Research Article

Thermo-Physiological Comfort Property of Military Combat Boot Material for Hot and Cold Climatic Conditions

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Military combat boots require materials that balance thermo-physiological comfort in hot and cold climates. The aim of this research was to analyze the thermo-physiological comfort properties of military combat boot materials in extreme hot and cold conditions to maintain optimal functionality. One-way ANOVA and Tukey’s pairwise comparison statistical tests were conducted, resulting in a p value less than 0.05, indicating statistically significant differences between the materials’ air permeability, water vapor permeability, and thermal resistance. For hot climates, plain nylon canvas four-thread upper and warp-knitted lining fabrics had thermo-physiological indexes of 8.15 and 119.5, respectively. The high airflow and moisture wicking of these materials kept feet cool and dry. For cold climates, chrome-tanned waterproof upper leather and sheepskin lining leather had thermo-physiological indexes of 33.33 and 24.18, respectively. Their waterproofing and insulation maintained warmth and dryness. The thermal properties of the sample uppers were determined to evaluate breathability and insulating ability for hot and cold climatic conditions. The selection of proper materials for military combat boots in different climates is the main approach to reducing foot heat, foot pain, and foot injuries under any condition, providing comfort for wearers, and protecting feet against harsh conditions.

1. Introduction

Military combat boots are an essential piece of equipment for soldiers operating in varied environmental conditions. The boots provide comfort and protection for the feet and ankles during demanding combat maneuvers while allowing a full range of motion. They have particular qualities that make it possible for soldiers to perform their jobs well. Military combat boots frequently provide features including comfort, traction, protection, better stability, and durability [1]. However, the thermo-physiological comfort of the boot material is a critical factor impacting soldier performance, health, and safety in different environmental conditions. High-quality materials able to survive challenging circumstances, such as severe terrain or extreme weather, are used to create durability. These boots’ soles provide a good grip on the ground, which lowers the chance of sliding and falling. Combat boots are made in a way that provides the feet with a lot of protection from harm or damage that could occur on the battlefield [2].

The human body maintains a narrow internal temperature range for optimal functioning. However, strenuous physical activity and extreme ambient temperatures push the body outside its comfort zone. Sweating and altered blood flow attempt to restore equilibrium, but thermal stress can impair physical and cognitive performance. Prolonged strain increases the risk of heat and cold illnesses. Thus, the boot material’s insulation, breathability, and moisture absorption and release properties directly impact the microclimate around the foot and the thermal comfort of the wearer. Ensuring the militarily effective thermo-physiological performance of combat boots across diverse operating environments is vital due to thermal-physiological characteristics, including their capacity to control the body’s temperature and moisture [3].
The defining thermo-physiological attributes of combat boot materials include thermal insulation, moisture vapor permeability, liquid (perspiration) absorption rate, and drying rate. Thermal insulation indicates the material’s ability to resist heat flow and is measured by thermal conductivity or insulation values. Low-conductivity materials better retain body heat in the shoe microclimate during cold exposure [4]. Moisture vapor permeability quantifies air and water vapor flow through the material. High permeability allows heat-liberating evaporation of sweat from the skin surface, which enhances cooling [5]. A higher water vapor permeability for military combat boots implies that the boots permit more moisture to escape from the feet, helping keep the feet dry and comfortable. The liquid absorption rate determines how quickly perspiration is pulled into the boot’s material structure from the foot. Rapid absorption prevents the pooling of moisture. The drying rate measures the speed at which absorbed moisture can be dissipated into the outside environment. Fast moisture evaporation restores the material’s insulation properties and comfort after wetting. The thermo-physiological comfort index (TPCI) of military combat boots would be a gauge of how well the boots strike a balance between these three elements to give the wearer the maximum level of comfort in a variety of situations and climatic circumstances. The wearer would enjoy comfort wearing a boot with a high thermo-physiological comfort index because it would have a good balance of heat resistance, air permeability, and water vapor permeability [6].

