Applying 3D scanning and CAD reverse engineering for clothing thermal analysis

Ivana Špelić

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Abstract: Combining 3D scanning and CAD reverse engineering is currently the only possible method to acquire the precise geometric calculation of clothed human body. To obtain realistic geometric CAD human body models, computer-assisted sequential reverse engineering was performed. The male modular jacket and corresponding whole-body clothing ensembles were afterwards tested by static thermal manikin. By combining precise thermal properties of clothing in respect to established geometrical features of each dressed CAD human body model, correlation has been ascertained between geometry and thermal insulation properties of clothing. The study has proven that the length of the outerwear items such as jackets, significantly impacts the changes in area and volume and substantially leads to increase in the thermal insulation value of the whole-body clothing ensembles. A 20 cm jacket’s length enlargement leads to as much as 10.4% area increase and 22.0% volume increase in overall clothing ensemble and accounts for more than 25% increase in effective thermal insulation. The maximum jacket’s length increase for 60 cm led to ensemble’s area increase of 26.5% and volume increase of 75.5%. As observed, the increase in length for 60 cm simultaneously led to substantial increased in both overall volume and area and accounted for effective insulation increase for as much as 41.7%. The study has proven the causal link between the garment’s length and consequential changes to geometrical clothing features, which directly affect the potential decrease or increase in the effective thermal insulation value.

Subjects: Human Performance Modeling; Nondestructive Testing; Computer Aided Design; CAD

ABOUT THE AUTHOR

Assistant professor Ivana Špelić, Ph.D. works as Assistant professor at the Department of Basic, Natural and Technical Sciences at the University of Zagreb Faculty of Textile Technology. The areas of special research interest are textile technology and engineering, clothing technology, energetics, technical thermodynamics, energy management in industry and new and renewable energy sources. In 2015, she finished three months research training at University of Maribor Faculty of Mechanical Engineering at Slovenia. She published 1 scientific monography, 1 book chapter, 8 original scientific papers, 13 scientific papers at international conferences, and several professional and scientific papers at national conferences. She worked as member of organisational, technical and implementing committees at several international scientific conferences and received two scientific awards.

PUBLIC INTEREST STATEMENT

The study describes the 3D CAD reverse engineering techniques applied on the human body modelling and their applications for precise calculations with various other techniques such as obtaining the thermal insulation, which is new innovative approach in clothing design analysis. The whole-body clothing ensembles and separated model of male modular jacket were tested through 3D scanning, followed by realistic model creation by CAD reverse engineering, which allowed precise geometry calculations. Afterwards, thermal manikin testing was applied to affirm precise thermal properties of clothing in respect to established geometrical features of each dressed 3D body model. To obtain realistic 3D human body model, computer-assisted sequential reverse engineering is performed and afterwards area and volume of each model were compared to basic model.
Keywords: 3D scanning; CAD reverse engineering; CAD human body model; precise area and volume calculation; non-contact infrared assessment; thermal insulation testing
Subjects: Human Performance Modeling; Nondestructive Testing; Computer Aided Design; CAD

1. Introduction

Clothing modifies the heat and moisture loss from body to the outer environment, thus playing a vital role in the maintenance of heat balance. Clothing acts as buffering material between the subject and the cold climate, offering a well-balanced protection if properly produced. Cold-protective clothing has to be designed in such manner to allow the subject to feel comfortable despite severe temperatures and wind. Clothing is aimed not to hinder the extremities movement or to add a lot of weight and friction during movements. On the other hand, sufficient thermal insulation is provided by dry unmovable air trapped beneath the clothing. The outerwear should be produced in such manner to prevent excessive body heat transfer to the environment without causing heat strain.

When designing the cold-protective jackets, one should primarily focus on several material properties such as thermal insulation, water vapour resistance, protection against external moisture, and air permeability (Wilson et al., 2002). Since the textile materials provide resistance to heat flow by resisting the conductive heat transfer by air trapped between the adjacent plies of materials and by resisting the radiative heat transfer, the material selection is the first step in designing outerwear clothing items with greater thermal protection. The air layers formed in-between material plies provide barrier to the conductive and radiative heat fluxes. The complex geometry of dressed human body presents a challenge when investigating the overall impact of material plies, clothing layers, type of clothing item, model variant or air enclosed between formed layers of clothing on the overall insulation value for specific environmental conditions. Except the looseness or tightness of fit, the length of a single outerwear clothing item such as jacket could significantly impact the overall comfort level simply by buffering the heat release to the surrounding environment.

The basic factors should be addressed for protective clothing, such as thermophysiological comfort (physical and physiological comfort, especially thermal comfort), sensorial comfort (touch and next-to-the-skin sensations), garment fit (correct size and fitting), psychological comfort (overall aesthetic appearance, design and colour, current fashion, prejudice, suitability for the occasion), performance, cleanability, storage and disposability; and availability and cost of materials, ease of fabrication and production (Cheng et al., 2012; Fung, 2002; Holmér, 1989; Williams, 2009).

When discussing the thermal comfort, both subject’s personal variables such as clothing insulation value, activity level and metabolism rate should be considered, as well as environmental variables such as dry-bulb air temperature, mean radiant temperature representing the radiant temperature of the surrounding surfaces, air relative humidity and air movement (ISO 7730:2005; Cheng et al., 2012). The thermal comfort is expressed as the condition of mind that expresses satisfaction with the thermal environment, and it mainly depends on favourable transport of heat and moisture through fabric (ISO 7730:2005).

Since 1940s, there has been a great change in producing waterproof protective clothing, which required greater wearing and thermal comfort, while at the same time increase in material demands was observed. Materials were required of being light weight, soft, capable of providing high performance in protection from the various climate elements along with improved breathability and phase change ability, as well as providing warmth without bulk and better performance at lower cost (Fung, 2002). When constructing the outerwear clothing items intended to cover and protect the upper body from specific climatic conditions, one has to take into account the application-specificities (e.g. protection against heat or cold climatic sources, protection against...
wind, exposure times, etc.), the requirements applying to materials (e.g., to protect in conformed environmental temperature range, waterproofness, breathability, windproof protection, comfortability, etc.), ergonomic specificities (e.g., body dimensions and comfort issues) and finally design.

One of the essential requirements addressed in cold-protective clothing is the ability to maintain the body microclimate beneath the outerwear clothing items dry, and in order for that to be accomplished appropriate materials should be combined to form diffusion of water vapour molecules and evaporation of liquid sweat outside the microclimate. Adverse material selection would lead to moisture diffusing through the layers of clothing item, gradually accumulating until sensible drop in thermal insulation is reached (Wang & Gao, 2014).

