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Analytical expressions for estimating endurance time and glove thermal resistance related to human finger in cold conditions

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ABSTRACT

Frostbite is considered the severest form of cold injury and can lead to necrosis and loss of peripheral appendages. Therefore, prediction of endurance time of limb's tissue in cold condition is not only necessary but also crucial to estimate cold injury intensity and to choose appropriate clothing. According to the previous work which applied a 3-D thermal model for human finger to analyze cold stress, in this study, an expression is presented for endurance time in cold conditions to prevent cold injury. A formula is also recommended to select a proper glove with specific thermal resistance based on the ambient situation and cold exposure time. By employing linear extrapolation and real physical conditions, the proposed formulas were drawn out from numerical simulation. Analytical results show good agreement with numerical data. The used numerical data had been also validated with experimental data existed in the literature. Furthermore, the effect of different parameters such as glove thermal resistance and ambient temperature is investigated analytically.

1. Introduction

The extremities, in particular, fingers and toes are highly susceptible to heat loss in cold conditions. This is because of unfavorable surface to mass ratio of these parts and little local metabolic heat production due to their small muscle mass. Also, the heat balance of extremities is greatly dependent on the supply of heat carried by the bloodstream, but this heat supply is diminished in the cold. Therefore, in this situation, a cold injury may develop in these limbs when heat loss from the tissues overrides the thermoregulatory capacity and temperature falls to levels, where damages to systems and cell occur (Hamlet, 1988; Wilkerson et al., 1986). Cold injury covers a spectrum of damage that ranges from reversible changes to severe tissue destruction and loss. Among these, frostbite is the severest form of cold injury that can have serious consequences. Ambient temperature, wind speed, exposure time and the amount of wear are the main factors that have direct effects on cold injuries. Several researchers tried to investigate the frostbite phenomenon and the related parameters. Shitzer et al., (1991, 1997) developed one- and two-dimensional models to predict the effectiveness of the finger models by comparing their results with experimental data. They also used those models to predict the times without any risk of frostbite at different low temperatures. Goldman (1994) proposed a simple heat balance model that handles the most critical factors: initial finger skin temperature, heat input, glove insulation, time constants of tissues and ambient climatic conditions. He also represented an expression about the temperature of finger skin during the cold exposure time. Tikusis (2004) suggested a tissue-cooling model that is applied for prediction of finger cooling. Wilson and Goldman (1970) reviewed the role of air temperature and wind in the time necessary for a finger to freeze. On the other hand, Elnäs and Holmer (1983), Endrusick et al. (1990) and Geng et al. (1997) were focused on hand wear as an important factor for preventing the hands from cold injuries. But in recent years, the numerical models have changed the approach to this subject. Kashcooli et al. (2017) used a finite element method to find temperature distribution in skin during thermal therapy. Baker and Mehlman (2012) studied transient heat transfer and frostbite phenomenon in fingers, numerically. Khanday and Hussain (2015) employed finite difference method to estimate human peripheral tissue temperatures during exposure to severe cold stress. Manda (2013) explored the risk of frostbite with the help of a 3D finger model. Even new techniques (eg: extraction of the 3-D model from MRI and/or CT scan images) are employed for studying of temperature distribution in human finger (He et al., 2008a, 2008b; Shao et al., 2010, 2012). Nevertheless, numerical simulations are good methods for modeling the frostbite phenomenon but usually are time consuming and accompanied with different complexities. Therefore, analytical correlations besides the numerical approaches can be used for validating the experimental data. Also, the analytical correlations develop initial reliable results that can be used for post

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processing of numerical methods.

Hence, in this study, an analytical correlation is presented for endurance time related to human finger that exposed to cold weather. A novel approach is engaged to extract this formula from validated numerical data in our previous work (Fallahi et al., 2017). Analytical results show good agreement with numerical ones. In the next step, these results are employed to extract an expression to select an appropriate glove to keep hands warm in different environmental condition against of frostbite. Freezing point of finger skin, total thermal resistance of finger, ambient temperature and wind speed are significant parameters that have direct impact on endurance time. The proposed formulas can provide the expedition of a winter exercise or trip depend of the exposure time. Prediction of the intensity of cold injury is possible accordingly.

2. Material and methods

In our previous research (Fallahi et al., 2017), a coupled 3-D thermo-fluid model was applied to simulate a human finger exposed to cold condition. The finger was modeled as a cylinder with a hemispherical cap representing the fingertip. The model was assumed to be composed of a bone core surrounded with a soft tissue layer. This layer includes skin, tendons and fat. In this model, blood flowed into the finger through two arteries, each one on either side of the bone core. Thermal vein effects were also simulated by two veins located beside the arteries with larger cross sections. A 3-D model and temperature distribution throughout the finger is presented in Fig. 1.