The environmental conditions dictate which attributes are optimal. Hot environments require boots that insulate less but readily transmit moisture vapor and liquid and then quickly dry. Cold conditions demand greater insulation but also sufficient breathability for vapor to escape. Military boot materials must balance these divergent needs. The prevailing climate interacts with activity levels to produce varying degrees of thermal and moisture strain. The ideal combat boot manages this strain for maximal soldier effectiveness and safety in both hot and cold settings. Combat boots are developed to suit a variety of performance needs, such as those for comfort, support, protection, and durability, and they can do this by utilizing various materials. Cold combat boots can be developed from leather, rubber, and synthetic fiber, while hot combat boots can be developed from textile upper materials, foam, mesh, and breathable materials. EVA foam, gel inserts, and cushioning materials can offer support, while Kevlar, steel, and reinforced materials can offer protection [4]. Manufacturers can produce combat boots that satisfy the requirements of military personnel in diverse circumstances and settings by combining these materials. In the evolution of modern military combat boots, various material types have been employed, each possessing unique advantages and shortcomings. Leather offers a robust structural framework, with inherent moisture management properties. However, increasing leather thickness proportionately reduces vapor permeability and liquid absorption. Textile composites can be engineered with superior precision for thermal insulation, breathability, and moisture control. Nevertheless, manufacturing processes restrict the attainable structures and performance attributes. High-performance boot linings and membranes have additionally been integrated to improve moisture transfer and insulation capabilities.

The military combat boot not only affects the materials used but also the interactions between personal protective equipment (PPE) systems, the human foot, and the external environment, which can impact human function, injury prevention and preserving mobility, and comfort [6]. Boots and socks can provide support and cushioning, protect against physical and environmental hazards, and reduce foot fatigue and pain. To optimize protection, support, and comfort for the foot across diverse locales and activities, appropriate PPE selection, fitting, and usage are critical [7]. For soldiers spending extensive time in abrasive environments, thermal comfort in combat boots is essential. The boots must have adequate insulation, ventilation, and moisture management properties to achieve this. The boots should be durable enough for military use and provide a comfortable fit. The thermal characteristics of boot materials can be evaluated via tests such as thermal conductivity and moisture vapor transmission rate. Providing soldiers with optimal thermal comfort enables more effective and safe operations.

In designing military combat boots, boot designers and researchers often neglect to account for the thermo-physiological comfort index of materials, determined by measuring the thermal conductivity, air permeability, and water vapor permeability of the upper and lining raw materials. This oversight results in hot feet, injuries, and discomfort. Analyzing the thermo-physiological comfort indices of raw materials used in military combat boots for hot and cold climates is the primary research objective of this study [8]. Hot climate combat boots are fabricated from thermally conductive, vapor-permeable, and breathable upper and lining materials [4]. Military combat boots are equipped with a pressure release valve that can be adjusted to regulate internal air pressure during high-altitude operations. Appropriate materials for cold-climate combat boots are selected, whereas cold-climate military combat boots are constructed from higher thermal resistance materials. The thermo-physiological comfort index of a material is calculated based on heat resistance, water vapor permeability, and air permeability under various climatic conditions [7]. In contrast to most prior work studying casual footwear, this research focuses specifically on analyzing the thermal comfort properties of materials used in military combat boots. Key properties including air permeability, water vapor permeability, and thermal resistance of various upper and lining materials are tested using laboratory experiments and statistical analyses. The research’s scientific novelty stems from its focus on specialized combat boot materials rather than generic footwear, the testing under extreme hot and cold conditions directly applicable to military contexts, the use of quantitative thermo-physiological indexes and rigorous statistical analysis to objectively evaluate materials, the examination of novel upper and lining material combinations for insights into comfort optimization, and the
A comprehensive investigation of both hot and cold climates unlike most studies which concentrate on just one temperature extreme. These factors can expand scientific knowledge related to optimizing materials for combat boot thermo-physiological comfort under varied conditions. In this research, some potential research gaps related to the thermo-physiological comfort properties of military combat boot materials are evident, as only a limited number of materials were evaluated under restricted conditions. Broadening the materials, components, comfort factors, testing conditions, and gender considerations analyzed could significantly strengthen the research’s ability to optimize military boot comfort and performance across environments and uses. In this research, some potential research gaps related to the thermo-physiological comfort properties of military combat boot materials are evident, as only a limited number of materials were evaluated under restricted conditions. Broadening the materials, components, comfort factors, testing conditions, and gender considerations analyzed could significantly strengthen the research’s ability to optimize military boot comfort and performance across environments and uses.