The composite layering structures, called the laminates, gained attention in the past decade to produce outerwear clothing suitable for outdoor activities by providing protection against outer weather factors, such as rain, snow, and wind (Li & Sitnikova, 2020). The multi-layered materials provide functionality that cannot be achieved with a single component (Eryuruk, 2018). As layered fabric structures with incorporated breathable membrane, the laminates allow hard-wearing but comfortable application with improved functionality. The breathable membranes, usually placed as lower or middle layer in laminated textile structure, should provide suitable breathability and water vapour diffusion from the inside of the garment microclimate, while simultaneously preventing water penetration from external sources. The membrane micropores are permeable to water-vapor molecules but impermeable to liquids (Singha, 2012). Laminates also provide reinforcement with appropriate thickness (O’Keeffe et al., 2021). By reducing the resistance to the permeability of water vapour one can accomplish greater sweat transportation from the skin to the surroundings due to the resistance reduction to mass transport through the laminate. Membranes are made with different chemical composition and construction, especially considering the number and an arrangement of the layers and by choosing the permeation possibility through membrane pores or simply by using water vapour diffusion mechanism through the bulk polymer. The membrane characteristics determine the final properties of the textile laminates and provide the users with the possibility to optimize the final garment design according to finite usage (Gulbiniené et al., 2011; Rothmaier et al., 2008; Sybilska & Korycki, 2010).

Among different layering options, the laminates with polytetrafluoretilen membrane (PTFE) have better insulating properties while the membrane has minimal resistance to the permeability of water vapour (Sybilska & Korycki, 2010). The jacket made from laminates with PTFE membrane provides minimal discomfort and good biophysical properties.

People tend to wear long raincoats during windy and rainy weather or long coats when cold. So how much does the change in the length tend to alter the insulation values? The clothing thermal insulation properties are related to the fit, the garment length and the amount of the body surface covered by the garments. The thermal insulation of the compounding clothing ensemble is affected by the size and the distribution of the air layers. The surface configuration and the layers arrangement affect the thermal insulation of both single clothing item as well as the whole-body clothing ensemble. The result is an increase in the thickness, configuration and length of the ensemble, which simultaneously increases the surface area of the clothing available for the heat exchange (Wilson et al., 2002). The volume of the enclosed air layers tends to change in parallel with the changes in fit and length of the ensemble. The total thermal resistance of the ensemble, including the boundary air layer and the clothing, is maximized in still air without the body movement. MacRea et al. reported the outerwear and additional air spaces appeared to dominate the overall thermal properties of clothing ensembles (MacRea et al., 2011) but none of the previous studies quantified the effects of the outerwear clothing items’ length on the overall ensembles’ insulation. Since the air entrapped inside the clothing provides more than 60% to the value of the intrinsic clothing insulation, the impact of the length of the clothing items on the overall increase in the area and the volume of the clothing ensemble have been observed by combining 3D body scanning and the reverse engineering aimed to calculate the complex geometry of dressed human
body. The thermal insulation values have been compared to the changes in dressed human body geometry in order to gain the insight on the impact of the length to the overall thermal insulation value.

During recent decade, 3D body scanning allowed an alternative to the widely used body mass index (BMI) by allowing non-invasive identification of the body volume index (BVI), which is much more sophisticated index for health risks (Steinach & Gunga, 2015). The 3D scanners generate polygonal approximation to human model and thus allow great advantage in calculating the complex geometry of the human body. The geometry of the surface changes and the stacking fabrics one over another may result in the additional air being enclosed between the layers of the fabrics during formation of the clothing ensembles or adversely result in compression of the inner fabric and air layers. Although fairly common in classical engineering, CAD reverse engineering is yet to be discovered for human body modelling. Since the dry heat loss from the body is a combination of both the resistance provided by the clothing and from the entrapped microclimatic air, 3D scan reconstruction is mandatory procedure to quantify the area and volume enlargement of the whole-body dressed models as the result of both material layers as well as air ply formed between those material layers. Experimental study covered the 3D scanning, the scan preparation and the thermal manikin testing in static conditions. The infrared thermography was also used to test the junctures between the basis of the produced jacket and the attachable modules. Following the scan restoration and 3D human body model creation, the thermal insulation values of the selected clothing ensembles were measured by means of the thermal manikin truly corresponding to the figure of the adult male with 185 cm height and 100 cm chest girth, thus complying to the body dimensions of the scanned human subject. The heat transfer rate was determined by both the material selection and air layers formation in-between material plies, and thus precise volume and area calculations are implicit.

2. Materials and methods

2.1. Material and clothing items selection

In order to study the effects of length to the overall insulation value of the combined clothing ensemble, jacket variants differing from one to another simply in length were to be constructed and produced. For the purpose of the study, male jacket with modular attachable parts was constructed by the CAD Lectra Systemes. The jacket was constructed as Parka model in four variants, with attachable length modules. It was constructed as a loose-fitting jacket to allow the study on the impact of the length as important construction parameter to both the volume and area increase on the final thermal properties.

In order to produce the jacket with sufficient thermal protection against harsher climatic conditions, materials should be tested in order to establish the mass per unit area, the air permeability (AP), the water vapour resistance (R_w), and the thermal resistance (R_t). The mass per unit area was determined according to Standard No. ISO 3801 (ISO 3801:1977) and the air permeability (AP) was determined according to Standard No. ISO 9237 (ISO 9237:1995; Gore et al., 2006). Afterwards, the Kawabata KES-F7 Thermo Labo II apparatus was used to establish the water vapor resistance (R_v) and the thermal resistance (R_t) according to Standard No. ISO 11092 (ISO 11092:2014).

The main idea behind the material testing was to detect the materials, which can be suitable to provide the jackets able to withstand cooler weather with the ambient temperatures above −5 °C and below 6 °C (EN 14058:2017; Špešić et al., 2020; ISO 7730:2005). The thermal resistance of selected materials should be in the range from 0.0387 to 1,6129 Clo. PTFE laminated and tightly woven fabrics were used as they have a higher vapour transport rate than those without lamimation (Song, 2011).

The materials testing parameters (Table 1 and 2):
Table 1. Jackets’ materials testing

| Material | Mass per unit area [kg/m²] | Air permeability AP [J/m²s] | Water vapour resistance $R_{wv}$ [m²Pa/W] | Thermal resistance $R_{th}$ [m²K/W] | Thermal resistance $R_{ct}$ [Clo] |
|----------|-----------------------------|-----------------------------|-------------------------------|---------------------------------|---------------------------------|
| outer three—layered laminate in twill weave | 0.189 | 0 | 9.38 | 0.071 | 0.46 |
| lining in plain weave | 0.055 | 121.4 | 10.02 | 0.068 | 0.44 |

the mass per unit area,

an air permeability—AP,

the water vapour resistance—$R_{wv}$ and

the thermal resistance—$R_{ct}$ at RH = 60%.

