mass and heat is transferred from the blood pool into the skin layer. These physiological responses are modeled based on the body's attempt to improve its thermal state. They are empirical functions of the differences between the hypothalamus and setpoint temperatures (approximated by the head core) and between the skin and their setpoint temperatures.

**C3.2.1 Sweating** – The latent loss of heat from the skin is comprised of two components: diffusion and active sweating.

\[
\dot{Q}_{\text{lat}} = \dot{Q}_{\text{dif}} + \dot{Q}_{\text{sweat}}
\]  
(38)

\[
\dot{Q}_{\text{dif}} = AG_{\text{empirical}} (P_{\text{v}_\text{air}} - P_{\text{g}_{\text{skin}}})^{or 0}
\]  
(39)

\[
\dot{Q}_{\text{sweat}} = -SK_{\text{sweat}}^2 (T_{\text{env}} - T_{\text{set}})^{or 0}
\]  
(40)

where

\[
S = (T_{\text{core}} - T_{\text{set,core}})^{or 0} (C_{\text{empirical}} + G_{\text{empirical}} \sum_{i=1}^{14} \gamma_{\text{sweat}} (T_{\text{sat}} - T_{\text{set}})^{or 0})
\]  
(41)

Eq. 40 is limited by the maximum evaporative capacity:

\[
\dot{Q}_{\text{sweat, cap}} = \left(1 - \exp \left( - \frac{\dot{Q}_{\text{sweat}} G_{\text{empirical}} T_{\text{air, abs}} R_{\text{water}}}{H_{\text{mass}} Ah_{\text{fg, air}} (P_{\text{g}_{\text{skin}}} - P_{\text{v}_{\text{air}}})} \right) \right) \frac{H_{\text{mass}} Ah_{\text{fg, air}} (P_{\text{g}_{\text{skin}}} - P_{\text{v}_{\text{air}}})}{T_{\text{air, abs}} R_{\text{water}}}
\]  
(42)

where

\[
H_{\text{mass}} = \left( \frac{V_{\text{air}}}{R} G_{\text{empirical}} \right)^{\frac{1}{2}} T_{\text{air, abs}} R_{\text{emp in}}^2 G_{\text{empirical}}
\]  
(43)

In Eq. 39, \( P_{\text{v}_{\text{air}}} \) and \( P_{\text{g}_{\text{skin}}} \) represent the water vapor pressure of air and the saturated partial pressure at the skin, respectively. In Eqs. 40-41, \( K_{\text{sweat}} \) and \( \gamma_{\text{sweat}} \) represent the
sweat distribution and skin mass distribution, respectively. In Eqs. 42-43, $R_{\text{water}}$, $h_{fg, \text{air}}$, $V_{\text{air}}$ and $R$ represent the universal gas constant, enthalpy of vaporization, wind velocity and outer skin radius.

In addition, it should be noted that $\dot{Q}_{\text{lat}}$ in Eq. 38 represents the total rate of latent heat loss from the skin for an entire element. It is assumed that the latent heat loss is distributed evenly between each outer skin node for a given element. Thus, the latent heat loss from each outer skin node is actually $\dot{Q}_{\text{lat}} / 6$, since there are six sectors within each element. Eqs. 38-43 are calculated for each element.

**C3.2.2 Shivering** – The rate of heat production due to shivering occurs in the muscle region of each element.

$$\dot{Q}_{\text{shiver}} = \left( \sum_{i=1}^{14} \left( T_{\text{set},i} - T_i \right)^{\gamma_{\text{shiver},i}} \right) \left( T_{\text{set,core}} - T_{\text{core}} \right)^{\gamma_{\text{shiver,core}}} G_{\text{empirical}} K_{\text{shiver}} \frac{M_m}{M_{m0}}$$ (44)

In Eq. 44, $\gamma_{\text{shiver}}$, $K_{\text{shiver}}$ and $M_m/M_{m0}$ represent the skin mass distribution, shiver distribution and total muscle mass to total nominal muscle mass ratio, respectively.

In addition, it should be noted that $\dot{Q}_{\text{shiv}}$ in Eq. 44 represents the total shivering heat production for an entire element. It is assumed that the heat produced from shivering is distributed evenly between each muscle node within a given element. Thus, the rate of heat production due to shivering within a muscle tissue node for each element is actually $\dot{Q}_{\text{shiv}} / 6$, since there are six sectors within each element.

**C3.2.3 Vasomotor Functions** – In this model, the vasomotor actions work either to increase or decrease the blood flow to the skin. During vasodilation, the blood flow rate to the skin is increased to encourage heat loss to the environment. During vasoconstriction, the blood flow rate to the skin is decreased to restrict heat loss to the
environment. The total thermal mass blood flow rate to the skin layer for each element is updated on-line using the following equation:

$$\hat{b}_{\rightarrow s} = \frac{\hat{b}_{\rightarrow s, basal} + \hat{d}_{dil}}{1 + \Re}$$  \hspace{1cm} (45)$$

where

$$\hat{d}_{dil} = (T_{core} - T_{set, core})_{\text{head}}^{\text{or}^0} G_{\text{empirical}} K_{dil} \frac{M_s}{M_{s0}}$$  \hspace{1cm} (46)$$

and

$$\Re = \left( (T_{set, core} - T_{core})_{\text{head}}^{\text{or}^0} + \sum_{i=1}^{14} \gamma_{\text{cons}} (T_{set, i} - T_{set, skin})^{\text{or}^0} \right) G_{\text{empirical}} K_{\text{cons}} \frac{M_s}{M_{s0}}$$ \hspace{1cm} (47)$$

where $K_{dil}$, $K_{\text{cons}}$ and $M_s/M_{s0}$ represent the vasodilation distribution for an element, the vasoconstriction distribution for an element, and the total skin mass to nominal total skin mass ratio.

**C3.3 Numerical Solution**

The inclusion of two-dimensional conduction introduces the necessity to solve equations with several partial derivatives. In this model, these heat transfer equations are solved numerically using MATLAB/SIMULINK™. Eqs. 1, 2, 4, 23, and 24 are energy balances involving several partial derivatives, thus require a numerical solution. They can be approximated using Taylor series first-order approximations.

$$\frac{\partial^2 T}{\partial r^2} \bigg|_{r, \theta} \approx \frac{T_{r+1, \theta} + T_{r-1, \theta} - 2T_{r, \theta}}{(\Delta r)^2}$$ \hspace{1cm} (48a)$$

$$\frac{\partial T}{\partial r} \bigg|_{r, \theta} \approx \frac{T_{r+1, \theta} - T_{r-1, \theta}}{2\Delta r}$$ \hspace{1cm} (48b)$$
\[ \frac{\partial^2 T}{\partial \theta^2} \bigg|_{r,\theta} \approx \frac{T_{r,\theta+1} + T_{r,\theta-1} - 2T_{r,\theta}}{(\Delta \theta)^2} \]  

(48c)

\[ \frac{\partial T}{\partial t} \bigg|_{r,\theta} \approx \frac{T_{r,\theta+1}^p - T_{r,\theta}^p}{\Delta t} \]  

(48d)

In Eq. 48, \( \Delta r \) and \( \Delta \theta \) represents the distance between two nodes in the radial direction and the angle in radians between two nodes, respectively. In this model, \( \Delta r \) varies for different tissue nodes, but \( \Delta \theta \) is always equal to \( \pi/3 \) since there are six evenly spaced sectors within each element.

Eq. 1 represents the energy balance for solid tissue nodes (excluding the outer skin nodes) for the human. After substituting Eq. 48, Eq. 1 has the following numerical approximation

\[ MC_p \frac{T_{r,\theta+1}^p - T_{r,\theta}^p}{\Delta t} = \frac{k\Delta \theta (R_r + R_{r+1}) L (T_{r+1,\theta}^p - T_{r,\theta}^p)}{2\Delta r} + \frac{k\Delta \theta (R_r + R_{r-1}) L (T_{r-1,\theta}^p - T_{r,\theta}^p)}{2\Delta r} \]  

\[ + \frac{k\Delta r L}{R_r \Delta \theta} (T_{r,\theta+1}^p - T_{r,\theta-1}^p - 2T_{r,\theta}^p) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{resp}} \]  

(49)

where \( R_r \) denotes the radius at the temperature node and \( L \) represents the length of the cylindrical element.

The heat flux equality at a tissue interface represented by Eq. 2 must also be numerically approximated.

\[ k_{in} \frac{T_{r,\theta} - T_{r-1,\theta}}{\Delta r} = k_{out} \frac{T_{r+1,\theta} - T_{r,\theta}}{\Delta r} \]  

(50)

The energy balance at the skin surface was used instead of a boundary condition to improve accuracy. The equation for an outer skin node can be numerically approximated as shown below.

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\[ MC_p \frac{T_{r+1} - T_r}{\Delta t} = \frac{k \Delta \theta (R_r + R_{r-1}) L}{2 \Delta r} \left( T_{r+1, \theta} - T_{r, \theta} \right) + \frac{k \Delta r L}{2 R_r \Delta \theta} \left( T_{r, \theta+1} + T_{r, \theta-1} - 2 T_{r, \theta} \right) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{ext}} \] (51)

As can be seen from inspection, Eq. 49 cannot be used to represent the central core temperature within an element, because the radius at the center of the core is zero. However, Osizik devised a finite-difference equation at the center of a cylindrical segment to be able to solve this particular problem [3]. Thus, using Osizik’s scheme, the energy balance at the core’s center node with radius \( \Delta r/2 \) can be approximated numerically as

\[ MC_p \frac{T_{0+1} - T_0}{\Delta t} = \frac{k \Delta \theta L}{2} \left( T_1 - T_2 + \ldots + T_6 - 6 T_0 \right) + \dot{Q}_{\text{blood}} + \dot{Q}_{\text{gen}} + \dot{Q}_{\text{exp}} \] (52)

where \( T_1, T_2, \ldots, T_6 \) represent the six temperatures corresponding to the six nodes (since there are six angular sectors) radially spaced at a distance \( \Delta r \) from the central core temperature node. \( T_0 \) represents the temperature at the central core node.