2. Experimental

2.1. Materials and Methods. The materials used for the analytical study were procured from different manufacturers, such as chrome-tanned water resistance cow upper leather (CTWRCU), chrome-tanned waterproof cow upper leather (CTWPCU), chrome-tanned water resistance suede cow leather (CTWRS), plain nylon canvas six thread (PNCST), plain nylon canvas four-thread (PNCFT), Cordura nylon for upper (CNU), plain polyester canvas six thread (PPCST) and plain polyester canvas four-thread (PPCFT) for the upper material and warp-knitted fabric (WNF), sheep lining (SL), and woven cotton fabric (WCF) for the lining material. Table 1 shows the selected material thickness, structure, fiber content, and treatment along with their images.

2.2. Equipment. In this study, a variety of equipment was used to assess the comfort properties of military boots’ upper materials and boots’ uppers. The physical testing laboratory equipment is available at the Technical and Vocational Training Institute (TVTI), the Textile Industry Developmental Institute (TIDI), and the Leather Industry Developmental Institute (LIDI).

2.3. Method. The following test methods are used for determining the thermal and strength properties of randomly selected materials. The tests and test methods for leather and textile materials are shown in Table 2. To analyze the thermal properties of the materials, one-way ANOVA and post hoc pairwise comparison were used. To analyze the test results, Minitab and Origin software were used for statistical analysis and graphical representation of the data, respectively.

2.3.1. Air Permeability. The performance of military combat boots’ materials, such as the upper and lining, depends significantly on their air permeability. Air permeability can be used to determine how breathable a material is, particularly coated fabrics and leather in general, as well as to identify changes that have occurred during the manufacturing process [9]. The results were represented in m²/m²-min by taking the average of five different measurements. The measurements were performed using circular textile fabric or leather with a 0.2 kPa pressure differential for 1 second. This test was conducted using the TEXTEST FX3300 air permeability tester manufactured by TEXTEST AG in Switzerland, as shown in Figure 1.

2.3.2. Water Vapor Permeability. One of the key characteristics that determine how quickly water vapor travels through a material used to make military combat boots is its water vapor permeability. This is a key factor in assessing a footwear material’s thermo-physiological comfort qualities. Under specified temperature and humidity levels, water vapor permeability is defined as the time rate at which water vapor transmits through a unit area of upper and lining material structure when there is a unit vapor pressure differential between two particular surfaces [10]. The upper and lining samples were sealed over the open mouth of a disc containing water and placed in the open air. The loss of mass was evaluated as the difference between the total weight at the start and the weight after a specific time of testing. This test was conducted using the SDL Atlas MVTR-1 water vapor permeability tester manufactured by SDL Atlas in the United States, as shown in Figure 2.