To validate the model in the next step, the spatial variability of

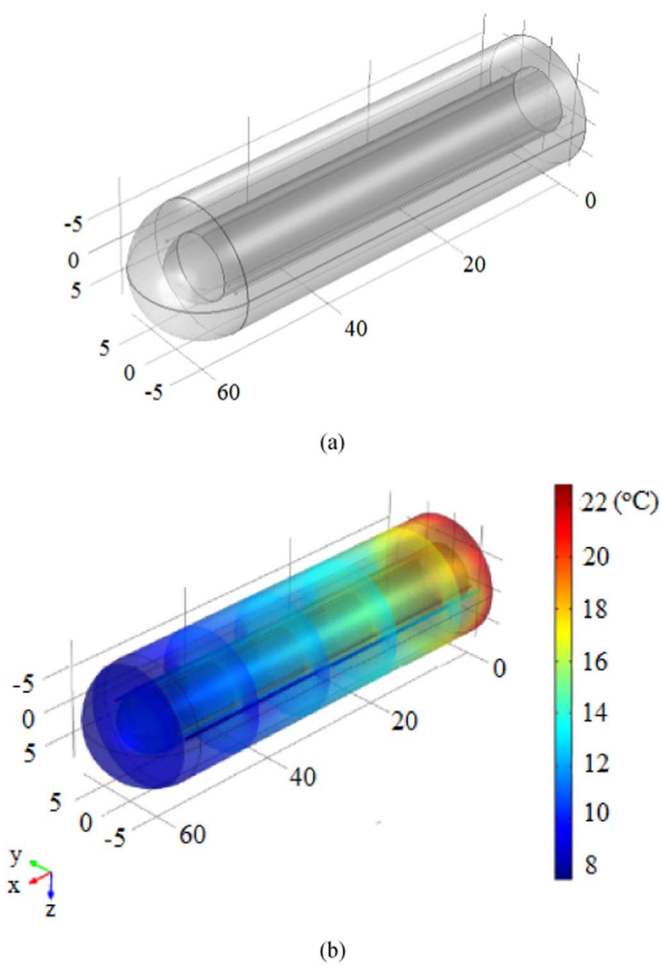

Fig. 1. (a) View of the 3-D model used in numerical simulation, (b) Temperature distribution throughout the finger at time 80 min (Fallahi et al., 2017).

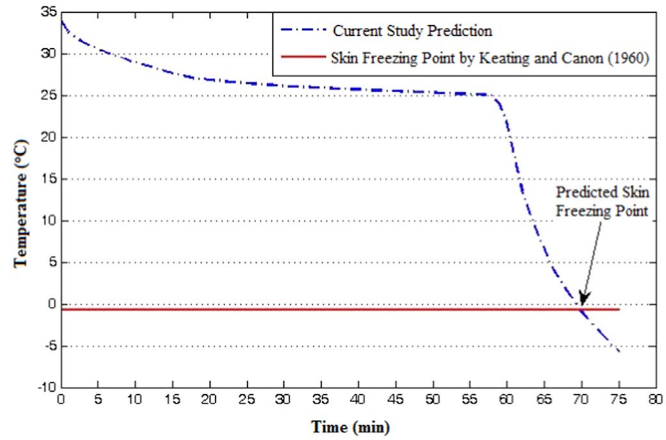

Fig. 2. Model prediction for Wilson et al. (1976) experiment in −15 °C ambient temperature and wind speed of 6.8 m/s.

finger-tip temperature was compared to experimental results found in Wilson et al. (1976). In Wilson et al. (1976) experiments volunteers' fingers were being precooled at 25.5 °C for 60 min and then exposed to cold. Also, Keatinge and Cannon (1960) reported skin freezing point is between −0.53 °C and −0.65 °C. Therefore, −0.6 °C was used as skin freezing point in this study and our previous work (Fallahi et al., 2017). Typical temperature distribution versus time is displayed in Fig. 2. As shown in this figure, the fingertip of the model reaches to freezing point at −15 °C and wind speed of 6.8 m/s in 9.7 min. Therefore, the amount of time takes for finger to reach to the skin freezing point temperature (endurance time) was chosen as an effective criterion for prediction of frostbite inception.

The current model was tested for different temperatures and wind speed to predict danger of frostbite in human finger for various types of hand gloves. The model estimated finger temperature in environmental temperatures of 0, −10, −20, −25 and −30 °C with a wind speed of 0, 3 and 6.8 m/s having three different clothing on the finger.

Table 1 represents endurance time for forty five simulations carried out for different environmental conditions. In some cases, the finger-tip temperatures did not reach the skin freezing point temperature (−0.6 °C) which are designated with "NO" while at 23 experiments, frostbite happened (bold numbers). Endurance time is specified in minutes for 23 cited experiments. Table 2 lists the final fingertip temperature of the model when frostbite temperature is not achieved in the experiment. All 23 frostbite cases were also shown in Table 2 (F_1 to F_{23}). Total finger resistance which is a sum of the glove and finger

Table 1
Endurance times in minutes at different environmental conditions (Fallahi et al., 2017).

Ambient temperature	Wind speed	Clothing		
		Bare	0.41 clo (Glove a)	0.75 clo (Glove b)
0 °C	Still air	No	No	No
	3 m/s	No	No	No
	6.8 m/s	No	No	No
−10 °C	Still air	No	No	No
	3 m/s	**28**	No	No
	6.8 m/s	**15.5**	No	No
−20 °C	Still air	No	No	No
	3 m/s	**13.5**	**57.5**	**133**
	6.8 m/s	**6.5**	**48.3**	**107.6**
−25 °C	Still air	**105.5**	No	No
	3 m/s	**10**	**44.1**	**79**
	6.8 m/s	**5.2**	**37.5**	**77.5**
−30 °C	Still air	**78.5**	**131.4**	No
	3 m/s	**8**	**36**	**53**
	6.8 m/s	**4.3**	**31.5**	**52**