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Reasonable Prediction of Thermo-Physiological Responses

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Description

Lots of people participate in cold weather activities or events, such as high-altitude mountaineering, cross-country running and all sorts of winter sports. The participants are at risk for cold-related injuries. For example, Frostbite usually occurs when the skin temperature is lower than -0.5 ˚C and hypothermia is defined as a core temperature lower than 35 ˚C. Meanwhile, the participants' thermal comfort, which is related to their skin and core temperatures, is essential to maintaining their athletic abilities. Therefore, proper thermo-physiological status, including skin and core temperatures within healthy ranges as well as good thermal comfort, is important for the participants' thermal safety and competition performance. Reasonable prediction of thermo-physiological responses such as skin temperature and core temperature can help to assess their health and exercise capacity during the activities.

Thermo-Physiological Responses

Numerical thermo-physiological model is a valuable tool to predict human thermo-physiological responses which is based on human body thermoregulation and body-clothing-environment heat exchange system. Numerous models have been proposed over the past decades. Gagge developed a two-node model simulating the human body as two concentric cylinders. The multi-node model proposed by Stolwijk divides human body into six segments, which is the basis of later multi-node models. For example, Fiala et al. improved the thermoregulation system using a wide range of human subject tests data. Huizenga et al. proposed the Berkeley model considering the effects of clothing, counter-current blood flow and contact on a body surface. Tanabe et al. developed a 65-node model and combined it with radiation exchange model and computational fluid dynamics. A blood vessel network is introduced into Salloum et al. model to improve the blood heat exchange calculation, based on which Karaki et al. took the AVA blood flow of digits into account for the simulation accuracy of extremities. Takahashi et al. proposed JOS_3 model characterized by the effects of individual factors such as age and gender. However, a majority of the current models are developed for the application in normal temperature environments and low activity intensity scenes (*e.g.* daily work in the offices, hand and arm work in the factories and low intensity activities outdoor). Some researchers such as Wu et al. and Xu et al. have studied in particular the thermo-physiological models for cold exposure by considering the effects like arteriovenous anastomoses and shivering. Also, human subject tests are conducted in a climate room with measurements of local skin temperatures, core temperature and clothing temperatures of subjects dressed in winter sports clothing and exercising in the cold for the collection of validation data. The predicted results are compared with the measured results to validate the presented model. Some works made efforts to combine a thermo-physiological model with a clothing model. Lotens integrated Gagge's two-node model with a clothing model to simulate body thermal responses. Then researchers proposed a number of multi-node thermo-physiological models coupled with clothing models that considers clothing thermal insulation, evaporative resistance and fabric properties including thickness, specific heat, thermal conductivity, tortuosity and porosity.

Thermo-Physiological Models

There are few works paying attention to the simulation of thermo-physiological responses of people exercising in the cold, where the bioheat status and exposure environments are much different from the scenes focused by previous models. For example, the body heat production by activities with middle or high intensity and heat-moisture transfer through multi-layer clothing. Also, basal metabolic rate and basal blood flow is found be affected by the difference of tissue temperature and its setpoint, and this temperature difference may be significant for those exposed to the cold environment for a long time. Clothing is a significant factor that affects human thermo-physiological responses by influencing heat and moisture exchange between the body and environment, especially in cold weather and with body's regulatory sweating. Various thermo-physiological models have taken into account the effects of clothing, a number of which simplify it by two parameters, thermal insulation and evaporative resistance. Given the complicated process of heat and moisture transfer through skin, air gap, clothing layers and environment, such a simplification can hardly explain the exact mechanism of the influence of clothing on human thermo-physiological responses. Some researchers have given further and microscopic insight in modelling the heat and moisture transfer in clothing by considering the processes of heat conduction, radiation, convection, moisture evaporation, diffusion, condensation and sorption. But these works are solely clothing models and cannot be directly utilized to calculate human thermo-physiological responses. However, most of these models only consider single layer clothing system or simplify the multi-layer clothing system as one layer. For those who exercise in cold environments, they usually wear multi-layer clothes with much different fabric properties of each layer. A simplified one-layer clothing model is not accurate enough to describe both the heat-moisture transfer process and the factors that may influence this process (*e.g.* the air gap between the adjacent layers). Wan and Wang proposed a multi-layer clothing model but their model was particularly applicable for clothing with PCM material and cooling fans used in normal or high temperature environments. Joshi et al. specifically studied the effect of air gap by considering its spatial heterogeneity, and then Joshi et al. developed a multi-layer clothing model considering the spatially heterogenous air gap coupled with a 3D thermoregulation model. But moisture sorption and pumping effect were neglected in their work, which is significant in the clothing of exercising people. Related research is still lacking for people exercising in cold, whose bodies sensible and latent heat dissipation are both significant and thus required to be properly modeled. In addition, a thermo-physiological model needs to be validated by human subject tests data. A number of models mentioned above are validated by experimental data in normal temperature conditions, while some researchers have conducted human subject experiments in cold environments to study thermo-physiological responses and provide model validation data. For example, Nielsen and Nielsen reported a test under a cool environment to explore the distribution of subjects' skin temperature and thermal sensation. Gavhed and Holmer conducted experiments in various cold environments to collect human thermo-physiological data to validate the Duration Limited Exposure Index. Male's thermo-physiological responses under extremely cold environments were studied by Wu et al. to test human responses in extreme weather conditions. However, the subjects in these experiments are all asked to keep rest or walk slowly dressed in cold protective clothing. Chen et al. conducted experiments to study the thermo-physiological responses of subjects exercising in various ambient temperature conditions. But local skin temperatures were not reported and air velocity, an important factor that affects people participating in cold weather activities, was not considered. In general, the experimental studies and dataset are still limited for thermo-physiological responses of subjects exercising in cold environment wearing specific activity suits. To address the prediction of thermo-physiological responses including skin and core temperatures of people exercising in cold environments, a multi-node thermo-physiological model based on Takahashi et al. work is presented in this paper, integrated with a proposed multi-layer clothing model and corrections considering exposure characteristics. The concept of net exercise efficiency is used to calculate the metabolic heat production during middle or high intensity exercise. The low temperature effects on the metabolic rate and blood flow are taken into consideration. The clothing model particularly considers the air gaps between the clothing layers to reflect the ventilation and air penetration effect affected by ambient wind.