2.3.3. Thermal Resistance. The thermal resistance of military combat boots is a key performance property that determines how well the boots can insulate the wearer’s feet in extreme cold and hot weather conditions. High thermal resistance minimizes heat loss from the feet to keep them warm in cold conditions, while low thermal resistance maximizes breathability to allow heat dissipation from the feet in hot conditions. The upper lining of combat boots is usually made from insulating materials that trap air and slow down the conduction of body heat to the outside. Thicker uppers and linings provide higher thermal resistance and warmth. Military combat boots’ upper and lining material is generally considered to be a conductor or resister of heat for the wearer, depending on the climatic condition of the geographical location [11]. Thermal resistance was determined by sandwiching a sample between two plates at various temperatures. While the temperature of the lower plate (the heat sink) fluctuated, that of the upper plate (the heat source) was maintained at a constant temperature. As thermal equilibrium is reached, the temperature differential between the heat source and the heat sink steadily approaches equilibrium. This test was conducted using the TEXTEST THERMA-1 thermal tester machine, manufactured by TEXTEST AG in Switzerland, as shown in Figure 3.
<table>
<thead>
<tr>
<th>Material</th>
<th>Average thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Structure</th>
<th>Fiber content</th>
<th>Treatment</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chrome-tanned water resistance cow upper leather</td>
<td>1.89</td>
<td>0.97</td>
<td>Woven collagen</td>
<td>Collagen</td>
<td>Acrylic coatings</td>
<td></td>
</tr>
<tr>
<td>Chrome-tanned waterproof cow upper leather</td>
<td>1.98</td>
<td>1.02</td>
<td>Woven collagen</td>
<td>Collagen</td>
<td>Fluorocarbon</td>
<td></td>
</tr>
<tr>
<td>Chrome-tanned water resistance sued cow leather</td>
<td>1.91</td>
<td>0.96</td>
<td>Woven collagen</td>
<td>Collagen</td>
<td>Acrylic coatings</td>
<td></td>
</tr>
<tr>
<td>Plain nylon canvas six thread</td>
<td>1.81</td>
<td>1.27</td>
<td>Plain woven</td>
<td>Nylon</td>
<td>Polytetrafluoroethylene</td>
<td></td>
</tr>
<tr>
<td>Plain nylon canvas four-thread</td>
<td>1.79</td>
<td>1.45</td>
<td>Plain woven</td>
<td>Nylon</td>
<td>Silicone</td>
<td></td>
</tr>
<tr>
<td>Cordura nylon upper</td>
<td>1.84</td>
<td>1.35</td>
<td>Plain woven</td>
<td>Nylon</td>
<td>Silicone</td>
<td></td>
</tr>
</tbody>
</table>
Table 1: Continued.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Structure</th>
<th>Fiber content</th>
<th>Treatment</th>
<th>Photo</th>
</tr>
</thead>
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<td>Plain polyester canvas four-thread</td>
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<td>1.31</td>
<td>Plain woven</td>
<td>Polyester</td>
<td>Silicone</td>
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<tr>
<td>Plain polyester canvas six thread</td>
<td>1.86</td>
<td>1.25</td>
<td>Plain woven</td>
<td>Polyester</td>
<td>Polytetrafluoroethylene</td>
<td></td>
</tr>
</tbody>
</table>

**Lining material**

<table>
<thead>
<tr>
<th>Material</th>
<th>Average thickness (mm)</th>
<th>Density (g/cm³)</th>
<th>Structure</th>
<th>Fiber content</th>
<th>Treatment</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp knitted fabric</td>
<td>0.61</td>
<td>1.21</td>
<td>Vertical knit fabric</td>
<td>Cotton</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Sheep lining</td>
<td>0.78</td>
<td>0.86</td>
<td>Collagen</td>
<td>Collagen</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Woven cotton fabric</td>
<td>0.72</td>
<td>1.23</td>
<td>Plain woven</td>
<td>Cotton</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
2.3.4. Mechanical Property. Mechanical testing is indispensable for military boots, evaluating durability under extreme conditions. The bursting test provides quantifiable data on a material’s rupture strength when subjected to high stress inflationary pressures, simulating real-world point loads. The tensile test gives key measurements of ultimate tensile strength, elongation, and elasticity as samples are stretched to failure, indicative of flexure and support capacities [12]. Additionally, the tear test assesses tear force and resistance as propagative tearing is induced in precut specimens, modeling rips, and snags during combat maneuvers. Carefully controlled test variables and strict methodologies ensure accuracy and repeatability, with research focused on predictive correlations to actual field performance. By testing various upper materials, overlays, and linings, researchers can optimize selection and design integration; engineering boots with sufficient bursting, tensile, and tearing capacities for the rigorous demands of military activities [13]. Manufacturers benefit from the wealth of data in developing quality protective footwear that meets safety standards and enhances soldier effectiveness. Mechanical testing continues to be an indispensable tool in military footwear development, providing critical insights into materials, prototypes, and finished products. This test was conducted using the Universal Strength Tester (Model 80-75), manufactured by SDL Atlas in the United States, as shown in Figure 4.

