The endurance time to loss of finger dexterity with protective gloves: effects of glove type, air temperature, and wind speed

Mengying Zhang[1,2], Rui Li[1], Guowen Song[1], Jun Li[2], Shankar Subramaniam[1], Alberto Passalacqua[1]
[1] Iowa State University, USA, [2] Donghua University, China
Keywords: human hand, manual performance, dexterity, glove, wind

1. Introduction Human hands are uniquely dexterous and play a critical role in work performance. The ability of a human being to perform manual tasks is critical to task success, human safety, or even survival. Hands are also one of the most vulnerable parts to cold injury due to their large surface area to volume ratio and the dramatic change in blood flow (Taylor et al., 2009). It is critical to maintaining manual performance when working or operating in a cold environment. As a result, protective gloves must be properly designed to provide adequate thermal insulation. Sufficient thermal insulation thus in turn maintains necessary manual performance. In this study, we estimated the endurance time to loss of finger dexterity based on a hands-specific thermoregulation model with simulations of two types of gloves in various environmental conditions. The outcome of this study will contribute to the improvement of human safety and work performance by directing the development of future protective gloves.

2. Method The thermal insulation of the gloves (Table 1) was measured using a thermal hand manikin (Thermetrics, Seattle, WA, USA) under wind speeds of 0.05 m/s and 2.0 m/s. N1 (size M) is a single-layer cotton glove, and N2 (size M) is a three-layer firefighters' glove (Figure 1 (a) and (b)). The thermophysiological model of the hand is three-dimensional, successfully validated, and has the ability to predict spatial and temporal skin temperature. The model used realistic anatomical, physiological, and thermo-physical data as human hands and has 16 segments, including palm, dorsal, and five fingers, with each finger subdivided into fingertip, middle segment, and finger root except for the thumb, which has no middle segment (Figure 2 (c)). Heat transfer throughout the hand by metabolism, blood perfusion, and conduction between the tissue and heat loss by convection and radiation from the skin were incorporated in the model. An average skin temperature of 15 ℃ of five fingers was used as the critical temperature for loss of dexterity (Heus et al., 1995; Zimmermann et al., 2008).

Table 1. Thermal insulation of the glove ($m^2 \cdot K/W$).

Glove type	Wind speed	Thumb	Index	Middle	Ring	Little	Palm	Dorsal	Total
N1	0.05 m/s	0.109	0.094	0.121	0.115	0.095	0.168	0.125	0.122
	2.0 m/s	0.025	0.020	0.023	0.024	0.020	0.057	0.027	0.028
N2	0.05 m/s	0.129	0.147	0.186	0.165	0.125	0.229	0.190	0.172
	2.0 m/s	0.080	0.107	0.133	0.113	0.083	0.121	0.123	0.111

3. Result and discussion The endurance times under air temperatures of -20 ℃, -10 ℃, 0 ℃, and 10 ℃ and wind speeds of 0.05 m/s and 2.0 m/s with or without glove were predicted. It can be found from Figure 2 that the endurance time increases exponentially with the air temperature.

There are considerable differences in skin temperatures among different hand segments (Figure 3), with the little fingertip always has the lowest skin temperature. The temperature differences also increase with the thermal insulation of gloves. For N1 at -20 °C air temperature and 2.0 m/s wind speed, the skin temperature at the little fingertip is 9 °C at the end of exposure, about half of the skin temperature at the finger root. While for N2 with the same condition, the skin temperature at the little fingertip is 5 °C at the end of exposure, only one-third of the corresponding skin temperature at the finger root. Both of the gloves can increase the endurance time, with N2 always has the highest endurance time due to its low air permeability and high thermal insulation value. Wind can enhance convective heat loss, thus decreasing the endurance time; however, the influence decreased as the thermal resistance of the glove increased. Although N2 can provide better thermal protection in cold environments, it will also limit the dexterity of the hand and fingers due to its considerable thickness and stiffness. It is crucial to optimizing the trade-off between the protection and dexterity for glove design and engineering.

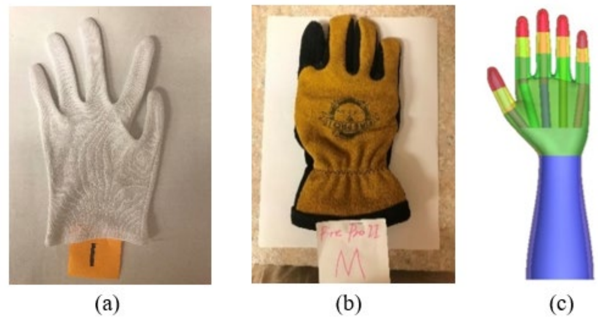

Figure 1. Gloves and hand model. (a) Cotton glove, (b) firefighters' glove, and (c) hand

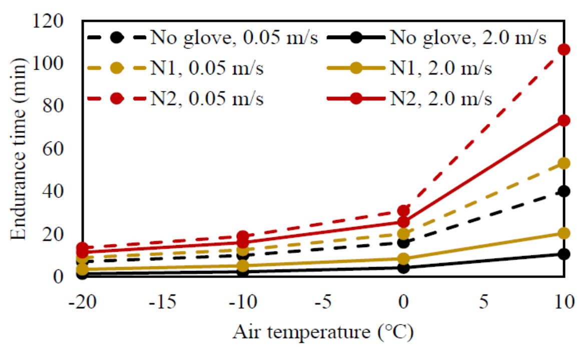

Figure 2. The predicted endurance times under different air temperature, wind speed, and glove conditions.

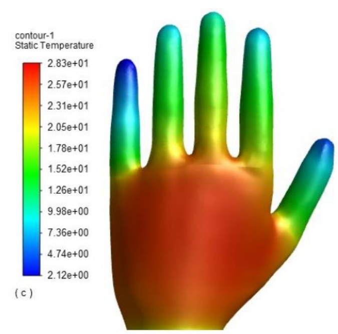

Figure 3. Skin temperature distribution with N2 glove at -20 °C and 2.0 m/s

4. Conclusion

The endurance time to loss of finger dexterity is defined based on literature. The finger skin temperatures were predicted based on a validated hand-specific thermoregulation model. The effect of air temperatures, wind speeds, and glove insulations on the endurance time to loss of finger dexterity was investigated. Gloves with higher thermal insulation are able to protect hands from cold. However, they can also induce significant differences in the skin temperature among different hand segments. Therefore, when designing gloves, each hand segment should have its specific materials to ensure thermal comfort and protection as well as the flexibility of the fingers and hands.

Reference

Heus, R., Daanen, H. A., & Havenith, G. (1995, Feb). Physiological criteria for functioning of hands in the cold: a review. *Applied Ergonomics, 26*(1), 5-13. https://doi.org/10.1016/0003-6870(94)00004-i

Taylor, N. A. S., Machado-Moreira, C., Heuvel, A. v. d., Caldwell, J., Taylor, E. A., & Tipton, M. J. (2009). *The roles of hands and feet in temperature regulation in hot and cold environments*. The 13th International Conference on Environmental Ergonomics, Boston, USA.

Zimmermann, C., Uedelhoven, W. H., Kurz, B., & Glitz, K. J. (2008, Sep). Thermal comfort range of a military cold protection glove: database by thermophysiological simulation. *European Journal of Applied Physiology, 104*(2), 229-236. https://doi.org/10.1007/s00421-007-0660-z