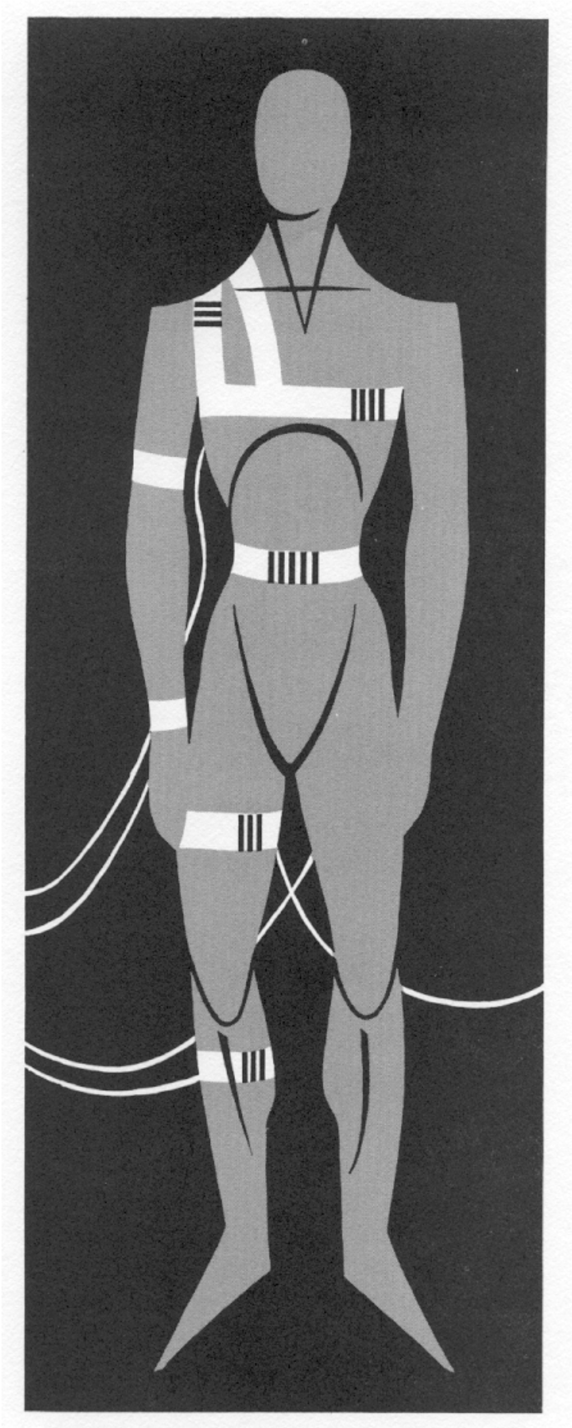

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A Report on

Thermal Insulation Values and Temperature Ratings for Cold Weather Clothing Ensembles

submitted to

BENCHMARK CLOTHING CO.
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Approved by

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The purpose of this project was to measure the thermal insulation value of cold weather garments tested with a base ensemble and determine the temperature ratings for comfort.

Methodology

Apparatus

The insulation values for the clothing systems were measured using an electrically-heated manikin in thermal equilibrium with its surroundings. The manikin at Kansas State University – STAN – consists of a shell formed to simulate the physical shape and size of a typical man (i.e., 1.80 m^2 surface area, 177.2 cm height). The manikin consists of 20 independently heated thermal zones (see Figure 1), with an additional fluid heater inside the manikin. All thermal zones are fit with heaters to simulate metabolic heat output rates and distributed wire sensors for measuring temperature. A chart describing the body segments (zones) and their surface areas is shown in Table 1.

The power cables, measurement cables, fluid supply tubes, and fluid return tubes connect to his face. A photograph of the manikin is shown in Figure 2. Stan hangs from a hook attached to his metal stand. A handle at the back of the stand is used to raise and lower the hook (and the manikin) for dressing. Stan hangs with his arms at his side during a test, or he can be connected to a locomotion device for walking.