When designing cold-protective outermost clothing items it is important to construct loose-fitting clothing items to trap enough still air beneath the clothing since the Havenith’s study showed that tight-fitting clothing items provides as much as 6–31 % lower insulation than loose-fitting (Havenith et al., 1990). The outer shell in constructed jacket was the three layered laminate in twill weave constructed in a manner that outer layer was 100 % polyester (PES), middle layer was polytetrafluoretilen membrane (PTFE) protected with polyurethane particles (PU) and inner layer, close to body, was also 100 % PES. The lining was then added to the inner part of the jacket composing from plain weave 100 % PES fabric. Breathable PTFE membrane combined as middle layer is windproof while at the same time keeps water vapour permeable, which allows evaporative cooling to ambient environment.

The jacket was constructed to fit adult males with the height ranging around 184 cm, chest girth ranging from 98 to 102 cm, waist girth ranging from 80 to 83 cm and hip girth ranging from 99 to 102 cm. In the later part of the study, human male subject was chosen in order to provide actual basis in 3D scanning upon above chosen body dimensions, which correspond to the exact measures of the thermal manikin for thermal insulation studies. Each jacket variant (B1 to B4) was 20 cm longer than the previous one. The jacket was constructed as the modular clothing item, with upper main module, and four attachable modules which serve for length increase.

Since jacket loses much of its thermal insulation properties when exposed to water since the heat conduction is more pronounced, jackets were produced with breathable waterproof three layered laminates, simultaneously sealing all of the seams by waterproof tapes. The microporous

Table 2. Jacket’s construction parameters

| Variant | Basic module +1 | Basic module +2 | Basic module +3 | Basic module +4 |
|---------|-----------------|-----------------|-----------------|-----------------|
| Symbol  | B1              | B2              | B3              | B4              |
| Chest   | 124             |                 |                 |                 |
| Waist   | 124             |                 |                 |                 |
| Length  | 68              | 88              | 108             | 128             |
PTFE membrane, set as middle layer, allows the perspiration of sweat from the inside of the garment microclimate, but are too small for liquid water such as rain to enter the jacket.

To conduct the study, basic whole-body ensemble was formed combining under-pants, under-shirt, pair of socks, jeans, and male shirt. All of the underlying clothing items were made from 100% cotton and tested as well. The clothing ensemble BE0 was the control ensemble without the jacket added on top, while the other ensembles varied only in the jacket variant added to the basic combination (named BE1 to BE4).

2.2. 3D scanning and reverse engineering
The accurate 3D scanning along with 3D CAD reverse engineering was conducted in order to fully reconstruct the complex geometry of dressed human body, which allows precise calculations of the area and volume of the selected whole-body clothing ensembles. The human subject with 185 cm height and 100 cm chest girth, thus complying to the body dimensions of the thermal manikin, was scanned in firm standing position imitating the thermal manikin measurements, wearing the produced jackets’ variants.

The 3D laser body scanner Vitus Smart XXL (Human Solutions GmbH, Germany) and 3D CAD system Geomagic Design X software (3D Systems, North Carolina, USA) were used to perform a detailed analysis of clothing geometric parameters such as jacket’s area and overall volume. In this study, the CAD systems were used reversely to provide accurate and detailed geometric data from actual designed jackets. The dressed body scanning, enabling the laser-scanning triangulation method to acquire 3D images with a stripe of light being emitted from eight laser diodes onto the scanning surface and recording by CCD camera attached to four scanning heads, made it possible to acquire information of the scanned object surface.

The volume quantification, formed between the layers of clothing items and the body, could be performed by comparing processed human body models (Špelić et al., 2018). The same applied when measuring the area increase due to jacket’s length enlargement. The 3D scanning provided mesh model as output lacking any object information besides the position of the triangles that define the shape. The meshes generated by 3D scanning were imported into the CAD software to extract the shape of the scan in order to create a solid model that is editable by CAD tools. The polygonal mesh generation representing the surface quality was done by the scan post processing, enabling the precise volume and surface area calculations. The scan post processing is basically the scan reconstruction in order to obtain realistic 3D models and it is called the reverse engineering or modelling. By using the remaining polygons, complex geometry can be restored through scan reconstruction made by 3D CAD software. The complex geometry of the human body was restored in stages since the automatic re-modelling is currently impossible. Multiple scanned obj. formats were imported and aligned by the Geomagic Design X software and then processed and reconstructed. The first step was to get a combined single fused mesh to perform manual reconstruction through stages to restore many of the surface features of the clothing complicated geometry. As the scanned dressed human body has a complicated geometry, many of the surface and the mesh features were imperfect or missing and should be reconstructed using the remaining polygons (Špelić et al., 2018). Once the 3D model is finished, it can be exported or saved for further usage. In this case, precise volume and area calculations are to be obtained.

2.3. Non-contact infrared assessment of jacket design
The FLIR ThermaCAM™ P65 mobile thermographic system that uses the long wave infrared spectral range (LWIR) of wavelengths up to 7.5 to 13 µm was used to detect eventual heat losses between the basis of the jacket and attachable modules. The lenses project the image of the object onto a microbolometer at a resolution of 640 × 480, 384 × 288, and 320 × 240 pixels. The electrical signal from the detector (microbolometer) is later processed by the internal electronics of the camera system.
Since the emissivity defines the ratio of the emitted thermal energy relative to that of a perfect emitter at the same temperature and wavelength and under the same viewing conditions, different materials heated to the same temperature tend emit infrared energy at different rates. The emissivity for human skin is therefore usually set at 0.98, but if the emissivity is set incorrectly, the possibility of device error increases (Foster et al., 2021). The emission coefficient was therefore simultaneously verified for both skin and jackets by measuring the skin or jacket’s surface temperature using the surface temperature sensors with precision ± 0.1 °C and operating temperature range from 25 °C to 40°C.

2.4. Insulation testing
To acquire thermal insulation values of the produced jackets, thermal manikin testing was performed on thermal manikin in firm standing position without any additional body movements, hands resting comfortably beside the body, which will later correspond to the position in which the human subject was scanned.

