Human Thermoregulation And Spatial Temperature For Frostbite Prediction With Bio-Heat Transfer Model

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Abstract

Introduction
Wind presence in extreme cold temperatures is an accelerator of frostbite in susceptible areas. The National Weather Service (NWS) Wind Chill Temperature Index (WCTI) accounts for exposure time to frostbite in the cheek based on simplified human thermoregulatory models [1]. However, the WCTI does not consider maximum exposure before frostbite onset in more susceptible areas (e.g., fingers and nose), various metabolic rates, protective clothing, or sex differences. Modeling changes in spatial temperature on the human body in extreme environments relies on the principles of heat transfer and effector responses. Human heat transfer models have historically used simplified geometries such as multi-layer cylinders to represent limbs and their thermal properties. The development of thermoregulatory models in COMSOL Multiphysics using medical images and finite element processes has allowed for a more geometrically and anatomically accurate model with precise boundary conditions.

Model
Male and female thermoregulatory models were developed using Extended Cardiac-Torso (XCAT) images of median U.S. adults, segmented with SimplewareTM Scan IP workflow from voxelized data to a CAD model and the final tetrahedral meshes were imported into COMSOL Multiphysics software. The imported mesh components were designated with attributes for thermoregulation, including thermal resistivity, conductivity, specific heat capacity and initial temperature conditions. The models used COMSOL's Bio-Heat Transfer module. Spatial temperature distribution on the surface is determined by the bio-heat transfer equation (passive system) and efferent system responses for thermoregulation by error signals from the hypothalamus (active system) [Eq.1]. Boundary conditions at the surface assumes that internal heat from conduction to the skin is equal to external outward heat loss by radiation, evaporation, and convection [Eq. 2].

$$\rho C_p (\partial T/\partial t) = \lambda \nabla^2 T+Q+ \beta \omega \rho_b C_{(p,b)} (T_b-T) \text{ [Eq.1]}$$

$$-\lambda (\partial T/\partial n) =(h_c+ h_r)(T_s+T_o)+E \text{ [Eq.2]}$$

Initial conditions of temperature are based on previous studies [2]. A central blood pool is assumed with temperature independent to spatial variation. Human models wore protective clothing (intrinsic insulation approximately 2.27 clo) with the hands uncovered. Model simulations were computed at rest, light exercise (+250W), and moderate exercise (+400W) for a temperature range of 35℉ to -45℉ (1.7°C to -42.8°C) and wind range of 0 to 45mph (0 to 20.12 ms-1).

Results
Model results confirm an increased susceptibility to frostbite in the nose and 5th finger compared to the cheek in this simulation (Figure 2) and NWS WCTI. Exercise created warmer body core temperatures compared to rest and increased time to frostbite in studied areas at warmer wind

chill temperatures (Figure 3). However, as conditions become more extreme, the influence from exercise on observed sites becomes negligible. There is no distinct difference between male and female model times to frostbite apart from the 5th finger, as the male model reaches frostbite approximately 1-4 minutes faster than the female at lower wind chill temperatures (Figure 4).

Conclusion

Accurate human thermoregulatory models are useful for predicting thermal responses in extreme conditions. From this simulation of extreme wind chill temperatures, a more accurate WCTI can be developed to estimate frostbite risk with the consideration of more susceptible skin sites, protective clothing, exercise, and sex.

Reference

1. National Weather Service, N., Windchill Temperature Index, W. Office of Climate, and Weather Services, Editor., National Oceanic and Atmospheric Administration: Washington, D.C. (2001)
2. Castellani, M.P., et al., A geometrically accurate 3-dimensional model of human thermoregulation for transient cold and hot environments. Comput Biol Med 138: p. 104892 (2021).
3. Gavhed, D., et al., Face cooling by wind in walking subjects. J Biometeorol, 47: p. 7 (2003).

Figures used in the abstract

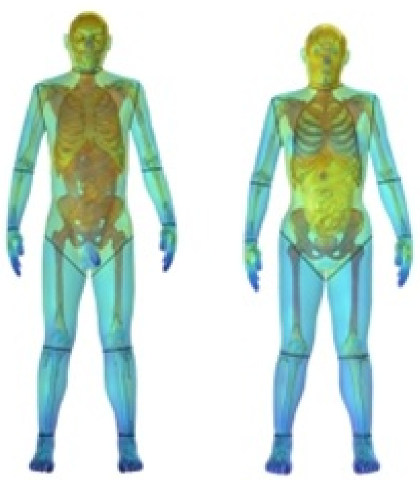

Figure 1 : Male and Female Finite Element Thermoregulatory Models from Medical Images

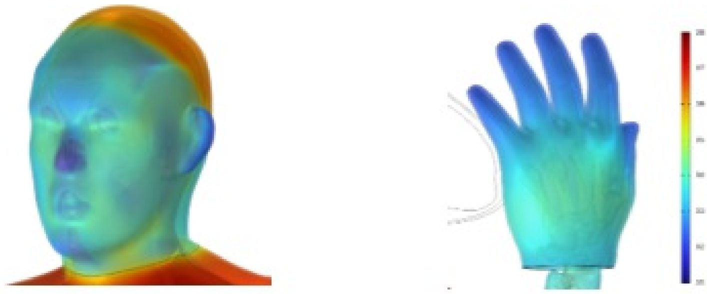

Figure 2 : Female model temperature distribution in the head and hand at 35℉ (1.7°C) and 5 mph (2.23 ms-1) wind after 180-minute exposure.

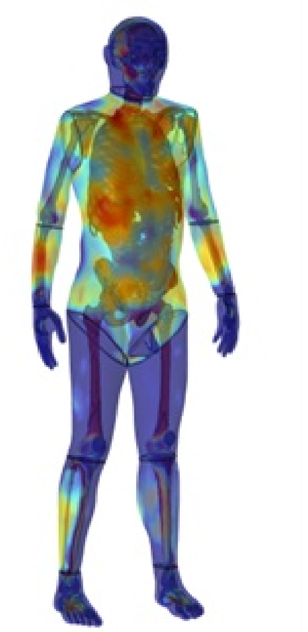

Figure 3 : Male model at moderate exercise (+400W) in temperature 35℉ (1.7°C) and 25 mph (11.17 ms-1) wind after 180-minute exposure.

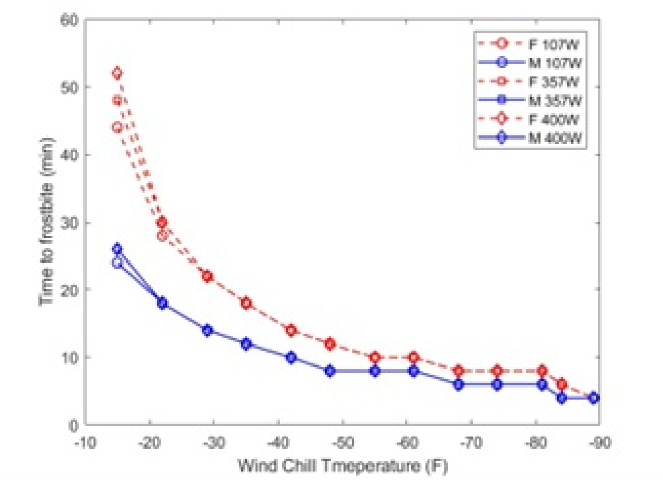

Figure 4 : Male (blue) and female (red) model 5th finger times to frostbite at various metabolic rates and respective wind chill temperatures.