The energy balance at a clothing layer node represented by Eq. 23 can be approximated using Eq. 48.

\[ M_{\text{cloth}} C_{\text{cloth}} \frac{T_{cl+1} - T_{cl, \theta}}{\Delta t} = \frac{k_{\text{cloth}} \Delta \theta (R_{cl} + \Delta r / 2) L}{\Delta r} \left( T_{\text{skin}, \theta} - T_{cl, \theta} \right) + \frac{k_{\text{cloth}} \Delta r L}{2 (R_{\text{outer, skin}} + \Delta r) \Delta \theta} \left( T_{cl, \theta+1} + T_{cl, \theta-1} - 2 T_{cl, \theta} \right) + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{conv}} \] (53)

It should be noted that the subscripts \( r \) and \( r-1 \) used in Eq. 48 are replaced by the subscripts \( cl \) and \( skin \) in Eq. 53, respectively, to clearly show which layers (clothing and skin) are being referred to in the equation.

The energy balance at an inner suit temperature node represented by Eq. 24 can be approximated using Eq. 48.
\[ M_{suit} C_{P_{suit}} \frac{T_{si,\theta}^{r+1} - T_{si,\theta}^r}{\Delta t} = \frac{k_{suit} \Delta \theta (R_{si} + \Delta r / 2)L}{\Delta r} \left( T_{so,\theta}^r - T_{si,\theta}^r \right) + \frac{k_{suit} \Delta r L}{2 R_{si} \Delta \theta} \left( T_{si,\theta}^r + T_{si,\theta-1}^r - 2T_{si,\theta}^r \right) + \dot{Q}_{rad,\text{egg}} + \dot{Q}_{\text{conv,si}} \]  

(54)

It should be noted that the subscripts \( r \) and \( r+1 \) used in Eq. 48 are replaced by the subscripts \( si \) and \( so \) in Eq. 53, which stand for suit-inside and suit-outside, respectively. This is to clearly show which layers are being referred to in the equation.

### C3.4 Other MU Model Equations

**C3.4.1 Convection Coefficients** – For the nude and clothed options, the forced convection coefficient for each element is computed as:

\[ h_{\text{forced}} = \overline{h} \left[ \frac{30.48}{D} \right]^{1/2} \quad \text{[J/(min-m}^2\text{-K)]} \]  

(55)

where

\[ \overline{h} = 0.0212 \left[ 285.506 V_{air}^P \right]^{1/2} 340.696 \quad \text{[J/(min-m}^2\text{-K)]} \]  

(56)

In Eq. 55, \( D \) is the outer diameter of the element in cm. In Eq. 56, \( V_{air} \) is the wind speed in m/s and \( P \) is the absolute air pressure in kPa. The free convection coefficient is computed as:

\[ h_{\text{free}} = 0.27969 \left[ P^2 \left( 32 - T_{air} \right) \right]^{1/4} \left[ \frac{106.68}{L} \right]^{1/4} \quad \text{[J/(min-m}^2\text{-K)]} \]  

(57)

where \( T_{air} \) is the dry bulb temperature in °C and \( L \) is the length of the element in cm. The model calculates both the free and forced convection coefficients, and then uses the greater value as the convection coefficient.
**C3.4.2 Muscle Blood Flow Rates** – The rate of blood flow to the muscle regions in each element increases as the work rate increases. The thermal mass blood flow rate to each muscle node within an element can be computed as

\[
\dot{e}_{b,\text{musc}} = G_{\text{empirical}} (\dot{Q}_{\text{gen}} + W)
\]  

(58)

where

\[
W = \frac{1}{6} d_v \eta (MR - BMR)
\]  

(59)

In Eq. 59, \(MR\) and \(BMR\) represent the total metabolic rate and total basal metabolic rate, respectively. The 1/6 coefficient is present in order to evenly distribute the work rate within each element between the six muscle nodes in each sector.

**C3.5 MU Model Assumptions**

Numerous assumptions were made during the development of the human thermal model as with any elaborate modeling effort. They are outlined here.

1. The human form is thermally equivalent to a collection of 14 cylinders.
2. There are four solid tissue varieties in a given segment that can be approximated as concentric cylindrical layers.
3. The digits on each hand and foot can be lumped together as one cylinder.
4. Each layer has thermal properties that do not vary with time.
5. Heat flow is strictly radial and angular (two-dimensional), neglecting axial flow and conduction between adjacent body elements.
6. There are 28 unique blood temperature regions in the human body such that there exists one arterial and venous blood within each element.
7. Perfect heat transfer takes place in the capillary beds.
Work is required to investigate the significance of several of these modeling assumptions, particularly those involving blood dynamics.

C4.0 MATLAB INITIALIZATION PROGRAM FOR NUDE AND CLOTHED

MATLAB/SIMULINK is the software chosen for the MU Man due to its ease of implementation, program usage, availability and modifiability. A common method used when building a complex SIMULINK model is to first write a MATLAB file (m-file) that initializes the parameters and inputs that are known to remain constant during the simulation. The description of the components of the initialization program for the nude and clothed cases (called: setup2D.m) follow with variable names in parentheses. The SIMULINK files used to run the nude and clothed cases are called nude2D.mdl and clothes2D.mdl, respectively, and require the use of setup2D.m. The following sections describe setup2D.m (listed in the Appendix) such that section 4.X describes section X.0 of setup2D.m.

C4.1 Adjustment Parameters

With many complex models, adjustment parameters are included to help fine tune the model's outputs to match desired responses. This is usually done when model structure is known, but accurate parameterization using first principles is difficult or ineffective. In this case of dynamically modeling the human thermal system, several adjustment parameters are used and are defined at the beginning of the m-file. There are seven parameters affecting the following model components:

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Wind Speed</td>
<td>Wind_Parameter</td>
</tr>
<tr>
<td>2 Sweating Heat Loss</td>
<td>Sweat_Parameter</td>
</tr>
</tbody>
</table>
3 | Respiratory Heat Loss | Resp_Parameter
4 | Radiation Heat Loss | Rad_Parameter
5 | Shivering | Shiver_Parameter
6 | Diffusion | Diff_Parameter
7 | Blood Flow | BF_Parameter

These mechanisms are subject to some degree of modeling error so they were chosen to have parameters that can be tuned. The default values (defined by having zero effect) for these parameters are listed in setup2D.m.

C4.2 Subject Prescription Inputs

This section defines characteristics specific to the individual subject. The prescription inputs include the subject's mass (BodyMass, kg), height (Height, cm), additional metabolic profile (AddRate, [min,W]: see Appendix for usage), useful mechanical efficiency (WorkEff, 0~1), and work distributions (WorkDist(i), 0~1).

C4.3 Environmental Prescription Inputs

This section defines properties defining the thermal state of the environment that are subject to variation between simulations. This includes dry bulb ambient temperature (Tdry, [min,°C]), adiabatic wet bulb temperature (Twet, °C), front radiant temperature (Tradf, [min,°C]), back radiant temperature (Tradb, [min,°C]), absolute air pressure (Press, kPa), and wind speed (AirSpd, m/s).

C4.4 Define Constant Environmental Properties

The properties defined here are either physically constant or functionally dependent on the environmental prescription inputs. Included properties are: a value used for °C to K conversion (C2K, °C), the specific heat capacity of water (Cpwat, kJ/(kg-K)) and air (CpAir, kJ/(kg-K))), universal gas constant for water vapor (Rwat,
kJ/(kg-K)), and the partial pressure of vapor in air ($P_{vair}$, kPa). Some of the properties defined in this section, which have a functional dependence on the environmental conditions, are curve fits indicated in the m-file.

**C4.5 Define Constant Tissue Properties**

This section defines and computes specific properties of the individual body tissues layers including the computed fatty tissue mass ($\text{MassFat}$, kg), the lean body mass ($\text{MassLean}$, kg), several mass distribution arrays ($\text{SkelDist}(i)$, $\text{ViscDist}(i)$, $\text{MassDist}(i,j)$), specific heat capacity ($\text{Cp}(i,j)$, J/(kg-K)), the mass of each tissue layer ($\text{Mass}(i,j)$, kg), the thermal mass of each solid tissue region (i.e. center core, outer core, muscle, fat, inner skin and outer skin) ($\text{MCp}(i,j)$, J/K), the total mass of each tissue compartment ($\text{TisMass}(j)$, kg), the mass of each body segment ($\text{SegMass}(i)$, kg), the nominal mass of the muscle compartment ($\text{NomMus}$, kg), the nominal mass of the skin compartment ($\text{NomSkin}$, kg), the thermal mass of the entire blood pool ($\text{MCpblood}$, J/K), the thermal mass of each arterial blood pool ($\text{MaCpb}(i)$, J/K), the thermal mass of each venous blood pool ($\text{MvCpb}(i)$, J/K), and the total surface area of the body as computed by the DuBois method:

$$A_{tot} = 71.84M^{0.425}H^{0.725}$$  \hspace{1cm} (Atot, cm$^2$) \hspace{1cm} (60)

Also contained is an area distribution array ($\text{Adist}(i)$), the surface area of each body segment ($\text{Area}(i)$, cm$^2$), the volume of the cylinder that each tissue layer’s outer radii encompasses ($\text{Vol}(i,j)$, cm$^3$), the length of each body segment and the outer radius of each tissue shell as computed by:

$$L_i = V_{i,d}/\pi(R_{outer, skin})^2$$ \hspace{1cm} (Length(i), cm) \hspace{1cm} (61)

$$R_{outer, tissue} = [V_{i,d}/(\pi L_i)]^{1/2}$$ \hspace{1cm} (Radius(i,j), cm) \hspace{1cm} (62)
Continuing, each tissue's thermal conductivity ($k(i,j), \text{J/(min-m-K)}$) and mid-radii ($\text{NodRad}(i,j), \text{cm}$) are included. The nodal radii ($R(i,j), \text{cm}$), the radius to each solid tissue and interface node, is also defined. Also included are the initial temperatures ($T_{\text{init}}(i,j), \text{°C}$), and setpoint conditions ($T_{\text{set}}(i,j), \text{°C}$), followed by the basal metabolic rate of each tissue ($Q_{\text{gen}}(i,j), \text{J/min}$), and the total basal metabolic rate of the subject ($\text{BasRate}, \text{J/min}$).