The thermal manikin fully corresponding in size and dimensions to adult human male (the height of 185 cm and chest girth of 100 cm with the surface area of 1.77 m²) is set up within the 8 m³ climatic chamber (2*2*2 m), both produced in cooperation by University of Zagreb Faculty of Textile Technology and company Mikrotakt LLC (Rogale et al., 2014). The thermal manikin consists of 24 sections, each heated to maintain a constant surface temperature of 34 °C. The ambient temperature was set to 20 °C with the relative humidity of 50% and kept constant during the course of each thermal testing. During the trials, the climatic conditions were set to be the air temperature (t₀) was set to 20 ± 0.5 °C, the relative humidity (RH) was set to 36% ±10%, and the air speed (ν₀) was set to 0.4 m/s ± 20% (ISO 9920:2009; ISO 15831:2004).

The jacket’s variants were left to condition for 24 h. When the thermal manikin steady state had been reached (a constant temperature over the surface of the manikin since a fixed amount of the heat energy is supplied to the heaters over time), the test procedure was performed. Single insulation measurement lasted for 20 min and each time the apparatus measured on average 240 measurements. The average effective thermal insulation value was automatically calculated using the parallel model, which calculates the surface area averaged thermal insulation. The surface area averaged thermal insulation is calculated by multiplying the total surface area by the temperature difference and dividing it by the total heat flow from the manikin’s body. The nude manikin test was conducted at the beginning of each manikin trial to test the thermal resistance of the air layer. The thermal insulation values of the garments and the ensembles are expressed as the effective and total thermal insulation with the stationary manikin (Kuklane et al., 2012; Špelić et al., 2019).

The effective clothing insulation of the clothing ensemble, $I_{clo}$ is simply said an increase in insulation provided to a thermal manikin by a whole-body ensemble compared to the nude manikin (Kuklane et al., 2004). The effective insulation of the ensemble, $I_{clo}$ is thermal insulation from the skin surface to the outer clothing surface including enclosed air layers under defined conditions measured with the stationary manikin (without any body movement):

$$I_{clo} = I_T - I_a(clo)$$  \hspace{5cm} (1)

where $I_a$ is the thermal insulation of the boundary air layer with the manikin stationary (clo), and $I_T$ is total thermal insulation of the clothing item (clo). It is calculated subtracting the total thermal insulation of the boundary air layer from the total thermal insulation of the clothing ensemble with the stationary manikin.

The higher the clo number, the more is the insulating value. A value of 1 clo is defined as the amount of clothing required by a resting human to be comfortable at a room temperature of 21 °C.
and equals to 0.155 m²·K/W, while \( 0 \) clo corresponds to a naked person (Kuklane et al., 2012; Song, 2011).

3. Results

3.1. Scan post-processing and geometry calculations
Eight consecutive scanned meshes are provided for each scanned model after 3D body scanning. To start scan reconstruction, three scans taken in the same position should be imported and aligned by Geomagic Design X (Špelić et al., 2021). The second step is to merge the 24 meshes in order to start reconstructing the scans and healing missing areas (Figure 1).

Figure 1. The scan post-processing and reverse CAD engineering.
The multiple scanned OBJ-formats are imported via Geomagic Design X. Three separate scans of each clothed subject dressed in the same selected ensemble were imported and aligned by picking points instead of relying on the auto-alignment. After the scan alignment, they are combined into a single fused mesh. Although the Geomagic Design X software has the ability to automatically clean-up the point cloud data, analyse the mesh and repair the scan, it is impossible to automatically re-mesh the complex geometry of the dressed human body. The reverse modelling and the building are done manually in stages.

The imported obj. files are processed and edited manually through stages (Špelić et al., 2018):

- multiple scan alignment and merging the several meshes into the single fused mesh,
- mesh preparation by filling holes and healing defects,
- reconstruction of the mesh features using the remaining polygons (missing area restoration),
- re-meshing and rewrapping and
- smoothing over the surface of the scans and finally 3D model creation.

After the manual editing phase, the scans were automatically finished by choosing the mesh build-up wizard. Once the model is finished, it can be exported or saved for further usage. When scan reconstruction is over, 3D models of both the jackets' model (Figure 2) and clothing ensemble formed by applying the jacket as the outerwear garment (Figure 3) are built.

Afterwards, area and volume calculations for each built jacket variant was performed by Geomagic Design X, since the current software version allows automatic calculations (Table 3).

By adding second module to the B1 variant, the area was increased by 14.9%, following volume enlargement of 28.2%, Figure 2. Adding another module resulted in area increase of 26.7% in comparison to B1 variant or 13.8% if compared to B2 variant. The volume increased was higher than observed in the first case, when comparing variants B1 and B2. B3 variant showed volume increase for 61.2% in comparison to B1 variant, or 25.8% when compared to B2 variant. The
| Jacket variant | Area (m²) | Jacket variant area increase in comparison to B1 (%) | Jacket variant area increase in comparison to prior variant (%) | Volume (m³) | Jacket variant volume increase in comparison to B1 (%) | Jacket variant volume increase in comparison to prior variant (%) |
|----------------|-----------|-----------------------------------------------------|---------------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------------------------------------------|
| B1             | 1.51      | -                                                   | -                                                             | 0.08        | -                                                   | -                                                             |
| B2             | 1.73      | 14.9                                               | 14.9                                                          | 0.11        | 28.2                                               | 28.1                                                          |
| B3             | 1.97      | 26.7                                               | 13.8                                                          | 0.13        | 61.2                                               | 25.8                                                          |
| BE             | 2.26      | 49.6                                               | 14.5                                                          | 0.16        | 93.3                                               | 19.9                                                          |
highest area and volume increase were showed in the case of the variant B4, where four length modules were added, leading to area increase of 49.6% and volume increase of 93.3% in comparison to variant B1. When we compare B4 to B3 variant, the area increase is 14.5%, while the volume increase is 19.9%.

The basis for the clothing ensemble was made by dressing the subject, and later the thermal manikin into layering manner, similar to the standard everyday clothing worn during transitional cooler seasons (Figure 3). The first layer of clothing consisted from underpants made from knitted 100 % cotton fabric, undershirt (made from knitted 100 % cotton fabric) and socks made from 100% knitted cotton. The second layer of clothing was made by combining cotton jeans in twill weave and classical cotton shirt in plain weave. The produced jackets served as third layer, dressed over the basic clothing combination as seen in Table 4 with jacket outer fabric being a three layered laminate in twill weave and jacket inner lining in plain weave. The measured physical characteristics of materials selected for jacket production and garments were mass per unit area in kg/m², air permeability (AP) in l/m²s, water vapour resistance (Rw) in m²Pa/W, and thermal resistance (Rct) in Clo.