2.4. Comfort Index. The comfort properties of military combat boots are the result of the overall integration of anthropometric factors, foot disorders, anatomical considerations, econometric considerations, ergonomics, and biomechanics of the foot and material selection. The comfort index of footwear material is determined by the thermo-physiological comfort index (TPCI), and it is anticipated that the thermo-physiological comfort index indices will offer a useful method for evaluating total wear comfort [14]. This index only determines the upper and lining material comfort properties, not the overall integration of socks, soles, and uppers. In the determination of the comfort index, the water vapor permeability, thermal resistance, and air permeability of the lining and upper material are closely related to a single factor, namely, the thermo-physiological comfort index (TPCI).
2.4.1. Comfort Index for Cold Weather. Cold climates are defined as regions where the average annual temperature remains below 8°C (46°F) [15]. For military operations in such freezing environments, combat boots require materials with specific thermal properties to maintain soldiers’ comfort and effectiveness. The boot’s upper and lining materials need high thermal resistance to retain heat and insulate the foot. Materials like closed-cell foams, felts, and insulated leathers are utilized. Additionally, low air permeability is important to block convection currents and wind chill. Coatings or tightly woven materials can achieve this. However, the materials cannot be completely impermeable to vapor transmission. Some moisture from sweat evaporation must be allowed to pass through to the boot exterior. If vapor accumulates inside, it will condense due to the temperature differential, making the boot interior damp and uncomfortable. Water vapor permeability is optimized through breathable membranes and linings. The thermo-physiological comfort index for cold climates (TPCIC) is directly proportional to thermal resistance but inversely proportional to water vapor permeability and air permeability; it quantifies these factors as shown in equation (1). The highest-counting materials balance thermal insulation, air resistance, and water vapor permeability for optimal cold-weather boot comfort.

\[
\text{TPCI}_C = (\text{TR} \times \text{WVP} \times \text{AR}).
\]  

TPCI_C—Resistance to Thermal (m²K/W). AR—Resistance to air (kPa·s/m). WVP—permeability of Water vapor (g/m²·hr).

Air resistance refers to the impedance or obstruction of air flow through a material. It is a measure of how difficult it is for air to pass through the material. When testing materials for boots, air resistance provides an indication of breathability and ventilation. Materials with low air resistance allow air to permeate more easily. The air resistance of the material is determined by the pressure difference during the test and the air permeability of the fabric, as shown in the following equation:

\[
\text{AR} = \frac{P}{\text{AP}}.
\]  

P—Pressure difference (kPa). AP—Air permeability (m³/ m²·min).

2.4.2. Comfort Index for Hot. Hot climatic conditions refer to regions where the average annual temperature exceeds 38°C (100°F) [15]. For military operations in severe heat, boot materials require specific thermal properties to maintain soldiers’ effectiveness and prevent heat injuries. The boot upper and lining materials need low thermal resistance to minimize insulation and dissipate heat from the foot. Open-cell foams, moisture-wicking linings, and lightweight and breathable upper materials are ideal. Additionally, high air permeability through the materials is crucial for ventilation and convection airflow around the foot. Mesh fabrics, perforations, and porous constructions allow air exchange to cool the foot. The materials must also have high water vapor permeability. As sweat evaporates from the foot, the vapor needs to readily pass through the boot to the exterior environment. Breathable membranes and hydrophilic linings enhance moisture transfer. The thermo-physiological comfort index for hot climates (TPCID) is directly proportional to water vapor permeability and air permeability but inversely proportional to thermal resistance; it is quantified based on these factors in equation (3). The highest-counting materials maximize heat dissipation, air flow, and vapor transmission for optimal hot-weather boot comfort.

\[
\text{TPCI}_D = \frac{\text{WVP} \times \text{AR}}{\text{TR}}.
\]  

TPCI_D—Resistance to Thermal (m²K/W). AR—Resistance to Air (kPa·s/m). WVP—permeability of Water vapor (g/ cm²·hr).