C4.6 Thermoregulators and Blood Flow

In the MU Model, there is a need for two arrays for shiver calculations. These come from Bue [1] and are called $\text{ShivDist}(i)$ and $\text{Mushiv}(i)$. $\text{Skindist}(i)$ and $\text{Condist}(i)$ are arrays used in the vasoconstriction calculations and $\text{Dildist}(i)$ is used for vasodilation calculation. The basal blood thermal mass flow rate into each tissue layer is defined here ($\text{mdotcb}(i,j), \text{J/(min-K)}$) along with the steady state gain between muscle blood flow and metabolic activity ($\text{Pow2Blood}, \text{l/K}$), and time constant ($\text{TauBlood}, \text{min}$).

C4.7 Respiratory Tract

This section defines the time constant of the first-order transfer function between breath rate and metabolic activity ($\text{TauResp}, \text{min}$) and a respiratory distribution array ($\text{RespD}$) that quantifies respiratory heat losses from specific tissues of the head and trunk.

C4.8 Radiation Contribution

This section defines the Stefan-Boltzmann radiation constant ($\sigma, \text{J/(min-cm}^2-\text{K}^4)$) and the view factor ($f(i)$).

C4.9 Latent Contribution
This section defines several values that are used in the latent heat loss calculation routine of the MU Man. This includes Sweatdist(i), Sweat_Gain, Sweat_Add, and Diff_Gain.

C4.10 Artery and Vein Heat Transfer Coefficients and Initial Temperatures

This section defines the heat transfer coefficients between the arteries and tissue \((na(i,j), J/(\text{min-K}))\) and between the veins and tissue \((hv(i,j), J/(\text{min-K}))\). In addition, the countercurrent heat transfer coefficients between the arterial and venous blood pools for each element is defined \((Hav(i), J/(\text{min-K}))\). The initial temperatures of the arterial blood pools \((T_{\text{init}}(i), ^\circ\text{C})\) and venous blood pools \((Tv_{\text{init}}(i), ^\circ\text{C})\) are also defined.

C4.11 Clothing

This section defines various thermal and physical properties of clothing and is required when utilizing the clothing option of the model \((\text{clothes2D.mdl})\), but not needed at all for the nude option. Specifically, this section defines the thermal conductivity \((k(i,5), J/(\text{min-m-K}))\), the specific heat \((CpCl(i), J/(\text{kg-K}))\), the density \((rhoCl(i), \text{kg/m}^3)\) and the thickness \((tCl(i), \text{m})\) of the clothing. In addition, the thermal mass of clothing for each element \((MCp(i,7), J/K)\) is also defined. The initial clothing temperatures \((T_{\text{init}}(i,5), ^\circ\text{C})\) are defined as well.

C5.0 MATLAB INITIALIZATION PROGRAMS FOR THE SUIT/LCVG CASE

The suit/LCVG option utilizes MATLAB files \((m\text{-files})\) to initialize the parameters and inputs that are known to remain constant during a simulation. The SIMULINK file for the suit/LCVG option is called \(olsuit2D.mdl\). The following MATLAB files are used
to initialize olsuit2D.mdl: runolsuit2D.m, human2D.m, suitdat2D.m, and olcase2D.m (listed in the Appendix).

The file, runolsuit2D.m, is used to call and run the other initialization files (human2D.m, suitdat2D.m, and olcase2D.m), and then to open the SIMULINK model (olsuit2D.mdl).

The file, human2D.m, is used to define constant thermal and physical properties of the human. This file is very similar to setup2D.m with a few minor exceptions. For one, the sections in setup2D.m that define the environmental prescription inputs, radiation contribution and clothing initializations are totally emitted from human2D.m, due to the introduction of the spacesuit. As a consequence, the parameters, Wind_Parameter and Rad_Parameter in section 1 of setup2D.m, are not needed in human2D.m. In addition, the specific heat of ventilation gas (\(C_{p\text{Gas}}, J/(g-K)\)) is introduced in human2D.m.

The file, suitdat2D.m, defines constant thermal and physical properties for the suit, ventilation garment (VG), liquid cooling garment (LCG) and undergarment. Specifically, the section defines the mass, surface area, conductivity, specific heat, thickness and emissivity of the suit. In addition, this section defines the mass flow rate, specific heat, viscosity, conductivity and universal constant of ventilation gas. Also, the section defines the mass flow rate, flow distribution, specific heat and conductivity of water flowing through the LCG. Initial suit, ventilation gas and LCG water temperatures are also defined in this section.
C6.0 SIMULINK MODEL

Figures 4-121 show the major SIMULINK block diagrams for the nude, clothed and suit/LCVG models. Specifically, Figures 4-85 show the blocks for the nude model, Figures 86-94 show the major blocks for the clothed model, and Figures 95-121 show the major blocks for the suit/LCVG model. In this model, of course, the human is a part of the clothed and suit/LCVG model. So, Figures 86-121, which comprise the clothed and suit/LCVG blocks, do not repeat any common blocks from the nude model (Figures 4-85) to avoid redundancy. Figures 4, 86, and 95 show the main windows for the nude, clothed and suit/LCVG models. Double clicking on any of the blocks in these figures will bring up other subsystems where all the heat rates, energy balances, temperatures, etc. are calculated. In addition, this model has subsystems that obtain the possibly changing environmental conditions. The default simulation outputs are mean skin temperature and body core temperature, which are common outputs of human thermal models. However, the model can be easily edited to include any other desired inputs.
C7.0 NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}$</td>
<td>Heat flow</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>$G_{\text{empirical}}$</td>
<td>Empirically derived gain</td>
</tr>
<tr>
<td>$W$</td>
<td>Work</td>
</tr>
<tr>
<td>$\mathcal{R}$</td>
<td>Blood flow reduction via vasoconstriction</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Weighting parameter</td>
</tr>
<tr>
<td>$K$</td>
<td>Various distribution value</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$P_v$</td>
<td>Partial water vapor pressure</td>
</tr>
<tr>
<td>$P_g$</td>
<td>Adiabatic saturation pressure of water</td>
</tr>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>$F$</td>
<td>Interchange factor</td>
</tr>
<tr>
<td>$S$</td>
<td>Drive for sweating</td>
</tr>
<tr>
<td>$C_{\text{empirical}}$</td>
<td>Empirically derived constant</td>
</tr>
<tr>
<td>$R_{\text{water}}$</td>
<td>Universal Gas constant for water</td>
</tr>
<tr>
<td>$H_{\text{mass}}$</td>
<td>Mass transfer coefficient</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>Heat of vaporization for water</td>
</tr>
<tr>
<td>$V_{\text{air}}$</td>
<td>Velocity of air</td>
</tr>
<tr>
<td>$P_{\text{empirical}}$</td>
<td>Empirically derived exponent</td>
</tr>
<tr>
<td>$H$</td>
<td>Height</td>
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<td>$L$</td>
<td>Segment length</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius</td>
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<tr>
<td>$\bar{h}$</td>
<td>Average forced convection coefficient</td>
</tr>
<tr>
<td>$C$</td>
<td>Look-up parameter for convection coefficient computation</td>
</tr>
<tr>
<td>$m$</td>
<td>Look-up parameter for convection coefficient computation</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$r$</td>
<td>Denotes radial direction in 2-D conduction</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Denotes angular direction in 2-D conduction</td>
</tr>
<tr>
<td>$\dot{e}_b$</td>
<td>Thermal mass blood flow rate</td>
</tr>
<tr>
<td>$hA_a$</td>
<td>Heat transfer coefficient between arteries and tissue</td>
</tr>
<tr>
<td>$hA_v$</td>
<td>Heat transfer coefficient between veins and tissue</td>
</tr>
<tr>
<td>$hA_{a\leftrightarrow v}$</td>
<td>Countercurrent heat exchange coefficient between arterial and venous blood</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
</tr>
<tr>
<td>$CLO$</td>
<td>CLO value for clothing</td>
</tr>
<tr>
<td>$CONV$</td>
<td>Unit conversion</td>
</tr>
<tr>
<td>$UA$</td>
<td>Heat exchange coefficient</td>
</tr>
</tbody>
</table>
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Figure C.1b: The tissue layers within each element.
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Head

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Sector 1

Outer Core  Muscle  Fat  Inner Skin  Outer Skin
Core-Muscle Interface  Muscle-Fat Interface  Fat-Skin Interface

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Head, Blood Calculations.

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Sector 1

Outer Core  Muscle  Fat  Inner Skin  Outer Skin

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R. Arm

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R. Hand

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Energy Balance at Clothing Layer

R. Arm  L. Arm

Conduction at Clothing Layer

R. Leg  L. Leg
R. Foot  L. Foot
R. Toes  L. Toes

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Trunk

Sector 1  Sector 2  Sector 3  Sector 4  Sector 5

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C10.0 SUPPLEMENTS

C10.1 Instructions on Running the Nude and Clothed Options

1. These are the files that should be contained in the directory where you will be running MATLAB: setup2D.m, and nude2D.mdl for the nude case or clothes2D.mdl for the clothed case.

2. Start MATLAB and use the unix command cd to change to the directory containing the necessary programs from step 1. Type: setup2D. You are told to enter the additional metabolic work profile. This represents the work rate (Watts) the subject is doing above the basal metabolic rate at each instant of time. This is keyed in as a 2D matrix where the first column represents the time dependence of this work profile, and the second column is the work profile itself. Here is an example: At time zero, exercise above the basal metabolic rate of begins at 50 W and lasts for 100 min. After this, the subject now increases his work rate to 150 W for duration of 75 minutes and then quits. The input for this work profile is: [0 50;100 50;100 150;175 150] where every row of the matrix represents a coordinate of the work profile where a change occurs.

3. Next, you are prompted for the mechanical work efficiency. This is a number between 0 and 1 and represents the efficiency of the work performed from Step 2. In other words, this is the portion of the energy expended by the subject beyond the basal metabolic rate will not be seen by the body as heat.

4. If the clothing option is desired, the user should open setup2D.m and change the thermal properties of the clothing (section 11.0 in setup2D.m) to whatever is desired (the default is cotton). Otherwise, ignore this step.
5. Type: `nude2D` (for the nude option) or `clothes2D` (for clothed option). The Simulink model should appear. Click on the Simulation menu, select Start to begin the simulation. The simulation will begin at time zero and end with the last time value of the additional metabolic rate time vector of Step 2.

6. The output can be viewed by the double clicking on the Output block located in the main window of the model. Double click on the scope block, and then double click on the picture of binoculars. The time history of the rectal and mean skin temperatures should appear.