The mean volumes and the surface areas of the reconstructed models, which represent the human subject dressed in the selected clothing ensembles, were calculated. One CAD human body model was reconstructed by merging three repeated consecutive scans. Afterwards, the area and the mean volume of each clothing ensemble was calculated. Basic clothing combination without jacket was named BE0, while other ensembles accompanied with jackets are named according to the variant added (BE 1 to BE 4), Table 5.

The increase in the length caused simultaneous volume amplification underneath clothing ensemble. The percentage of the volume increase for the ensembles was calculated in comparison to referent clothing ensemble BE0 (without jacket) as seen in Table 5. By adding 3 length modules to the basic jacket variant, or 60 cm in length since each module adds for 20 cm, will increase overall ensemble’s area for 26.5%, thus simultaneously increasing the overall ensemble’s volume.

![Figure 5. Temperature rise at the cuff and neckline region observed by mobile thermographic system.](image)

| Selected materials | Mass per unit area (kg/m²) | AP (l/m²s) | Rwet (m²Pa/W) | Rct (m²K/W) | Rct (Clo) |
|--------------------|---------------------------|------------|---------------|-------------|----------|
| underpants fabric  | 0.134                     | 1121.2     | 7.97          | 0.112       | 0.73     |
| undershirt fabric  | 0.157                     | 1895.2     | 8.66          | 0.115       | 0.74     |
| shirt fabric       | 0.121                     | 331.8      | 7.38          | 0.084       | 0.54     |
| jeans fabric       | 0.425                     | 48.4       | 11.17         | 0.099       | 0.64     |
Table 5. Area and volume calculation by Geomagic Design X for the reconstructed 3D models of clothing ensemble accompanied by jackets’ variants

| Ensemble accompanied by jacket variant | Area (m²) | Ensemble area increase in comparison to BE0 (%) | Ensemble area increase in comparison to prior ensemble (%) | Volume (m³) | Ensemble volume increase in comparison to BE0 (%) | Ensemble volume increase in comparison to prior ensemble (%) |
|----------------------------------------|-----------|-------------------------------------------------|----------------------------------------------------------|-------------|-------------------------------------------------|----------------------------------------------------------|
| BE0 (no jacket variant added)          | 2.26      | -                                               | -                                                       | 0.10        | -                                               | -                                                       |
| BE1                                    | 2.49      | 10.4                                            | -                                                       | 0.12        | 22.0                                            | -                                                       |
| BE2                                    | 2.68      | 18.7                                            | 7.5                                                     | 0.13        | 34.7                                            | 10.4                                                    |
| BE3                                    | 2.79      | 23.5                                            | 4.0                                                     | 0.16        | 55.5                                            | 15.4                                                    |
| BE4                                    | 2.85      | 26.5                                            | 2.5                                                     | 0.18        | 75.5                                            | 12.9                                                    |

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for almost 75.5%. Although adding a single length module increases the final ensemble's area value by merely around 10.4%, adding two consecutive modules will account for 18.7% of ensemble area increase.

The ensemble's overall volume was increased for more than 22.0% in comparison to referent clothing ensemble BE0 when single length module was added, 3.4.7% in the case of BE2 to BE0 comparison, and by adding three length modules the volume increase was as much as 55.5% in comparison to referent clothing ensemble BE0.

The jacket variant B4, which was the longest and accounted for as much as 2.5% of ensemble's area increase when compared to the predecessor BE3 ensemble's variant instead of 0.7% of area increase, which was the case in comparison between former two adherent ensemble's variants BE2 and BE1, or 4.0% of area increase between two adherent ensemble's variants BE3 and BE2. The ensemble's volume was increased for more than 10% in the case of BE2 to BE1 comparison, 15.4% in the case of BE3 to BE2 comparison and 12.9% in the case of BE4 to BE3 comparison.

3.2. Thermal imaging analysis
Thermographic images showed the maximum and minimum surface temperatures of the jackets as well as possible heat dissipation through the neckline or cuffs. Figures represent the processed thermograms with minimum and maximum temperature of characteristic points on the surface of the jacket (Figure 4). The maximum temperature value was recorded in the shoulder region, while the minimum surface temperatures were recorded at the lower back region.

When analysing the thermographic images, higher temperatures were also recorded in the cuff and neckline regions, which also points to warm air channelling from the inside of the microclimate to the outer environment as seen in Figure 5.

This points to conclusion that both neck opening and cuffs around the wrist should be fully tightened in order to prevent bodily heat maintained in the microclimate area beneath the jacket from dissipating to the environment. The infrared thermography was also used to test the juncture between the basis of the jacket and the attachable modules and no heat leakages were observed.

3.3. Thermal insulation
The thermal insulation values of the selected clothing ensembles are expressed as effective (I_{clo}) and total (I_{j}) insulation. The ensemble BE0 without any jacket added on top of the basic clothing garments worn together, was taken as the control ensemble. Ensembles BE1 to BE4 are formed by adding one of the selected variants (B1 to B4) as the outerwear garment covering the basic clothing items combined together in usual manner of dressing as described earlier. The first

Figure 4. The recorded thermogram.
Figure 6. 3D surface plot correlation presenting effective thermal insulation dependence to area and volume enlargement.

Figure 7. Correlation presenting effective thermal insulation dependence to area enlargement.

Polynomial correlation between assembly’s effective insulation increase (%) in static conditions against assembly’s area increase (%)

- Assembly’s effective insulation increase (%) in static conditions (polynomial): $y = 32,1439-1,2178*x+0,0595*x^2$
- Assembly’s effective insulation increase (%) in static conditions (linear): $y = 14,7488 + 0,9489*x$; $r = 0,9624$; $p = 0,0376$
layer of clothing consisted from underpants, undershirt and socks. The second layer of clothing consisted of jeans and classical male shirt. The produced jacket variants were dressed as outerwear third layer, dressed over the basic clothing combination.

Table 5 shows the measured values of the effective thermal insulation for each whole-body clothing ensemble. All insulation values were obtained by thermal manikin resting in firm standing position without any limb movements. Each thermal manikin trial lasted for 20 min and during that time span 240 single measurements were recorded. Table 6 shows mean value of the effective and total thermal insulation for the 20-min measurement interval taken by means of the stationary thermal manikin.

The thermal insulation increase for the overall clothing ensembles were calculated in comparison to nude manikin test. The nude manikin test for the ensembles' insulation measurements was performed for the whole body. The percentage of the thermal insulation increase were calculated in comparison to basic clothing ensemble BE0 without any jacket variant added. The observed data points to conclusion that the jackets' length extension will correspondingly induce the thermal insulation increase due to the larger amount of the body surface area covered by the clothing.