The entire system is computer operated. The ThermDAC control software is a Windows based program that provides control capabilities, data recording, and real-time numerical and graphical displays of section temperatures.

Manikin Procedures

The insulation value (clo) was measured at Kansas State University according to ASTM F1291-22, Standard Test Method for Measuring the Thermal Insulation of Clothing using a Heated Manikin (ASTM, 2023) and the ASTM F2732-23, Standard Practice for Determining the Temperature Ratings of Cold Weather Clothing (ASTM, 2023). The garments were received at Kansas State University on December 19, 2023 and were unpacked and hung on a clothing rack. The environmental conditions in the chamber were controlled as follows:

- ambient air temperature, 7°C (45°F)
- air velocity, 0.35 m/s (69 ft./min.)
- relative humidity (30-80%), with the dew point temperature controlled to ± 1°C (i.e., not changing during a test)
- manikin surface temperature, 35°C (95°F)

Two air temperature sensors and one relative humidity sensor were hung 0.5 m in front of the manikin and spaced at equal height intervals. The air velocity was measured periodically using an anemometer.

To conduct a test on a jacket, coverall, or jacket/pants set, the manikin was first dressed in the ASTM Base Ensemble #1 consisting of the following garments:

- *Shirt* – Long-sleeve mock turtle neck shirt, interlock knit, 100% cotton, 214 g/m^2 [6.3 oz/yd^2]; worn with shirttail over jeans.
- *Jeans* – Denim 5-pocket jeans, 100% cotton 397 g/m^2 [11.7 oz/yd^2].
- *Men's Underwear Briefs* – Jersey knit briefs, 100% cotton, 180 g/m^2 [5.3 oz/yd^2]; jockey style that fits snugly at the waist and legs.
- *Men's Socks* – Basic knit sock that covers foot and extends up the calf no more than 25.4 cm [10 in.] from the bottom of the heel. Socks must be composed of at least 75 % cotton and shall weigh 65 ± 10 g each.
- *Athletic Shoes* – Fabric/soft leather and soft sole.
- *Gloves* – Insulated knitted fleece gloves, 100% polyester, all layers 454 g/m^2 [13.4 oz/yd^2]; cuffs worn under jacket sleeves.
- *Hat* – Knitted fleece hat, 100% polyester 129 g/m^2 [3.8 oz/yd^2]; worn pulled down to eye brows.

According to the standard, the intrinsic clothing insulation value (I_{cl}) of Base Ensemble #1 should be 0.80 clo ± 10%. (See Figure 2.)

The manikin was then dressed in the cold weather clothing and all closures were secured. Jackets with a hood were tested with the hoods pulled up over the head. The manikin was hanging from his metal stand by a hook in his head. Photographs of the manikin dressed in the cold weather clothing ensembles are shown in figures at the end of the report. Equilibrium was maintained for at least 1 ½ hours prior to testing. Equilibrium was indicated by a steady-state power reading that had not changed more than 1%. Data were collected by computer every 60 seconds for a 30-minute test.

The total thermal insulation value (I_t) of the clothing plus the surrounding air layer was calculated to the nearest 0.01 clo using Eq. 1: (6.45 is a units constant)

$$I_t = (T_s - T_a)\, A \cdot 6.45 / H \qquad (1)$$

where:

I_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (clo),
A = area of the manikin's surface (m^2),
T_s = temperature at the manikin surface (°C),
T_a = temperature in the air flowing over the clothing (°C), and
H = power required to heat manikin (W).

Only one sample of each garment was provided by the sponsor. Therefore, the total insulation value (I_t) for each ensemble was determined as the average of three replications made on one sample set of clothing. Then the average intrinsic insulation value of the clothing alone (I_{cl}) was determined using Eq. 2:

$$I_{cl} = I_t - (I_a/f_{cl}) \qquad (2)$$

where:

I_{cl} = intrinsic clothing insulation (clo),
I_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (clo),
I_a = thermal resistance of the air layer on the surface of the nude manikin (clo), and
f_{cl} = clothing area factor (dimensionless).