**NOTE:** To change other model inputs, open `setup2D.m` and make the changes in the file, then save. Many of the inputs can be set up so that the user is prompted for the inputs. For instance the following line:

```
WorkDist(i) = 0.00;     %input('Enter Work Distribution for the Head: ');  
```

could be changed to:

```
WorkDist(i) = input('Enter Work Distribution for the Head: ');  
```

and the result would be that the program would ask for this specific user-defined input when it is run.

**C10.2 Instructions on Running the Suit/LCVG option**

1. These are the files that should be contained in the directory where you will be running MATLAB: `runolsuit2D.m`, `human2D.m`, `suitdat2D.m`, `olcase2D.m`, and `olsuit2D.mdl`.

2. Open MATLAB and change to the correct directory. Before running the model, the desired environmental and subject conditions should be prescribed. To prescribe desired physical or thermal characteristics for the human open and edit `human2D.m`. 
To alter suit, VG, and LCG parameters suitdat2D.m can be opened and edited, however these parameters most likely won’t need to be changed. The inputs into the system (outer suit temperature, inlet LCG temperature and work rate) can be prescribed by opening and editing o1case2D.m (see note below). It should be noted that the inputs in o1case2D.m should be keyed in as a 2D matrix as described in step 2 of section 10.1. All m-files should be saved after editing.

7. Type: runolsuit2D. The SIMULINK model o1suit2D.mdl should appear. Click on the Simulation menu, select Start to begin the simulation. The simulation will begin at time zero and end with the last time value of the additional metabolic rate time vector.

8. The output can be viewed by the double clicking on the Output block located in the main window of the model. Double click on the scope block, and then double click on the picture of binoculars. The time history of the rectal and mean skin temperatures should appear.

**NOTE:** Section 10.9 of this report gives an example listing for o1case2D.m. It should be noted that this example uses the NASA metabolic rate and environmental profile prescribed for EVA (extra-vehicular activity) missions.
### C10.3 Variable Definition for setup2D.m and human2D.m

<table>
<thead>
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<td>J/K</td>
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<td>J/K</td>
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<td>Mass of clothing at each element</td>
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<td>Distribution of skin mass at the inner skin</td>
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<td>J/min</td>
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<td>Basal heat generation of tissue i,j</td>
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<td>Qmuscle</td>
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<td>J/min</td>
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<td>R(i,j)</td>
<td>Radial distance to solid tissue and interface node</td>
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<td>Radius(i,j)</td>
<td>Layer shell outer radius</td>
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<td>Feet to meters conversion</td>
<td>m/ft</td>
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<td>Interchange factor between UG and suit</td>
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<td>BTU/(hr-ft-°F)*</td>
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<td>BTU/(hr-ft-°F)*</td>
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<td>Pounds to kg conversion</td>
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<td>Length of each segment</td>
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</table>
Msuit(i) Mass of each suit segment
MsuitDist(i) Mass distribution factors for suit
MsuitTot Total mass of suit
Mugas Viscosity of gas
MWratio Molecular weight ratio
P Used to calculate dens
Pbase Pressure of gas in VL
PSI2KPA Psi to Kpa conversion
Pv Pressure of gas in VL
pw Used in saturation pressure table
Pwcl Pressure of water cooling loop
PwTable Used in saturation pressure table
Rgas Ideal gas constant
rse(i) Inside suit radius for each segment
RowTso(i) Tso temps. for Tinvgol lookup table
RO2 Ideal gas constant
RunTime Simulation length
Sgap(i) Length of gap from skin to suit wall
SIGMA Stefan-Boltzmann constant
T Used to calculate dens
Tinlucgol(i,j) Inlet LCG temperature 2D matrix
Tsof(i,j) Back outer suit temperature 2D matrix
Tsof(i,j) Front outer suit temperature 2D matrix
TdewTable Used in saturation pressure table
tdvvg(i) Transport delays for each suit segment
timedelaylcg Total transport delay through LCG
timedelayvg Total transport delay through suit
Tindewol Dewpoint temperature of gas entering suit
Tinvgol(i,j) 2D look up table for inlet VG temperature
Tsiic Suit inner wall initial temperature
Tvcic Initial condition of ventilation gas
Twcl Water initial condition for integration
UA capsule factor Constant used to calculate UA
V(i) Velocity of gas for each segment
W2BTUPHR Watts to BTU/hr. conversion

+ These variables are located in olcase2D.m.

* NOTE: convr usually equals 1, thus the simulation is in minutes, and the hr. in the units should be replaced with min.
C10.5 MATLAB setup2D.m Listing

```matlab
% (1.0) Adjustment Parameters
Wind_Parameter = 0.00; %Default is 0
Sweat_Parameter = 1.00; %Default is 1
Resp_Parameter = 1.00; %Default is 1
Rad_Parameter = 0.85; %Default is 0.85 (15% shaded skin)
Shiver_Parameter = 1.00; %Default is 1
Diff_Parameter = 1.00; %Default is 1
BF_Parameter = 1.00; %Default is 1

% (2.0) Subject Prescription Inputs
BodyMass = 69.8532; %input('Enter Body Mass (kg): ');
Height = 170.18; %input('Enter Body Height (cm): '');
AddRate = input('Enter Additional Metabolic Work Profile [Min, Watts]: ');
AddRate = [AddRate(:,1) AddRate(:,2)*60];
Entry = size(AddRate);
RunTime = AddRate(Entry(1,1),1);
WorkEff = input('Enter Mechanical Work Efficiency: ');
if (WorkEff>1.0) %Check for '%' or decimal
    WorkEff = WorkEff/100;
end
WorkDist(1) = 0.00; %input('Enter Work Distribution for the HEAD: ');
WorkDist(2) = 0.30; %input('Enter Work Distribution for the TRUNK: ');
WorkDist(3) = 0.04; %input('Enter Work Distribution for the ARMS: ');*0.5;
WorkDist(4) = WorkDist(3);
WorkDist(5) = 0.0025; %input('Enter Work Distribution for the HANDS: ')*0.5;
WorkDist(6) = WorkDist(5);
WorkDist(7) = 0.0025;
WorkDist(8) = WorkDist(7);
WorkDist(9) = 0.30; %input('Enter Work Distribution for the LEGS: ');*0.5;
WorkDist(10) = WorkDist(9);
WorkDist(11) = 0.0045; %input('Enter Work Distribution for the FEET: ');*0.5;
WorkDist(12) = WorkDist(11);
WorkDist(13) = 0.0005;
WorkDist(14) = WorkDist(13);

% (2.1) Normalize WorkDist in case the sum does not equal 1 This allows for %
% entry
% Value = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1]
if (Value>1.01)
    Warning = 'Work Distribution does not sum to 1'
    Factor = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1]
    for (i=1:14)
        WorkDist(i) = WorkDist(i)/Factor;
    end
end
if (Value<0.99)
    Warning = 'Work Distribution does not sum to 1'
    Factor = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1]
```

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for (i=1:14)
    WorkDist(i) = WorkDist(i)/Factor;
end

% (3.0) Environmental Prescription Inputs
Tdrys = input('Enter Dry Bulb Temperature [min, C]: ');
Ttwet = 10;
%input('Enter Dew Point (C): ')
Press = 101.35;  %input('Enter Absolute Air Pressure (kPa): ');
AirSpd = 0.015;  %input('Enter Air Speed (m/s): ');
Trafd = Tdrys;  %input('Enter Frontal Radiant Temperature [min, C]: ');
Tradb = Trafd;  %input('Enter Back Radiant Temperature [min, C]: ');

% (4.0) Define constant environmental properties
C2K = 273.15;  %K
Cpwat = 4.1868;  %kJ/(kg*K)
CpAir = 1.0057;  %kJ/(kg*K)
Rwat = 0.4619;  %kJ/(kg*K)
Tsat(1) = 0;
for i=2:1001
    Tsat(i) = Tsat(i-1)+50/1000;
    T(i) = Tsat(i)*1.8+32;
    F = -0.07086745;
    G = 0.001626943*T(i)-1.0;
    H = -0.0004286517*T(i)^2+0.03533457*T(i)-2.519124;
    Pgwet(i) = 0.4912*exp(((-G-(G*G-4*F*H)^0.5)/(2*F))*101.35/14.7;  %kPa
end
T = Twet*1.8+32;
F = -0.07086745;
G = 0.001626943*T-1.0;
H = -0.0004286517*T^2+0.03533457*T-2.519124;
Pvair = 0.4912*exp(((-G-(G*G-4*F*H)^0.5)/(2*F))*101.35/14.7;  %kPa

% (4.1) Define Pi
Pi = 4*atan(1);
dcheta = Pi/3;

% (5.0) Define constant tissue properties
Segment(1):
    % Head = 1
    % Trunk = 2
    % R-Arm = 3
    % L-Arm = 4
    % R-Hand = 5
    % L-Hand = 6
    % R-Fing = 7
    % L-Fing = 8
    % R-Leg = 9
    % L-Leg = 10
    % R-Foot = 11
    % L-Foot = 12
    % R-Toes = 13
    % L-Toes = 14

% (5.1) Tissue Mass and Heat Capacity
MassFat = BodyMass*(5.546/(0.8*Height^0.242/(BodyMass*1000)^0.1+0.162)-5.044);  %kg
MassLean = BodyMass-MassFat;
SkelDist = [0.0192920, 0.0470400, 0.0118780, 0.0118780];
0.0009120;
0.0009120;
0.0009120;
0.0009120;
0.0395840;
0.0395840;
0.00263178;
0.00263178;
0.00029242;
0.00029242];

ViscDist=[0.028320;
0.1870400;
0.0058820;
0.0058820;
0.0001176;
0.0001176;
0.0001176;
0.0001176;
0.0001176;
0.0151760;
0.0151760;
0.00042354;
0.00042354;
0.0004706;
0.0004706];

MassDist=[SkelDist(1)+ViscDist(1) 0.005880 0.033300 0.00423;
SkelDist(2)+ViscDist(2) 0.283400 0.633300 0.02130;
SkelDist(3)+ViscDist(3) 0.026640 0.043350 0.00382;
SkelDist(4)+ViscDist(4) 0.026640 0.043350 0.00382;
SkelDist(5)+ViscDist(5) 0.000297 0.003332 0.00073;
SkelDist(6)+ViscDist(6) 0.000297 0.003332 0.00073;
SkelDist(7)+ViscDist(7) 0.000297 0.003332 0.00073;
SkelDist(8)+ViscDist(8) 0.000297 0.003332 0.00073;
SkelDist(9)+ViscDist(9) 0.080500 0.106650 0.00947;
SkelDist(10)+ViscDist(10) 0.080500 0.106650 0.00947;
SkelDist(11)+ViscDist(11) 0.0005346 0.00900 0.001692;
SkelDist(12)+ViscDist(12) 0.0005346 0.00900 0.001692;
SkelDist(13)+ViscDist(13) 0.0000594 0.00100 0.000188;
SkelDist(14)+ViscDist(14) 0.0000594 0.00100 0.000188];