4. Discussion
Since thermal comfort prediction is highly complex area of study involving a wide range of parameters, often very subjective, information on thermal insulation is imminent. De Dear attempted creating first global database covering six groups of identifiers influencing thermal comfort: basic identifiers (date and time of measurement, building code, demographic features); thermal questionnaire specificities (thermal sensations, preferences, metabolic rates, insulation values); climate variables (air temperature, velocity, turbulence, humidity, etc.); calculated thermal comfort indices (operative temperature, predicted men vote, predicted percentage dissatisfied, etc.); personal environmental control (covering adaptive voluntary opportunities such as opening
Table 6. The effective and total thermal insulation values of ensemble's variants (BE0 to BE4) obtained by thermal manikin resting in firm standing position where BE0 is control ensemble without any jacket variant added as the outwear garment

| Minute | Effective thermal insulation, \( I_{\text{e}} \) (clo) | Total thermal insulation, \( I_{\text{T}} \) (clo) |
|--------|---------------------------------|---------------------------------|
|        | BE0 | BE1 | BE2 | BE3 | BE4 | BE0 | BE1 | BE2 | BE3 | BE4 |
| Average | 0.89 | 1.12 | 1.16 | 1.21 | 1.26 |
| Insulation increase in comparison to BE0 (%) | - | 25.9 | 30.2 | 36.4 | 41.7 |
|       | 1.38 | 1.61 | 1.64 | 1.70 | 1.75 |
|       | -   | 16.8 | 19.5 | 23.5 | 27.0 |
and closing windows, doors shut, thermostat control, etc.) and outdoor meteorological observations. One of the most puzzling thermal comfort parameters with high degree of estimation errors is clothing insulation, especially considering field estimates. In order to minimize degree of errors, reasonably accurate measurements on thermal insulation require thermal manikin testing in a controlled climatic chambers (De Dear, 1998).

Results given by the thermal manikins are expressed as total thermal insulation ($I_T$) and effective thermal insulation ($I_{cl}$). Total thermal insulation of the clothing ensemble ($I_T$) is defined as thermal insulation from the body surface to the environment including all clothing, enclosed air layers and boundary air layer under reference conditions and measured with the thermal manikin stationary. Effective thermal insulation of the clothing ensemble ($I_{cle}$) is increase in insulation provided to a thermal manikin by a clothing ensemble compared to the nude manikin insulation (ISO 2009:2009; ISO 15831:2004). But in order to fully comprehend the impact of geometrical features of clothing on clothing thermal insulation, one has to consider the basic clothing insulation, also known as intrinsic clothing insulation ($I_o$). Basic thermal insulation of clothing is defined as thermal insulation from skin surface to the outer clothing surface including enclosed air layers under reference conditions measured with thermal manikin stationary. Basic thermal insulation is calculated as difference between total thermal insulation reduced by ratio of insulation of the boundary air layer ($I_b$) and the clothing area factor ($f_{cl}$). The surface of the clothed manikin is greater than the body surface area (or in that manner nude manikin) and this relation is expressed as clothing area factor. Basically, clothing fit and posture affects clothing area factor ($f_{cl}$) and correspondingly affects basic thermal insulation of clothing ($I_o$). In other words, the clothing area factor is the correction factor and accordingly explains the heat transfer changes due to increase in surface area of the clothed body to the environment. The clothing area factor is affected by clothing fit and posture as difference in garment layering, fit and length affects the volume of air trapped inside the ensemble microclimate while at the same time affecting the heat transfer measured as clothing thermal insulation by means of the thermal manikin (Kakitsuba, 2004).

By combining formulas defining the total clothing insulation:

$$I_T = I_{cl} + \frac{I_o}{f_{cl}}$$

and basic clothing insulation:

$$I_{cl} = I_{cle} + I_o \cdot \left(1 - \frac{1}{f_{cl}}\right)$$

The total thermal insulation becomes:

$$I_T = I_{cle} + I_o \cdot \left(1 - \frac{1}{f_{cl}}\right) + \frac{I_o}{f_{cl}} = I_{cle} + I_o - \frac{I_o}{f_{cl}} + \frac{I_o}{f_{cl}} = I_{cle} + I_o$$

explaining how both basic, effective and total thermal insulation are affected by clothing area factor, i.e. by clothing area.

But clothing insulation is not solely dependent on the effective area changes altering heat exchange due to dressing-up. Additional clothing items added to the basic ensemble also change the volume of air trapped underneath the clothing layers. Since the total thermal insulation of clothing is defined as thermal insulation from the body surface to the environment including all clothing, enclosed air layers and boundary air layer under reference conditions, one has to consider the changes in volume of the air enclosed beneath the clothing. The study has proven that the
length of the outerwear jackets, considerably affects the ensemble’s area and volume and substantially leads to increase in the thermal insulation value of the whole-body clothing ensembles.

As Wilson et al. stated air and air spaces are invisible addition to thermal insulation since the differences in the thermal insulation of garments have been related to differences in fit (i.e. the size of the air space), garment length and the amount of body surface covered by garments (Wilson et al., 2002). Most of the studies (Bouskill et al., 2002; MacRea et al., 2011; McCullough et al., 1985) simply measured the total thermal insulation without quantifying the volume of the air beneath the clothing or clothing area affecting the heat exchange with the environment. Daenen et al. (2002) and Lee et al. (2007) were the first ones to try to quantify the volume of air layers beneath clothing by using 3D phase-shifting Moiré topography. The starting point in using 3D scanning technology was done by Lu et al. (2013) and Frackiewicz-Kaczmarek et al. (2015). Those studies involved the scanning of the motionless manikin by 3D scanner and scan post processing in order to compare cross-section at different positions. The average air gap size was calculated by aligning two scans and comparing horizontal slices at different positions (Lu et al., 2013) or by super-imposition of the scans, splitting scans into particular zones and determining the distance between super-imposed surfaces recognized as the air gap thickness and the contact area (Frackiewicz-Kaczmarek et al., 2015). But none of the previous studies used precise CAD reverse engineering in order to calculate volume or area of the dressed human body and compare the results to nude human body as done by Petrak et al. (2018). Further studies (Špelć et al., 2021, 2019, 2018) have proven the combination of 3D scanning and 3D CAD reverse engineering more precise tool for quantification of both the clothing volume and the area. In previous study, effects of the jackets’ fit and the microclimatic air volume on the thermal insulation values of both the jackets and the overall clothing ensembles were investigated with the stationary manikin and computed by the parallel model. It was proven that the overall ensembles’ insulation increased due to the microclimatic air volume enlargement (Špelć et al., 2021). However, none of the previous studies quantified the effects of the outerwear clothing items’ length on the overall ensembles’ insulation.

