It's Time to Rethink Reused: Denim Fabric Properties and Their Effects on Foot Thermal Sensation

Changhyun Nam and Eulanda Sanders, Iowa State University, USA
Jie Yang, Xi'an University of Science and Technology, China

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Introduction. According to the U.S. Environmental Protection Agency (EPA), more than 16 million tons of textiles in 2015 and more than one million pieces of denim clothing are thrown away in landfills every year (EPA, 2018; Recyclebank, 2018). Repurposing waste, such as worn or old jeans made from denim fabrics is a viable material for sustainable shoe design. Denim fabrics yield incredible opportunities for transformation into a variety of different products (e.g., shoes, bags, hats), becoming the perfect circular product (Roberts-Islam, 2018). Moreover, recycled denim fabrics can not only be used as a material for pattern-making in footwear, but also play an important role as a reinforcing material in the upper or middle shells of casual shoes. The main issues in footwear are related to thermal comfort (57%) including discomfort, cold sensation, and sweat, because footwear is unable to completely maintain a wearer's foot temperature during wearing time (Bergquist & Abeysekera, 1994; Kuklane, 1999, p 6). However, rarely do footwear designers and researchers investigate foot thermal sensations based on the material properties of denim fabric, environmental conditions, and human thermoregulation, despite understanding the importance of thermal sensation.

Thermal sensation is a human sense that relates to both the psychological and the physiological states of a person (Konz et al., 1977). Generally, thermal sensation can be determined by indices of thermal comfort, which can be divided into three categories: (a) direct indices are measured by instruments, (b) empirical indices are derived from the measured physiological responses, and (c) rational indices are calculated by heat balance equations (ASHRAE, 2013). In order to investigate the material properties in foot thermal sensation, it is necessary to present a foot thermal sensation model. In this study, a foot sensation model will be proposed based on an improved human thermoregulation model (Yang et al., 2014) and thermal sensation model (Zhang et al., 2010). The purpose of this study was: (a) to examine the thermal resistance (R_{ct}) and water vapor resistance (R_{et}) of cotton denim fabric and hemp fabric in developing a new, two-layered material configuration for denim footwear, and (b) obtain a foot thermal sensation model for the denim footwear. Therefore, an empirical prediction model of footwear and material properties can serve as a useful research tool contributing to the improvement of materials and application of functional design processes for footwear.

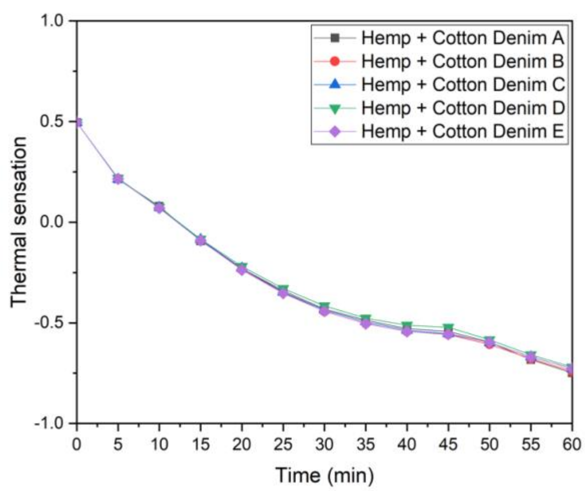
Methods. Five different thicknesses of 100% cotton denim fabrics (twill weave, outer layer) and one 100% hemp fabric (plain weave, inner layer) were examined. Measurements of thickness (using a Frazier Schiefer Compressometer), thermal insulation (R_{ct}), and evaporative resistance (R_{et}) of the fabrics were conducted using a sweating guarded hot plate according to ASTM-F1868. The permeability was calculated based on the R_{ct} and R_{et} (see Table 1).

Table 1. *Properties of Hemp and Cotton Denim Fabrics*

No.		A total of thickness (mm)	R_{ct} ($^oC \cdot m^2/W$)	R_{et} ($Pa \cdot m^2/W$)	Permeability Index
1	Hemp + Cotton Denim A	1.12	0.1277	13.398	0.5781
2	Hemp + Cotton Denim B	1.17	0.1271	14.458	0.5331
3	Hemp + Cotton Denim C	1.20	0.1273	14.888	0.5186
4	Hemp + Cotton Denim D	1.31	0.1282	14.268	0.5444
5	Hemp + Cotton Denim E	1.39	0.127	15.688	0.4909

Note. hemp (inner layer) =100 % hemp with plain weave; cotton denim (outer layer) = 100% cotton with twill weave; hemp fabric's thickness = 0.50 mm.

Results and Discussion. A multi-node human thermoregulation model (Yang et al., 2014) was applied to predict physiological responses (core temperature and skin temperature) using metabolic rate, thermal insulation, evaporative resistance, ambient temperature, relative humidity, and wind speed. In this thermoregulation model, the human body was divided into 20 segments and each segment was comprised of four layers including core, muscle, fat, and skin layers. Based on the predicted physiological responses, foot thermal sensation was simulated by the thermal sensation model proposed by Zhang et al. (2010).



The thermal sensation was expressed on a nine-point scale: 4 = 'very hot', 3 = 'hot', 2 = 'warm', 1 = 'slightly warm', 0 = 'neutral', -1= 'slightly cool', -2 = 'cool', -3 = 'cold', -4 = 'very cold.' It is essential for footwear designers and researchers to understand the relationship between material properties and thermal conditions sufficient for comfort in thermal footwear. The results showed that each material composition (hemp and cotton denim fabric layer) is similarly performed for thermal sensation ranged from 0.5 to -0.75 during one hour, regardless of the different thickness of cotton denim fabrics (see Figure 1).

Figure 1. Foot thermal sensation wearing cotton denim shoes.

Therefore, it can be stated that both summer jeans (i.e., made of cotton denim A and B) or winter jeans (i.e., made of cotton denim D and E) can be reused to make a pair of denim shoes with the same function in thermal comfort.

The findings allow footwear designers and researchers to not only comprehensively utilize the principles of human thermoregulation and footwear material properties, but also consider the development of thermal comfort features in denim shoes. This foot comfort model predicts the key parameters of footwear materials and provide a scientific basis for developing footwear material and design. We suggest that sustainable footwear manufacturing companies collaborate to form a sustainable project with jean apparel companies to use less waste or rethink recycled denim fabrics. Further research will enhance the creation of the model involving human trials, which will simulate a wearer's physiological responses with great accuracy and account for the fabric and garment properties of footwear.

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