Cp=[0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9];

%Kcal/(kg*K) -> J/(kg*K)

Atot = 71.8*BodyMass^0.425*Height^0.725; % sq. cm

Adist = [0.07;
0.3602;
0.06705;
0.06705;
0.0125;
0.0125;

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Area = Atot*Adist; \%cm^2

A=Area/10000; %Segment areas in m^2

for i=1:14
    Mass(i,1) = MassDist(i,1)*MassLean;
    Mass(i,2) = MassDist(i,2)*MassLean;
    Mass(i,3) = MassDist(i,3)*MassFat;
    Mass(i,4) = MassDist(i,4)*MassLean;
end

for i=1:14
    Vol(i,1) = 1000*Mass(i,1);
    Vol(i,2) = 1000*(Mass(i,1)+Mass(i,2));
    Vol(i,3) = 1000*(Mass(i,1)+Mass(i,2)+Mass(i,3));
    Vol(i,4) = 1000*(Mass(i,1)+Mass(i,2)+Mass(i,3)+Mass(i,4));
    Length(i) = Area(i)^2/(4*Pi*Vol(i,4));
    for j=1:4
        Radius(i,j) = (Vol(i,j)/(Pi*Length(i)))^0.5;
    end
end

k = [6.9372 0.3240 0.5567 0.5567;
     0.6908 0.5971 0.3328 0.3328;
     1.9634 1.2954 0.6961 0.6961;
     1.9634 1.2954 0.6961 0.6961;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.5683 1.8182 0.4451 0.4451;
     1.5683 1.8182 0.4451 0.4451;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501]*6.978; %Cal/(hr*cm*K) -> J/(min*m*K)

% (5.2) Nodal Radii
for i=1:14
    NodRad(i,1) = 0.5*Radius(i,1);
    NodRad(i,2) = 0.5*(Radius(i,1)+Radius(i,2));
    NodRad(i,3) = 0.5*(Radius(i,2)+Radius(i,3));
    NodRad(i,4) = 0.5*(Radius(i,3)+Radius(i,4));
end

for i=1:14
    R(i,1)=NodRad(i,1)/100;
    R(i,2)=Radius(i,1)/100;
    R(i,3)=NodRad(i,2)/100;
    R(i,4)=Radius(i,2)/100;
    R(i,5)=NodRad(i,3)/100;
    R(i,6)=Radius(i,3)/100;
R(i,7)=NodRad(i,4)/100;
R(i,8)=Radius(i,4)/100;
end

L=Length/100;  % Length of each segment in meters

MD=[0 0 0.005886 0.033300 0 0;
     0 0.283400 0.633300 0 0;
     0 0.026640 0.043350 0 0;
     0 0.026640 0.043350 0 0;
     0 0.000297 0.003332 0 0;
     0 0.000297 0.003332 0 0;
     0 0.080500 0.106650 0 0;
     0 0.080500 0.106650 0 0;
     0 0.0005346 0.009000 0 0;
     0 0.0005346 0.009000 0 0;
     0 0.0000594 0.001000 0 0;
     0 0.0000594 0.001000 0 0];

for (i=1:14)  %Loop for determining the Mass Distribution
    A0(i)=R(i,1)^2;
    A1(i)=(R(i,2)+R(i,1))^-2-R(i,1)^2;
    A7(i)=(R(i,8)+R(i,7))^2-(R(i,7)+R(i,6))^2;
    A8(i)=(2*R(i,8))^2-(R(i,8)+R(i,7))^2;
    P0(i)=A0(i)/(A0(i)+A1(i));
    P1(i)=1-P0(i);
    P7(i)=A7(i)/(A7(i)+A8(i));
    P8(i)=1-P7(i);
    MD(i,1)=P0(i)*MassDist(i,1);
    MD(i,2)=P1(i)*MassDist(i,1);
    MD(i,5)=P7(i)*MassDist(i,4);
    MD(i,6)=P8(i)*MassDist(i,4);
end

for i=1:14
    Cp(i,1) = (SkelDist(i)*0.5+ViscDist(i)*0.9)/(SkelDist(i)+ViscDist(i))^4186.8;
    M(i,1) = MD(i,1)*MassLean;
    MCP(i,1) = M(i,1)*Cp(i,1);
    M(i,2) = MD(i,2)*MassLean;
    MCP(i,2) = M(i,2)*Cp(i,1);
    M(i,3) = MD(i,3)*MassLean;
    MCP(i,3) = M(i,3)*Cp(i,2);
    M(i,4) = MD(i,4)*MassFat;
    MCP(i,4) = M(i,4)*Cp(i,3);
    M(i,5) = MD(i,5)*MassLean;
    MCP(i,5) = M(i,5)*Cp(i,4);
    M(i,6) = MD(i,6)*MassLean;
    MCP(i,6) = M(i,6)*Cp(i,4);
end

TisMass = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]*Mass;
SegMass = Mass*[i;1;1;1];
NomMus = 30.56;
NomSkin = 3.55;
MCpblood = 2.25*4186.8*BodyMass/70;
MCP(2,1) = MCP(2,1)-P0(2)*MCpblood; %Adjust for 2.5 L of blood in trunk core
MCP(2,2) = MCP(2,2)-P1(2)*MCpblood;

NaCpb=SegMass*MCPblood/BodiesMass/2; %Thermal Mass of blood for arteries and veins

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MvCpb=MaCpb; % in each segment, J/K

for i=1:14
    Hm(i) = 0.007*(106.68/Length(i))^0.25; m/s
end

% (5.4) Initial tissue temperatures (C) (41-Node Man 3.19)
Tinit = [37.00 36.44 36.11 35.89;
    37.11 36.83 35.50 34.67;
    35.61 35.06 34.50 34.28;
    35.61 35.06 34.50 34.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    36.44 35.83 35.06 34.72;
    36.44 35.83 35.06 34.72;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28];

% (5.5) Set point tissue temperatures (C) (41-Node Man 3.19)
Tset = [37.00 36.44 36.11 35.89;
    37.11 36.83 35.50 34.67;
    35.61 35.06 34.50 34.28;
    35.61 35.06 34.50 34.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    35.50 35.39 35.33 35.28;
    36.44 35.83 35.06 34.72;
    36.44 35.83 35.06 34.72;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28;
    35.44 35.28 35.39 35.28];

% (5.6) Metabolic heat generation
QBMR   = 38.67/10000*69.78; % kcal/(h*m^2) -> J/(min*cm^2)
Qcore  = 0.1*QBMR*Atot;
Qsf    = 0.3*(TisMass(3)+TisMass(4));
Qmuscle = (0.18*QBMR*Atot-Qsf);
for i=1:14
    Qgen(i,1) = Qcore*Mmass(i,1)/TisMass(1); % J/min
    Qgen(i,2) = Qmuscle*Mmass(i,2)/TisMass(2);
    Qgen(i,3) = Qsf*Mmass(i,3)/(TisMass(3)+TisMass(4));
    Qgen(i,4) = Qsf*Mmass(i,4)/(TisMass(3)+TisMass(4));
end
Qgen(1,1) = Qcore*Mmass(1,1)/TisMass(1)+0.16*QBMR*Atot;
Qgen(2,1) = Qcore*Mmass(2,1)/TisMass(1)+0.56*QBMR*Atot; % J/min
BasRate = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1] * Qgen*[1;1;1;1]; % J/min

% (6.0) Thermoregulation and blood flow
% (6.1) Shiver calculations
Shiver_Gain = 696.21;
ShivLim = 1000*60;
Shivdist=[0.0827; 0.5870; 0.0411; 0.0411; 0.0055375];
0.0055375;
0.0055375;
0.0055375;
0.0930;
0.0930;
0.017955;
0.017955;
0.001995;
0.001995;

Mushiv=[0.02300;
0.94800;
0.00265;
0.00265;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;
0.000575;

% (6.2) Vasoconstriction calculations
Con_Gain = 9.99;
Skindist = Shvidist;
Condist=[0.05;
0.15;
0.025;
0.025;
0.0875;
0.0875;
0.0875;
0.0875;
0.025;
0.025;
0.0875;
0.0875;
0.0875;
0.0875;

% (6.3) Vasodilation calculations
Dil_Gain = 10454.69;
Dildist=[0.132;
0.322;
0.0475;
0.0475;
0.0305;
0.0305;
0.0305;
0.0305;
0.115;
0.115;
0.025;
0.025;
0.025;
0.025;

% (6.4) Blood thermal mass flow calculations
Mbas=[105.6 0.594 0.264 3.700;
510.0 14.08 5.060 4.620;
0.759 1.364 0.352 0.550;
0.759 1.364 0.352 0.550;
0.055 0.0275 0.0275 1.100;
0.055 0.0275 0.0275 1.100;
0.055 0.0275 0.0275 1.100;
0.055 0.0275 0.0275 1.100;
2.320 4.070 0.880 3.135;
2.320 4.070 0.880 3.135;
0.1485 0.0297 0.0792 2.970;
0.1485 0.0297 0.0792 2.970;
0.0165 0.0033 0.0088 0.330;
0.0165 0.0033 0.0088 0.330]*BodyMass/70*31.65*BF_Parameter;
mdotcb = Mbas; %J/(min*K)
Pow2Blood = 0.9972; %Power to Blood rate steady state gain
TauBlood = 2; %Blood rate from power time constant

% (7.0) Respiratory Tract
TauResp = 2; %Breath Rate from MR time constant
RespD = [0 0 0.172 0.0574 0.0 0.0;
         0 0 0.523 0.0000 0.0 0.0]/2;
RespD(1,1)=0.771*P0(1)/2;
RespD(1,2)=0.771*P1(1)/2;
RespD(2,1)=0.476*P0(2)/2;
RespD(2,2)=0.476*P1(2)/2;
Resp_Gain = [1/231.64;1.0;5.8743]; %Various Respiratory Gains