When analysing the results obtained by current study, it is obvious that the increase in the length of the jacket correspondingly causes the area and volume increase, while simultaneously increasing the final insulation value measured by thermal manikin.

The results given in Table 6 showed that the area increase for 10.4% resulted in 22.0% volume increase for the BE1 ensemble, when adding B1 variant to the basic whole-body ensemble (BE0), while the effective thermal insulation rose for 25.9%. 18.7% area increase resulted in 34.7% BE2 ensemble volume increase when adding B2 variant to the basic whole-body ensemble, while the effective thermal insulation rose for 30.2%.

Further area increases in amount of 23.5%, resulted in the ensemble’s BE3 volume increase for 55.5% when compared to basic whole-body ensemble and substantially resulting in the effective thermal insulation for 36.4%. By adding final length module and increasing the length of the jacket to the maximum value, resulted in area increase for as much as 26.5%, thus accounting for 75.5% of the volume increase and 41.7% of the effective thermal insulation increase.

The length increase resulted in increase to the surface area of the clothing available for the heat exchange. The correlation between the increase in the value of the effective thermal insulation against ensembles’ overall area and volume enlargement is shown in Figure 6.

The correlation analysis showed strong positive linear correlation for both comparisons (effective thermal insulation to area and effective thermal insulation to volume) in the case of the whole-body ensembles with one of the jacket variants added.

Considering the effects of the length of the jacket to the effective thermal insulation of the whole-body clothing ensemble, the volume of BE2 ensemble was 10.4% bigger than the volume of
BE1 ensemble, while the area of BE2 ensemble was 7.5% bigger than the area of BE1 ensemble, which accounted for effective thermal insulation increase for 3.4% in the case of BE2 compared to BE1. The volume of BE3 ensemble was 15.4% enhanced when compared to BE2 ensemble, while the area was 4.0% bigger, followed by the effective thermal insulation increase for 4.8% when comparing both ensembles. The volume of BE4 ensemble was 12.9% enhanced, while the area was 2.5% enhanced in comparison to BE3 ensemble and this enlargement resulted in the effective thermal insulation increase for 3.9% in reference to BE3 ensemble. As further statistical analysis showed the strong polynomial correlation is seen in the case of the effective thermal insulation dependence to the area change (Figure 7), while the strong linear predictive relationship is seen in the case of the effective thermal insulation dependence to the volume change (Figure 8).

The strong linear predictive relationship is seen in the case of the effective thermal insulation dependence to the area change. The calculated R-square ($R^2$) is 0.9263. However, as seen in Figure 7, polynomial correlation leads to far better causal statistical relationship explaining the effective thermal insulation dependence to ensemble's area changes.

In the case of effective insulation dependence to the volume increase, the correlation analysis showed strong positive linear relationship between ensemble's insulation increase to the ensembles volume increase, measured with the thermal manikin stationary (Figure 8). The scatter plot points to strong linear correlations since $R^2$ is 0.9979.

5. Conclusions
The effects of the length of the jacket added as the outerwear clothing item on the overall thermal insulation values for the combined clothing ensembles were investigated combining CAD reverse engineering and thermal manikin measurements. The increase in the length of the jacket will substantially led to increase in the 3D body model area and volume. The effective thermal insulation values were obtained by the stationary manikin and computed by the parallel model. It was found that the length of the jacket has a tremendous impact on the final geometry of the 3D model of the clothing ensembles, finalized by the scan post processing and reconstruction in order to obtain realistic 3D models. The increase in jacket variant length, which has been worn as the outerwear garment covering basic clothing items, led to area increase in amount of 10.4 to 26.5% and overall volume increase from 22 to 75.5%. The present study has also demonstrated that the jackets’ length has a big effect on the dry thermal insulation value of the three layered clothing ensembles. The increase in the effective thermal insulation value was above 25% and led to more than 4% extra growth for 20 cm length enlargement. Further length’s increase for 40 cm led to effective thermal insulation increase for 36.4%, while the maximum length’s increase for the observed jacket variant in amount of 60 cm leads to the effective thermal insulation increase for as much as 41.7%. Understanding the classical clothing items and the impact of materials, construction and other elements on final thermal insulation properties can serve as a basis for further development of thermal protective and intelligent clothing items with adaptive thermal insulation properties.

The dynamic testing should be performed differing in walking and wind speed in order to validate the possibility of the effective thermal insulation decrease since the impact of ventilation is presumably more pronounced. There is also obvious lacking in evidence on length increase influencing the effective thermal insulation for various other fabric types and garment selection (skirts, dresses, traditional woolen coats, etc.). The current challenge is to link 3D scanning and thermal insulation measurements under dynamic conditions due to limitations to the existing measuring methods and 3D scanner performance, which assumes subjects to stand still in precise postures and often brings a limitation in a form of scanning area. Consecutive scanning over longer period of time with human subjects walking is still impossible and therefore doesn't allow insights to changes in air layers within the clothing microclimate due to compression caused by limb movements or higher wind speeds.
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Author details
Ivana Špelić 1
E-mail: ivana.spelic@tfi.unizg.hr
ORCID ID: http://orcid.org/0000-0002-4069-5455
1 Department of Basic Natural and Engineering Sciences, University of Zagreb Faculty of Textile Technology, Prilaz Baruna Filipavića 28a, Zagreb 10000, Croatia.

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References
Bouskill, L. M., Havenith, G., Kuklane, K., Parsons, K. C., & Withey, W. R. (2002). Relationship between clothing ventilation and thermal insulation. AJHA Journal, 63(3), 262–268. https://doi.org/10.1080/15428110208984712.

BS EN 14058:2017. Protective clothing — garment for protection against cool environments.

Cheng, Y., Niu, J., & Gao, N. (2012). Thermal comfort models: A review and numerical investigation. Building and Environment, 47, 13–22. https://doi.org/10.1016/j.buildenv.2011.05.011.

Daanen, H., Hatcher, K., & Havenith, G. (2002). Determination of clothing microclimate volume. In: Y. Tochihara & T. Ohnaka, (eds.), Proceedings of the 10th International Conference on Environmental Ergonomics 2002 September 23–27 (pp. 665–668). Fukuoka (Japan): Kyushy Institute of Design.

De Dear, R. J. (1998). A global database of thermal comfort field experiments. ASHRAE Transactions, 104( pt. 1B), 1141–1152. https://www.osti.gov/biblio/649444-
global-database-thermal-comfort-field-experiments.

Eryuruk, S. H. (2010). Effects of fabric layers on thermal comfort properties of multilayered thermal protective fabrics. Autex Research Journal, 19(3), 271–278. https://doi.org/10.1515/out-2018-0051.