The f_{cl} values given in the standard were used for the base ensembles and the cold weather clothing ensembles.

The air velocity in the environmental chamber affects the insulation provided by the air layer around the manikin's body, and consequently, the total insulation values. For consistency within a lab and between labs, a *standardized* total insulation value ($I_{t,s}$) of the cold weather clothing ensembles was calculated by using a standard air layer resistance of 0.5 clo in Eq. 3:

$$I_{t,s} = I_{cl} + (I_{a,s}/f_{cl}) \qquad (3)$$

where:

I_{cl} = intrinsic clothing insulation (clo),
$I_{t,s}$ = standardized total thermal resistance (insulation) of the clothing ensemble and surface air layer (clo),
$I_{a,s}$ = standard thermal resistance of the air layer on the surface of the nude manikin, 0.5 clo, and
f_{cl} = clothing area factor (dimensionless).

Temperature Ratings

According to ASTM F2732, the standardized total insulation value for each ensemble ($I_{t,s}$) was used in a whole body heat loss model to determine the air temperature for comfort for an adult with an activity level of 2 MET (i.e., walking slowly) and an activity of 4 MET (i.e., walking fast). The linear regression equations for the model are:

$$\boldsymbol{TR_2 = -23.78\, I_{t,s} + 89.83}$$

$$\boldsymbol{TR_4 = -48.61\, I_{t,s} + 86.7}$$

where:

TR_2 = temperature rating (°F) for 2 MET of activity,
TR_4 = temperature rating (°F) for 4 MET of activity, and

$I_{t,s}$ = standardized total thermal resistance (insulation) of the clothing ensemble and surface air layer (clo)

Caution in the Use of the Temperature Rating Model

The user of the temperature rating model should never forget the assumptions that were used for inputs to the model and its limitations. This information should be communicated to consumers.

- This is a **steady-state model** for adults. When people are working or playing outside, the conditions are usually changing. Environmental conditions change throughout the day. People adjust their clothing, change activity, etc. Therefore, the temperature prediction is a guideline.

- The model in the standard is a **whole body heat loss model** that predicts overall comfort for the body under steady-state conditions. The model treats the insulation of the ensemble as if it were **evenly distributed** over the body surface. In reality, some parts of the body are better insulated than others in outdoor ensembles. Localized cooling and discomfort can still occur on different parts of the body like the hands, feet, and face – particularly if they are exposed to the environment.

- **Radiant temperature** is assumed to be equal to air temperature in the model. In outdoor environments, the radiant heat from the sun may affect thermal comfort during the day.

- The effect of **wind** was not used in the model. Wind-chill temperature tables can be used to determine the equivalent temperature for heat loss at different levels of air velocity. For example, if the model predicts a temperature rating of 10°F for an ensemble worn during low activity with no wind, an equivalent temperature would be about 20°F with a 10 mph wind. Users should be cautioned about the effect of wind in cold environments and use the model with wind-chill adjusted temperatures.

- An average 50% **relative humidity** was used in the model since this parameter varies widely within a 24 hour period and from day to day. Humidity is not as critical a parameter in cold environments as it is in hot environments where it affects the body's ability to evaporate sweat from its surface (i.e., provide cooling).

- The **moisture vapor permeability** of the clothing was estimated in the model. This variable might be lower for ensembles that are very thick (because there is a longer path for the moisture vapor to travel through from the body to the environment) and for ensembles that are made with shell fabrics that impede moisture vapor transport. However, if a person gets over heated in the cold, he/she can adjust garment closures or open the garment to provide cooling.