% (8.0) Radiation contribution
sigma = 5.669E-8*60/10000; %J/(min*cm^2*K^4)
fr = [0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9;
       0.9]*Rad_Parameter;

% (9.0) Latent contribution
Sweatdist=[0.0810; %=Ks'
           0.4820;
           0.0765;
           0.0765;
           0.00775;
           0.00775;
           0.00775;
           0.0.1090;
           0.1090;
           0.01575;
           0.01575;
           0.00175;
           0.00175];
Sweat_Gain = 69.04*60; %J/(min*K^2)
Sweat_Add = 466.33*60; %J/(min*K)
Diff_Gain = 0.0182832*Diff_Parameter; %J/(min*KPa*cm^2)
% (10.0) Artery & Vein Heat Transfer Coefficients and Initial Temperatures
da=0.004; % Diameter of blood vessels, m

for (i=1:14) % HT coeff. between arteries and tissue, J/(min*K)
  ha(i,1)=2*Pi*k(i,1)*L(i)/log(R(i,1)/da);
  ha(i,2)=2*Pi*k(i,1)*L(i)/log(2*R(i,1)/da);
  ha(i,3)=2*Pi*k(i,2)*L(i)/log(2*R(i,3)/da);
  ha(i,4)=2*Pi*k(i,3)*L(i)/log(2*R(i,5)/da);
  ha(i,5)=2*Pi*k(i,4)*L(i)/log(2*R(i,7)/da);
  ha(i,6)=2*Pi*k(i,4)*L(i)/log(2*R(i,8)/da);
end
hv=ha; % HT coeff. between veins and tissue, J/(min*K)

Hav=[0.00; 4.13; 4.13; 0.285; 0.285; 0.285; 6.90; 6.90; 3.06; 3.06; 0.34; 0.34]*60; % => J/(min*K)

Tainit=[36.38; 36.40; 36.25; 36.25; 35.53; 35.53; 31.89; 31.89; 36.16; 36.16; 34.74; 34.74; 33.88; 33.88]; % Initial Arterial Temperatures, deg. C

Tvinit=[36.44; 36.38; 35.35; 35.35; 34.28; 34.28; 31.01; 31.01; 35.79; 35.79; 34.07; 34.07; 33.03; 33.03]; % Initial Venous Temperatures, deg. C

% (11.0) Clothing (Default material is cotton)

kshirt=3.5478; % input('Enter thermal conductivity of shirt [J/(min*m*K)]: ')
kpants=3.5478; % input('Enter thermal conductivity of pants [J/(min*m*K)]: ')
kshoes=3.5478; %input('Enter thermal conductivity of shoes [J/(min*m*K)]: ')
Cpshirt=1297.8314; %input('Enter specific heat of shirt [J/(kg*K)]: ')
Cppants=1297.8314; %input('Enter specific heat of pants [J/(kg*K)]: ')
Cpshoes=1297.8314; %input('Enter the specific heat of shoes [J/(kg*K)]: ')
rhoshirt=1473.6977; %input('Enter the density of shirt [kg/m^3]: ')
rhopants=1473.6977; %input('Enter the density of pants [kg/m^3]: ')
rhoshoes=1473.6977; %input('Enter the density of shoes [kg/m^3]: ')
tshirt=0.001; %input('Enter shirt thickness [m]: ')
tpants=0.0015; %input('Enter pants thickness [m]: ')
tshoes=0.005; %input('Enter shoe thickness [m]: ')

k(:,5)=[0;
kshirt;
kshirt;
kshirt;
0;
0;
0;
kpants;
kpants;
kshoes;
kshoes;
kshoes;
kshoes]; %Clothing thermal conductivity [J/(min*m*K)]

Cpcls=[0;
Cpshirt;
Cpshirt;
Cpshirt;
0;
0;
0;
0;
Cppants;
Cppants;
Cpshoes;
Cpshoes;
Cpshoes;
Cpshoes]; %Clothing specific heat [J/(kg*K)]

rhocls=[0;
rhoshirt;
rhoshirt;
rhoshirt;
0;
0;
0;
0;
rhopants;
rhopants;
rhoshoes;
rhoshoes;
rhoshoes;
rhoshoes]; %Clothing density [kg/m^3]

tcls=[0;
tshirt;
tshirt;
tshirt;
0;
0;
0;
0;
tpants;
tpants;
tshoes;
tshoes;
tshoes;
tshoes;\%Clothing thickness [m]

for (i=1:14)
  Aclm2(i)=2*Pi*(R(i,8)+tcl(i))*L(i);
  Vcl(i)=Pi*((R(i,8)+tcl(i))^2-R(i,8)^2)*L(i);
  Mcl(i)=rhocl(i)*Vcl(i);
  MCp(i,7)=Mcl(i)*Cpcl(i);
end

Aclcm2=Aclm2*10000; \%Clothing surface area [cm^2]

Tinit(:,5)=[35.67;
  34.20;
  34.06;
  34.06;
  35.22;
  35.22;
  35.22;
  35.22;
  34.20;
  34.20;
  35.10;
  35.10;
  35.10;
  35.10]; \%Clothing Initial Temperatures, deg. C
C10.6 MATLAB runolsuit2D.m Listing