Foster, J., Lloyd, A. B., & Havenith, G. (2021). Non-contact infrared assessment of human body temperature: The journal temperature toolbox. Temperature. Advance online publication. https://doi.org/10.1080/23328940.2021.1895946.

Frackiewicz-Kaczmarek, J., Psikuta, A., Bueno, M.-A., & Rossi, R. M. (2015). Air gap thickness and contact area in undershirts with various moisture contents: Influence of garment fit, fabric structure and fiber composition. Textile Research Journal, 85(20), 2196–2207. https://doi.org/10.1177/0040517514551458.

Fung, W. (2002). Coated and laminated textiles (1st ed.). The Textile Institute, CRC Press, Woodhead Publishing Limited.

Gore, S. E., Loing, R. M., Wilson, C. A., Carr, D. J., & Niven, B. E. (2006). Standardizing a pre-treatment cleaning procedure and effects of application on apparel fabrics. Textile Research Journal, 76(6), 455–464. https://doi.org/10.1177/0040517506063191.

Gulbinienė, A., Jankauskaite, V., & Kondratas, A. (2011). Investigation of the water vapour transfer properties of textile laminates for footwear linings. Fibres & Textiles in Eastern Europe, 19(3–86), 78–81. http://www.fibtex.lodz.pl/article528.html

Havenith, G., Heus, R., & Lotens, W. A. (1990). Resultant clothing insulation: A function of body movement, posture, wind, clothing fit and ensemble thickness. Ergonomics, 33(1), 67–84. https://doi.org/10.1080/00140139008927094.

Holmér, I. (1989). Recent trends in clothing physiology. Scandinavian Journal of Work, Environment & Health, 15 (Suppl. 1), 58–65. https://www.sjweh.fi/article/1892

ISO 11092:2014. Textiles — physiological effects — measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test).

ISO 15831:2004. Clothing-physiological effects-measurement of thermal insulation by means of a thermal manikin.

ISO 8901:1977. Textiles — Woven fabrics — Determination of mass per unit length and mass per unit area.

ISO 7730:2005. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

ISO 9237:1995. Textiles — Determination of the permeability of fabrics to air.

ISO 9920:2009. Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble.

Kakitsubo, N. (2004). Investigation into clothing area factors for tight and loose fitting clothing in three different body postures. Journal of the Human-Environment System, 7 (2), 75–81. https://doi.org/10.1618/jhes.7.75.

Kuklane, K., Goo, C., Wang, F., & Holmér, I. (2012). Parallel and serial methods of calculating thermal insulation in European Manikin standards. International Journal of Occupational Safety and Ergonomics, 18(2), 171–179. https://doi.org/10.1080/10803548.2012.11076926.

Kuklane, K., Sandsund, M., Reinertsen, R. E., Tochihara, Y., Fukazawa, T., & Holmér, I. (2004). Comparison of thermal manikins of different body shapes and size. European Journal of Applied Physiology, 92(6), 683–688. https://doi.org/10.1007/s00421-004-1116-3.

Lee, Y., Hong, K., & Hong, S.-A. (2007). 3D quantification of microclimate volume in layered clothing for the prediction of clothing insulation. 3D quantification of microclimate volume in layered clothing for the prediction of clothing insulation. Applied Ergonomics, 38(3), 349–355. https://doi.org/10.1016/j.apergo.2006.04.017.

Li, S., & Sinitskova, E. (2020). Applications to textile composites, Chapter 12. Representative volume elements and unit cells: Concepts, theory, applications and implementation 1st ed. (pp. 371–415). Woodhead Publishing, Elsevier Ltd.

Lu, Y., Song, G., & Li, J. (2013, November 19–20). A novel approach for fit analysis of protective clothing using three-dimensional body scanning. In N. D’Azzaro (Eds.), Book of Proceedings of the 4th International Conference on 3D Body Scanning and Processing Technologies, 3DBODY.TECH 2013 (pp. 327–334). Lugano (Switzerland): Hometrix Consulting, Long Beach (California, USA).

MacRea, B. A., Loing, R. M., & Wilson, C. A. (2011). Importance of air spaces when comparing fabric thermal resistance. Textile Research Journal, 81(19), 1962–1965. https://doi.org/10.1177/0040517510395999.

McCullough, E. A., Jones, B., & Huck, J. (1985). A comprehensive database for estimating clothing insulation. ASHRAE Transactions, 91, 29–47. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.258.8876&rep=rep1&type=pdf.

O’Keeffe, C., Pickard, L. R., Cao, J. M., Allegri, G., Partridge, I. K., & Ivanov, D. S. (2021). Multi-material braids for
Špelić, I., Rogale, D., & Mihelić-Bogdanić, A. (2019). The laboratory investigation of the clothing microclimatic layers in accordance with the volume quantification and qualification. The Journal of the Textile Institute, 110(1), 26–36. https://doi.org/10.1080/00405000.2018.1462087.

Špelić, I., Rogale, D., & Mihelić-Bogdanić, A. (2020). The study on effects of walking on the thermal properties of clothing and subjective comfort. Autex Research Journal, 1(3), 228–243. https://doi.org/10.2478/aut-2019-0016.

Špelić, I., Rogale, D., Mihelić-Bogdanić, A., Petrok, S., & Mohnić Naglić, M. (2018). Changes in ensembles’ thermal insulation according to garment’s fit and length based on athletic figure. Fibers and Polymers, 19(6), 1278–1287. https://doi.org/10.1007/s12221-018-1074-8

Steinach, M., & Gungo, H.-C. (2015). Cold environments chapter 6. Human physiology in extreme environments 1st ed (pp. 215–272). Academic Press, Elsevier Inc.

Sybilská, W., & Korycký, R. (2010). Analysis of coupled heat and water vapour transfer in textile laminates with a membrane. Fibres & Textiles in Eastern Europe, 18(3–80), 65–69. http://www.fibtext.ied.tl/el/fibtext/Fib_text_12ju46td3kbcicrco.pdf

Wang, F., & Gao, C. Eds. (2014). Protective clothing: Managing thermal stress. 1st ed. The Textile Institute, Woodhead Publishing Limited, Elsevier Williams, J. T. Eds. (2009). Textiles for cold weather apparel. 1st ed. The Textile Institute, CRC Press, Woodhead Publishing Limited

Wilson, C. A., Loing, R. M., & Carr, D. J. (2002). Air and air spaces - the Invisible addition to thermal resistance. Journal of the Human-Environment System, 5(2), 69–77. https://doi.org/10.1618/jhes.5.69

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