- The **insulation of an ensemble decreases as a person's activity increases**. This occurs because convection heat transfer increases as air is pumped between garment layers during body movement (McCullough & Kim, 1996). This decrease in insulation is quite variable (10-50%) and is related to garment design and fit. It is typically around 20% for outdoor ensembles since garment openings are usually restricted at the wrists, neck, ankles, etc. to prevent cold air from getting inside the ensemble. Therefore, the "pumping effect" was not accounted for in the calculations. Consequently, the air temperature for comfort may be higher than that predicted by the model when a person is actively moving his/her arms and legs.

- The **activity level** of a person varies when a person is wearing cold weather clothing. The more active a person is, the lower the temperature rating for comfort will be.

- **Human variability** affects comfort. The average "standard man" was used in the modeling. Physical and physiological variables such as percent body fat, percent muscle mass, hormone levels, etc. were not incorporated into the model, but they can affect a person's perceptions of comfort.

Results

The insulation values were measured at Kansas State University between December 20 and 21, 2023. The insulation values and temperature ratings for the ensembles are given in Table 2. These values are realistic because the experimental garments were worn over other clothing. Local insulation values for the jackets worn over the ASTM long-sleeve knit shirt are given in Table 2 also. Only zones #3-6 (arms) and #9-12 (torso) were used in the calculation. Some jackets do not cover the hips completely, so the hip zones were not included in the local insulation calculation. The results relate only to the ensemble evaluated and for the specific conditions of the test.

References

American Society for Testing and Materials. (2023). *Annual Book of ASTM Standards – Part 11.03*. Conshohocken, PA: ASTM.

McCullough, E.A., Kim, C.S. (1996). Insulation values for cold weather clothing under static and dynamic conditions, in *Environmental Ergonomics: Recent Progress and New Frontiers*, Y. Shapiro, D.S. Moran, and Y. Epstein (editors). Tel Aviv: Freund Publishing House, Ltd., 271-274.

Table 1
Surface Area Measurements for STAN

No.	Body Segments Marked on Stan	Surface Area of Each Part (m^2)	% of Total Body Surface Area Represented by Each Segment
1.	Face	0.0457	2.5
2.	Head	0.0962	5.3
3.	R Upper Arm	0.0817	4.5
4.	L Upper Arm	0.0817	4.5
5.	R Forearm	0.0648	3.6
6.	L Forearm	0.0648	3.6
7.	R Hand	0.0442	2.4
8.	L Hand	0.0442	2.4
9.	Chest	0.1201	6.7
10.	Shoulders	0.1007	5.6
11.	Stomach	0.1194	6.6
12.	Back	0.0930	5.2
13.	R Up Thigh	0.0777	4.3
14.	L Up Thigh	0.0777	4.3
15.	R Low Thigh	0.1509	8.4
16.	L Low Thigh	0.1509	8.4
17.	R Calf	0.1357	7.5
18.	L Calf	0.1357	7.5
19.	R Foot	0.0595	3.3
20.	L Foot	0.0595	3.3
Total Body		**1.8041**	**100.0**

Table 2
Insulation Data and Temperature Ratings for Ensembles

Clothing Ensemble	Total Local Thermal Insulation Value (clo)[a]	Standardized Total Thermal Insulation Value, $I_{t,s}$ (clo)	Temperature Rating Range (°F)[b]			Temperature Rating Range (°C)[b]	
			2 MET of Activity	4 MET of Activity		2 MET of Activity	4 MET of Activity
A. Flame Resistant Zip-Up Hooded Sweatshirt, 19 Cal, 2112, USA Made, Navy S (SKU: 3025FRN-S)	2.03	**1.53**	53.4	12.3		11.9	-10.9

[a] ***Local insulation values for the areas covered by the jacket and ASTM shirt were calculated using zones #9-12 (torso) and zones #3-6 (arms).***

[b] ***The low temperature rating may not be used on product labels and catalog descriptions unless it is part of the range given in the table.***