clear
human2D
mplssdat2D
olcase2D
olsuit2D
C10.7 MATLAB human2D.m Listing

```matlab
% (1.0) Adjustment Parameters
Sweat_Parameter = 1.00; % Default is 1
Resp_Parameter = 1.00; % Default is 1
Shiver_Parameter = 1.00; % Default is 1
Diff_Parameter = 1.00; % Default is 1
BF_Parameter = 1.00; % Default is 1

% (2.0) Subject Prescription Inputs
BodyMass = 69.8532; % input('Enter Body Mass (kg): ');
Height = 170.18; % input('Enter Body Height (cm): ');
BasRate = 81.4; % input('Enter Basal Metabolic Rate (Watts): ');
BasRate = BasRate*60;
WorkEff = 0.0; % WorkEff = input('Enter Mechanical Work Efficiency: ');

if (WorkEff>1.0) % Check for '%' or decimal
    WorkEff = WorkEff/100;
end
WorkDist(1) = 0.00; % input('Enter Work Distribution for the HEAD: ');
WorkDist(2) = 0.30; % input('Enter Work Distribution for the TRUNK: ');
WorkDist(3) = 0.04; % input('Enter Work Distribution for the ARMS: ')*0.5;
WorkDist(4) = WorkDist(3);
WorkDist(5) = 0.0025; % input('Enter Work Distribution for the HANDS: ')*0.5;
WorkDist(6) = WorkDist(5);
WorkDist(7) = 0.0025;
WorkDist(8) = WorkDist(7);
WorkDist(9) = 0.30; % input('Enter Work Distribution for the LEGS: ')*0.5;
WorkDist(10) = WorkDist(9);
WorkDist(11) = 0.0045; % input('Enter Work Distribution for the FEET: ')*0.5;
WorkDist(12) = WorkDist(11);
WorkDist(13) = 0.0005;
WorkDist(14) = WorkDist(13);

% (2.1) Normalize WorkDist in case the sum does not equal 1 This allows for '%
Value = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1];
if (Value>1.01)
    Warning = 'Work Distribution does not sum to 1'
    Factor = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1];
    for (i=1:14)
        WorkDist(i) = WorkDist(i)/Factor;
    end
end
if (Value<0.99)
    Warning = 'Work Distribution does not sum to 1'
    Factor = WorkDist*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1];
    for (i=1:14)
        WorkDist(i) = WorkDist(i)/Factor;
end
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end

% (3.0) Define constant properties
Tsat(1) = 0;
for i=2:1001
    Tsat(i) = Tsat(i-1)+50/1000;
    T(i) = Tsat(i)*1.8+32;
    F = -0.07086745;
    G = 0.001626943*T(i)-1.0;
    H = -0.00004286517*T(i)^2+0.03533457*T(i)-2.519124;
    Pgwt(i) = 0.4912*exp(\[-G-(G*G-4*F*H)^0.5)/(2*F)\]*101.35/14.7; %kPa
end

C2K=273.15; % (C)
Cpwat=4.1868; %J/(g*K)
Rwat=0.4619; %J/(g*K)
CpAir=1.0057; %J/(g*K)
CpO2=0.9211; %J/(g*K)
CpGas=CpO2; %J/(g*K)

% (4.0) Define Pi
Pi=4*atan(1);
dtheta=Pi/3;

% (5.0) Define constant tissue properties
% Segment(i):
%    Head = 1
%    Trunk = 2
%    R-Arm = 3
%    L-Arm = 4
%    R-Hand = 5
%    L-Hand = 6
%    R-Fing = 7
%    L-Fing = 8
%    R-Leg = 9
%    L-Leg = 10
%    R-Foot = 11
%    L-Foot = 12
%    R-Toes = 13
%    L-Toes = 14

% (5.1) Tissue Mass and Heat Capacity
MassFat=BodyMass*(5.548/(0.8*Height^0.242/(BodyMass*1000)^0.1+0.162)-5.044);%kg
MassLean=BodyMass-MassFat;
SkelDist=[0.0192920;
    0.0470400;
    0.0118780;
    0.0118780;
    0.0009120;
    0.0009120;
    0.0009120;
    0.0009120;
    0.0395840;
    0.0395840;
    0.00263178;
    0.00263178;
    0.00029242;
    0.00029242];
ViscDist=[0.0282320;
    0.1870400;
    0.0058820;
    0.0058820;
    0.0001176;
    0.0001176;

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MassDist=[SkelDist(1)+ViscDist(1) 0.005880 0.033300 0.00423;
SkelDist(2)+ViscDist(2) 0.283400 0.633300 0.02130;
SkelDist(3)+ViscDist(3) 0.026640 0.043350 0.00382;
SkelDist(4)+ViscDist(4) 0.026640 0.043350 0.00382;
SkelDist(5)+ViscDist(5) 0.000297 0.003332 0.00073;
SkelDist(6)+ViscDist(6) 0.000297 0.003332 0.00073;
SkelDist(7)+ViscDist(7) 0.000297 0.003332 0.00073;
SkelDist(8)+ViscDist(8) 0.000297 0.003332 0.00073;
SkelDist(9)+ViscDist(9) 0.080500 0.106650 0.00947;
SkelDist(10)+ViscDist(10) 0.080500 0.106650 0.00947;
SkelDist(11)+ViscDist(11) 0.0005346 0.00900 0.001692;
SkelDist(12)+ViscDist(12) 0.0005346 0.00900 0.001692;
SkelDist(13)+ViscDist(13) 0.0000594 0.00100 0.000188;
SkelDist(14)+ViscDist(14) 0.0000594 0.00100 0.000188];

Cp=[0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9;
0 0.9 0.6 0.9];

\text{4186.8} \text{Kcal/(kg*K)} \rightarrow J/(kg*K)

\text{Atot} = 71.84*\text{BodyMass}^{0.425}*\text{Height}^{0.725} \text{ sq. cm}

\text{Adist} = [0.07;
0.3602;
0.06705;
0.06705;
0.0125;
0.0125;
0.0125;
0.0125;
0.1587;
0.1587;
0.03087;
0.03087;
0.00343;
0.00343];

\text{Area} = \text{Atot} \times \text{Adist} \times \text{cm}^2

A = \text{Area}/10000 \text{ Segment areas in m}^2

\text{for} \ i = 1:14
\quad \text{Mass}(i,1) = \text{MassDist}(i,1) \times \text{MassLean};
\quad \text{Mass}(i,2) = \text{MassDist}(i,2) \times \text{MassLean};
\quad \text{Mass}(i,3) = \text{MassDist}(i,3) \times \text{MassFat};
\quad \text{Mass}(i,4) = \text{MassDist}(i,4) \times \text{MassLean};
\end{array}

\text{end}
for i=1:14
    Vol(i,1) = 1000*Mass(i,1);
    Vol(i,2) = 1000*(Mass(i,1)+Mass(i,2));
    Vol(i,3) = 1000*(Mass(i,1)+Mass(i,2)+Mass(i,3));
    Vol(i,4) = 1000*(Mass(i,1)+Mass(i,2)+Mass(i,3)+Mass(i,4));
    Length(i) = Area(i)^2/(4*Pi*Vol(i,4));
    for j=1:4
        Radius(i,j) = (Vol(i,j)/(Pi*Length(i)))^0.5;
    end
end
k = [6.9372 0.3240 0.5567 0.5567;
     0.6908 0.5971 0.3328 0.3328;
     1.9634 1.2954 0.6961 0.6961;
     1.9634 1.2954 0.6961 0.6961;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.7426 0.3752 0.6049 0.6049;
     1.5683 1.8182 0.4451 0.4451;
     1.5683 1.8182 0.4451 0.4451;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501;
     1.3390 0.4347 0.5501 0.5501; *6.978;  %Cal/(hr*cm*K)->J/(min*m*K)
\
% (5.2) Nodal Radii
for (i=1:14)
    NodRad(i,1) = 0.5*Radius(i,1);
    NodRad(i,2) = 0.5*(Radius(i,1)+Radius(i,2));
    NodRad(i,3) = 0.5*(Radius(i,2)+Radius(i,3));
    NodRad(i,4) = 0.5*(Radius(i,3)+Radius(i,4));
end
for (i=1:14)
    R(i,1)=NodRad(i,1)/100;
    R(i,2)=Radius(i,1)/100;
    R(i,3)=NodRad(i,2)/100;
    R(i,4)=Radius(i,2)/100;
    R(i,5)=NodRad(i,3)/100;
    R(i,6)=Radius(i,3)/100;
    R(i,7)=NodRad(i,4)/100;
    R(i,8)=Radius(i,4)/100;
end
L=Length/100;  % Length of each segment in meters

MD= [0 0 0.005880 0.033300 0 0;
     0 0 0.283400 0.633300 0 0;
     0 0 0.026640 0.043350 0 0;
     0 0 0.026640 0.043350 0 0;
     0 0 0.000297 0.003332 0 0;
     0 0 0.000297 0.003332 0 0;
     0 0 0.000297 0.003332 0 0;
     0 0 0.000297 0.003332 0 0;
     0 0 0.080500 0.106650 0 0;
     0 0 0.080500 0.106650 0 0;
     0 0 0.0005346 0.00900 0 0;
     0 0 0.0005346 0.00900 0 0;
     0 0 0.000594 0.00100 0 0;
     0 0 0.000594 0.00100 0 0];
for (i=1:14)  %Loop for determining the Mass Distribution
    Ao(i)=R(i,1)^2;
    A1(i)=(R(i,2)+R(i,1))^2-R(i,1)^2;
    A7(i)=(R(i,8)+R(i,7))^2-(R(i,7)+R(i,6))^2;

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A8(i)=(2*R(i,8))^2-(R(i,8)+R(i,7))^2;
P0(i)=A0(i)/(A0(i)+A1(i));
P1(i)=1-P0(i);
P7(i)=A7(i)/(A7(i)+A8(i));
P8(i)=1-P7(i);
MD(i,1)=P0(i)*MassDist(i,1);
MD(i,2)=P1(i)*MassDist(i,1);
MD(i,5)=P7(i)*MassDist(i,4);
MD(i,6)=P8(i)*MassDist(i,4);
end

for i=1:14
  Cp(i,1) = 
  (SkelDist(i)*0.5+ViscDist(i)*0.9)/(SkelDist(i)+ViscDist(i))*4186.8;
  M(i,1) = MD(i,1)*MassLean;
  MCp(i,1) = M(i,1)*Cp(i,1);
  M(i,2) = MD(i,2)*MassLean;
  MCp(i,2) = M(i,2)*Cp(i,1);
  M(i,3) = MD(i,3)*MassLean;
  MCp(i,3) = M(i,3)*Cp(i,2);
  M(i,4) = MD(i,4)*MassFat;
  MCp(i,4) = M(i,4)*Cp(i,3);
  M(i,5) = MD(i,5)*MassLean;
  MCp(i,5) = M(i,5)*Cp(i,4);
  M(i,6) = MD(i,6)*MassLean;
  MCp(i,6) = M(i,6)*Cp(i,4);
end

TisMass = [1 1 1 1 1 1 1 1 1 1 1 1 1 1] *Mass;
SegMass = Mass*[1;1;1;1];
NomMus = 30.56;
NomSkin = 3.55;
MCpblood = 2.25*4186.8*BodyMass/70;  % Adjust for 2.5 L of blood in trunk core
MCp(2,1) = MCp(2,1) - P0(2) * MCpblood;
MCp(2,2) = MCp(2,2) - P1(2) * MCpblood;
MaCpb = SegMass * MCpblood / BodyMass / 2;  % Thermal Mass of blood for arteries and veins
MvCpb = MaCpb;  % in each segment, J/K

% (5.4) Initial tissue temperatures (C) (41-Node Man 3.19)
Tinit = [37.00 36.44 36.11 35.89;
  37.11 36.83 35.50 34.67;
  35.61 35.06 34.50 34.28;
  35.61 35.06 34.50 34.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28;
  36.44 35.83 35.06 34.72;
  36.44 35.83 35.06 34.72;
  35.44 35.28 35.39 35.28;
  35.44 35.28 35.39 35.28;
  35.44 35.28 35.39 35.28;
  35.44 35.28 35.39 35.28];

% (5.5) Set point tissue temperatures (C) (41-Node Man 3.19)
Tset = [37.00 36.44 36.11 35.89;
  37.11 36.83 35.50 34.67;
  35.61 35.06 34.50 34.28;
  35.61 35.06 34.50 34.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28;
  35.50 35.39 35.33 35.28];
36.44 35.83 35.06 34.72;
36.44 35.83 35.06 34.72;
35.44 35.28 35.39 35.28;
35.44 35.28 35.39 35.28;
35.44 35.28 35.39 35.28;
35.44 35.28 35.39 35.28;

% (5.6) Metabolic heat generation