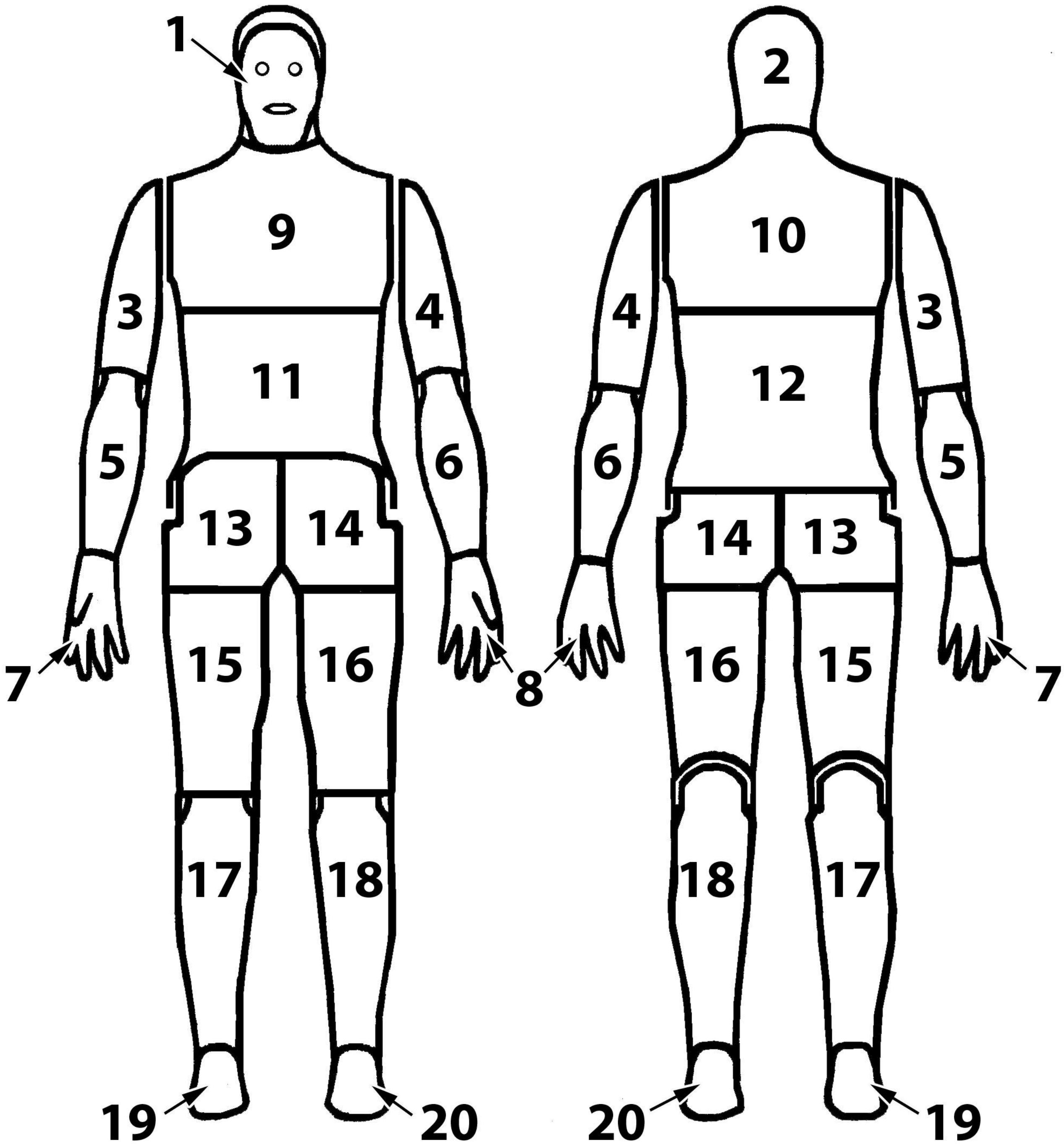

Figure 1. Manikin body segments (20).

Figure 2. Stan dressed in ASTM Base Ensemble #1.

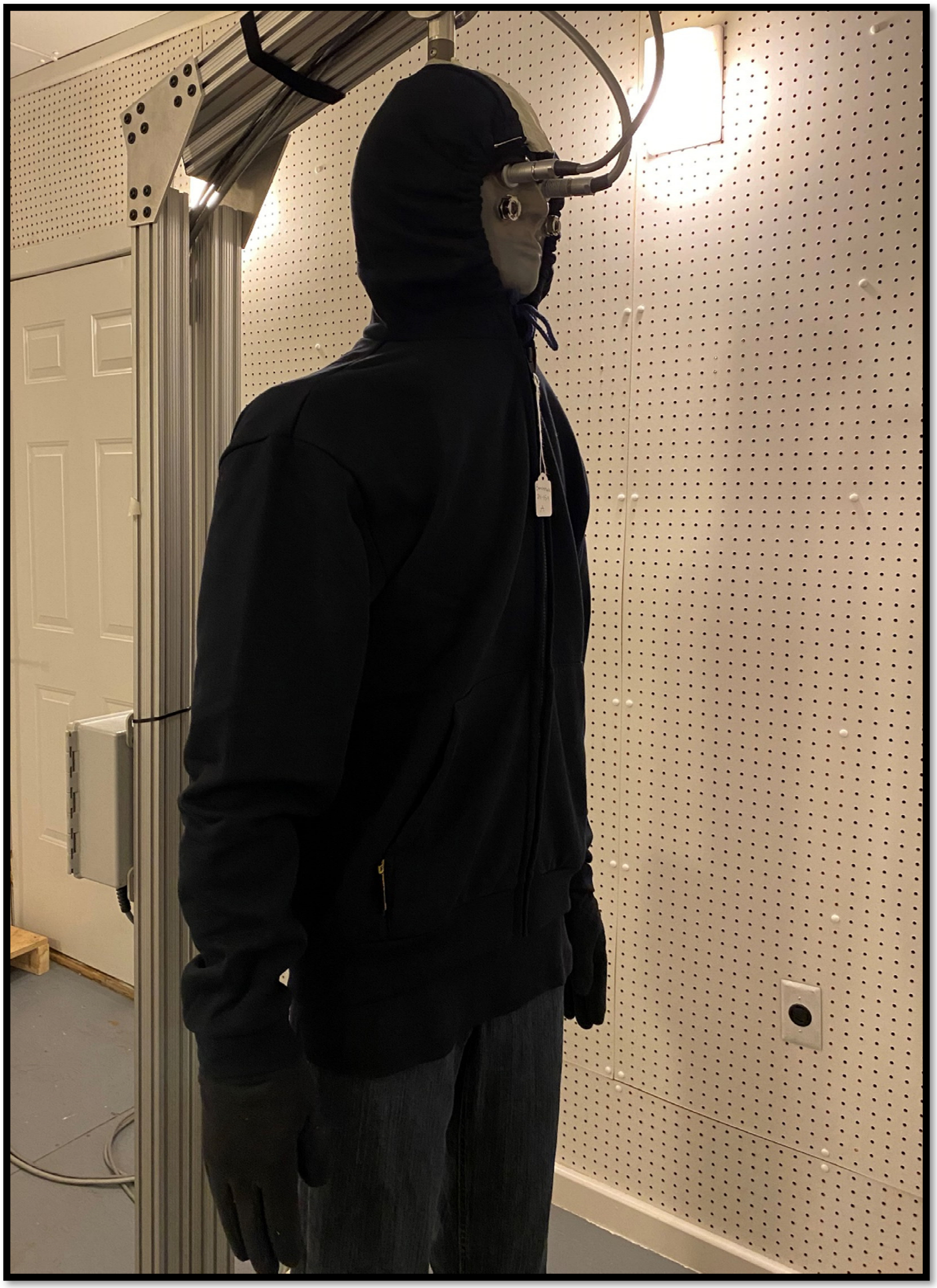

Figure 3. Stan dressed in ensemble A.