QBMR = 38.67/10000*69.78; \[ \text{kcal/(h*cm}^2)\rightarrow J/(\text{min}*\text{cm}^2) \]
Qcore = 0.1*QBMR*Atot;
Qsf = 0.3*(TissueMass(3)+TissueMass(4));
Qmuscle = (0.18*QBMR*Atot-Qsf);
for i=1:14
  Qgen(i,1) = Qcore*Mass(i,1)/TissueMass(1); \[ \text{J/min} \]
  Qgen(i,2) = Qmuscle*Mass(i,2)/TissueMass(2);
  Qgen(i,3) = Qsf*Mass(i,3)/(TissueMass(3)+TissueMass(4));
  Qgen(i,4) = Qsf*Mass(i,4)/(TissueMass(3)+TissueMass(4));
end
Qgen(1,1) = Qcore*Mass(1,1)/TissueMass(1)+0.16*QBMR*Atot;
Qgen(2,1) = Qcore*Mass(2,1)/TissueMass(1)+0.56*QBMR*Atot; \[ \text{J/min} \]
BasRate = [1 1 1 1 1 1 1 1 1 1 1 1 1 1]*Qgen([1;1;1;1]); \[ \text{J/min} \]

% (6.0) Thermoregulation and blood flow
% (6.1) Shiver calculations
Shiver.Gain = 696.21;
ShivLim = 1000*60;
Shivdist = [0.0827; 0.5870; 0.0411; 0.0411; 0.0055375; 0.0055375; 0.0055375; 0.0055375; 0.0930; 0.0930; 0.017955; 0.017955; 0.001995; 0.001995];
Mushiv = [0.02300; 0.94800; 0.00265; 0.00265; 0.000575; 0.000575; 0.000575; 0.000575; 0.00950; 0.00950; 0.001080; 0.001080; 0.000120; 0.000120];

% (6.2) Vasoconstriction calculations
Con.Gain = 9.99;
Skaidist = Shivdist;
Condist = [0.05; 0.15; 0.025; 0.025; 0.0875];

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\[
0.0875; \\
0.0875; \\
0.0875; \\
0.025; \\
0.025; \\
0.0875; \\
0.0875; \\
0.0875; \\
0.0875; \\
\]

% (6.3) Vasodilation calculations
Dil_Gain = 10454.69;
DilDist = [0.132; \\
0.322; \\
0.0475; \\
0.0475; \\
0.0305; \\
0.0305; \\
0.0305; \\
0.0305; \\
0.0305; \\
0.0305; \\
0.115; \\
0.115; \\
0.025; \\
0.025; \\
0.025; \\
0.025]; \\

% (6.4) Blood thermal mass flow calculations
Mbas=[105.6 0.594 0.264 3.700; \\
510.0 14.08 5.060 4.620; \\
0.759 1.364 0.352 0.550; \\
0.759 1.364 0.352 0.550; \\
0.055 0.0275 0.0275 1.100; \\
0.055 0.0275 0.0275 1.100; \\
0.055 0.0275 0.0275 1.100; \\
0.055 0.0275 0.0275 1.100; \\
2.320 4.070 0.880 3.135; \\
2.320 4.070 0.880 3.135; \\
0.1485 0.0297 0.0792 2.970; \\
0.1485 0.0297 0.0792 2.970; \\
0.0165 0.0033 0.0088 0.330; \\
0.0165 0.0033 0.0088 0.330]*BodyMass/70*31.65*BF_Parameter;

mdotcb = Mbas; %J/(min*K)
Pow2Blood = 0.9972; %Power to Blood rate steady state gain
TubBlood = 2; %Blood rate from power time constant

% (7.0) Respiratory Tract
TubResp = 2; %Breath Rate from MR time constant
RespD=[0 0 0.172 0.0574 0.0 0.0; \\
0 0 0.523 0.0000 0.0 0.0]/2;
RespD(1,1)=0.771*P0(1)/2;
RespD(1,2)=0.771*P1(1)/2;
RespD(2,1)=0.476*P0(2)/2;
RespD(2,2)=0.476*P1(2)/2;

Resp_Gain = [1/231.64;1.0;5.8743]; %Various Respiratory Gains

% (8.0) Latent contribution
SweatDist=[0.0810; %Ks'
0.4820; \\
0.0765; \\
0.0765; \\
0.0765; \\
0.0765; \\
0.0765];

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0.00775;
0.00775;
0.00775;
0.00775;
0.00775;
0.1090;
0.1090;
0.01575;
0.01575;
0.00175;
0.00175;
Sweat_Gain = 69.04*60;   %J/(min*K^2)
Sweat_Add = 466.33*60;   %J/(min*K)
Diff_Gain = 0.0102832*Diff_Parameter;   %J/(min*KPa*cm^2)

% (9.0) Artery & Vein Heat Transfer Coefficients and Initial Temperatures
da=0.004;  %Diameter of blood vessels, m

for (i=1:14)  %HT coeff. between arteries and tissue, J/(min*K)
    ha(i,1)=2*P1*k(i,1)*L(i)/log(R(i,1)/da);
    ha(i,2)=2*P1*k(i,1)*L(i)/log(2*R(i,1)/da);
    ha(i,3)=2*P1*k(i,1)*L(i)/log(2*R(i,3)/da);
    ha(i,4)=2*P1*k(i,1)*L(i)/log(2*R(i,5)/da);
    ha(i,5)=2*P1*k(i,1)*L(i)/log(2*R(i,7)/da);
    ha(i,6)=2*P1*k(i,1)*L(i)/log(2*R(i,8)/da);
end

hv=ha;  %HT coeff. between veins and tissue, J/(min*K)

Hav=[0.00;  %Counter-current HT coeff. between veins and arteries
     4.13;
     4.13;
     0.285;
     0.285;
     0.285;
     6.90;
     6.90;
     3.06;
     3.06;
     0.34;
     0.34]*60;  %=>J/(min*K)

Tainit=[36.38;
        36.40;
        36.25;
        36.25;
        35.53;
        35.53;
        31.89;
        31.89;
        36.16;
        36.16;
        34.74;
        34.74;
        33.88;
        33.88];  %Initial Arterial Temperatures, deg. C

Tvinit=[36.44;
        36.38;
        35.35;
        35.35;
        34.28;
34.28;
31.01;
31.01;
35.79;
35.79;
34.07;
34.07;
33.03;
33.03]; %Initial Venous Temperatures, deg. C
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%echo on
% Hours ---- 0
% Minutes -- 1
% Seconds -- 2
%echo off;
%convr=input('Type the number corresponding to the time scale desired: '); convr = 1; %min;
CONV = 1/(60^convr);

%UNIT CONVERSIONS
F2R = 459.67;
RO2 = 48.29;
FT2M = 0.3048;
IN2CM = 2.54;
FT2IN = 12;
BTU2J=1055.056;
W2BTUHPHR = 3.4121;
PSI2KPA = 6.8948;
LB2KG = 0.4536;

% Dew point - Sat. Pressure table
for i=1:1:10000
    PwTable(i)=8*(i)/10000;
pw=PwTable(i);
    TdewTable(i)=100.45 + 33.193*log(pw) + 2.319*log(pw)^2 + 0.17074*log(pw)^3 ...
        + 1.2063*pw^0.1984;
    if (TdewTable(i)<32)
        TdewTable(i)=90.12 + 26.142*log(pw) + 0.8927*log(pw)^2;
    end;
end;

%LCG
UAlcgfactor = 0.85; %0.45;
Mdotlg = 200*CONV; %lbm/hr(conversion)
timedelaylgc = (20/3600)/CONV; %hr/(conversion)
Flow=[0.000;0.200;0.125;0.125;0.000;0.000;0.000;0.275;0.275;0.000;0.000;0.000;0];

%SUIT
%VG
MNratio = 18/32;
Mdotgas = 5.5*CONV;  %lbm/hr(Conversion factor)
timedelayvg = (1/60)/CONV; %hr/(conversion) (1 min.)
%new
AsuitTot = 35.36;    %ft2
AskinTot = Atot/(100^2)*(0.3048^2));  %m2 to m2 to ft2
Askin=AskinTot*Adist;
emsuit = 0.8;          %suit emissivity
MsuitTot=54.066;  %lbm
MsuitDist=[0.061;0.268;0.087;0.087;0.012;0.012;0.012;0.012;0.012;0.171;0.171;0.049;0.049;0.049;0.049;0.049;0.049];
AsuitDist=MsuitDist;
Msuit=MsuitTot*MsuitDist;
Asuit=AsuitTot*AsuitDist;
Cpsuit = 0.220;   %BTU/lbm-F (from Shuttle Suit)
Eis = 0.9;
Bug = 0.9;
Fugis = Eis*Bug/(Eis + Bug - Eis*Bug);
ALUG = 0.0141;  %ft
AKUG = 0.046*CONV; %BTU/hr-ft-F (conversion)
CLO = ALUG/ AKUG;
Sgap=3.2*[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1]; %cm (gap from skin to suit wall)
Tskin=70; %F
hconv_par = 1; %Suit convection adjustment parameter

for i=1:14
    if (i==1)
        ALS(i)=0.0210; %Suit thickness, ft
        AKS(i)=0.02155*CONV; %Suit conductivity, Btu/(ft-F-hr) (conversion)
    else
        ALS(i)=0.0156;
        AKS(i)=0.000383*CONV;
    end
end
rsi=(Radius(:,4)+Sgap)/IN2CM/FT2IN; %Inside suit radius, ft
Lft=Length/IN2CM/FT2IN; %Segment length, ft

%Transport Delays for indiv. suit segments
T=80; %F
P=3.7; %psi
dens=P*144/(48.29*(T+459.67)); %lbm/ft3
di=Radius(:,4);
do=di+Sgap;
motgas=mdotgas*[1;0.25;0.375;0.375;0.375;0.375;0.375;0.375;0.125;0.125;0.125;0.125;0.125;0.125;0.125];

for i=1:14
    Ac(i)=(pi/4)*(do(i)^2 - di(i)^2);
    V(i)=motgas(i)/((dens/((12*2.54)^3))*Ac(i));
    tdvg(i)=Length(i)/V(i);
end;

%Water
Cpwater = 1.0; %BTU/lbm-F
Densewater = 62.4; %lbm/ft^3
Kwater = 0.32*CONV; %BTU/hr-ft-F (Conversion factor)
Pwcl = 15; %psi
Twclic = 72.0; %F

SIGMA = (0.1714e-08)*CONV; %BTU/hr-ft2-R (conversion)
Tvlic = Twclic;

%Gas
Cpgas = 0.220; %BTU/lbm-F
Kgas = 0.0155*CONV; %BTU/hr-ft-F (Conversion factor)
Mugas = 2.085*(2419.1)*CONV; %N-s/m2 to lbm/ft-h-CONV
Rgas = 48.29; %ft-lbf/lbm-R
Pgbase = 3.7; %psi
Pvl = Pgbase;

HFGest = 1040; %BTU/lb estimated at 95 F

% JDF 5/27/99
Tindewol=40;

Tinvcol=[91.51 77.59 67.25;
        81.51 70.84 61.03;
        78.32 68.69 61.30;
        74.08 65.52 67.69];
ColMR={150 275 400};
RowTso=[-97;28;68;137];
C10.9 MATLAB olcase2D.m Example Listing

% NASA Metabolic Rate Profile [min, W]
XPLSSMR=[0 300;30 300;30 200;70 200;70 600;80 600;80 375;120 375; ...
120 250;160 250;160 100;220 100;220 200;280 200;280 300; ...
340 300;340 600;350 600;350 200;390 200;390 250;420 250];
AddRate = [XPLSSMR(:,1) XPLSSMR(:,2)*60-BasRate];
Entry = size(AddRate);
RunTime = AddRate(Entry(1,1),1);

% NASA Environmental Profile [min, F]
Tso=[0 45.6;30 45.6;30 46.03;70 46.03;70 45.61;80 45.61; ... 
80 45.3;120 45.3;120 45.81;150 45.81;150 27.06;160 27.06; ... 
160 28.45;210 28.45;210 83.22;220 83.22;220 82.69;280 82.69; ... 
280 82.35;340 82.35;340 82.51;350 82.51;350 82.69;360 82.69; ... 
360 125.4;390 125.4;390 125.3;420 125.3];
Tsof=Tso;
Tso=Tso;

Tin1cgol = [0 75;RunTime 75];
VITA

Anthony Iyoho was born September 10, 1978 in Tulsa, Oklahoma. He attended public school is Rolla, Missouri finishing in the top four of his class. He received his B.S. and M.S. in Mechanical Engineering from the University Of Missouri-Columbia in 2000 and 2002, respectively. He is currently enrolled in the graduate program in the department of Mechanical and Aerospace Engineering at the University of Missouri-Columbia where he is pursuing a Ph.D. His academic background includes automatic control, dynamic system modeling, heat transfer, analysis and design. His personal interests include music, astrology, religion, chess, and all kinds of sports.

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