3. Results and Discussion

3.1. Thermal Comfort Property of Upper and Lining Material

3.1.1. Air Permeability of the Upper and Lining Materials. The rate of airflow through a known area perpendicularly under a specified air pressure differential between two surfaces of a material, known as air permeability, applies to most fabrics and leather materials. The air permeability property of the upper and lining materials affects the user’s comfort. Particularly for application areas that employ energy-expenditure tasks, there will be enough air-permeable clothing for ease of air exchange (breathable). There is a significant difference in air permeability between eight upper materials and three lining materials, with degrees of freedom of seven and two, respectively, showing a p value less than 0.05. So, both the upper and the lining materials have different characteristics in terms of air permeability. This result indicates that with different air permeability, it will be used for different combat boots in different climatic conditions. The use of material for specific climatic conditions will be determined by using the comfort index calculation. The air permeability of the upper and lining materials is shown in Figure 5.
Te permeability of an upper and lining material to air is a property of fundamental importance from the standpoint of a material’s construction and intended usage. Figure 1 shows that the air permeability of different upper and lining materials such as CTWRCU, CTWPCU, CTWRS, PNCST, CNU, PNCFT, PPCFT, PPCST, WKF, SL, and WCF has a mean air permeability of 2.87, 0.74, 5.65, 10.23, 12.96, 15.20, 13.46, 7.43, 310.52, 32.90, and 71.39 with a standard deviation of 0.47, 0.25, 0.52, 0.69, 0.59, 0.87, 0.69, 0.61, 0.84, 0.68, and 0.15. The air permeability of boot upper and lining materials is influenced by multiple interrelated factors, including fibers density, alignment, thickness, porosity, surface texture, hydrophobicity, and finishing processes. Tight materials with smooth, thick, and aligned fibers tend to have low permeability. More open, porous, and hydrophobic materials with rough surfaces and random fiber orientations favor higher air exchange through the material structure. Tightly technical materials like CTWRCU and CTWPCU with closed, aligned fibers exhibit lower air permeability. More open knits, like WKF, favor air exchange [16]. Each material has a certain use depending on its air permeability and the thermo-physiological comfort index will decide what that use is. To compare the mean of each product, the Tukey pairwise comparison method was used. The Tukey comparison is tabulated in Table 3.

The permeability of an upper and lining material to air is a property of fundamental importance from the standpoint of a material’s construction and intended usage. Figure 1 shows that the air permeability of different upper and lining materials such as CTWRCU, CTWPCU, CTWRS, PNCST, CNU, PNCFT, PPCFT, PPCST, WKF, SL, and WCF has a mean air permeability of 2.87, 0.74, 5.65, 10.23, 12.96, 15.20, 13.46, 7.43, 310.52, 32.90, and 71.39 with a standard deviation of 0.47, 0.25, 0.52, 0.69, 0.59, 0.87, 0.69, 0.61, 0.84, 0.68, and 0.15. The air permeability of boot upper and lining materials is influenced by multiple interrelated factors, including fibers density, alignment, thickness, porosity, surface texture, hydrophobicity, and finishing processes. Tight materials with smooth, thick, and aligned fibers tend to have low permeability. More open, porous, and hydrophobic materials with rough surfaces and random fiber orientations favor higher air exchange through the material structure. Tightly technical materials like CTWRCU and CTWPCU with closed, aligned fibers exhibit lower air permeability. More open knits, like WKF, favor air exchange [16]. Each material has a certain use depending on its air permeability and the thermo-physiological comfort index will decide what that use is. To compare the mean of each product, the Tukey pairwise comparison method was used. The Tukey comparison is tabulated in Table 3.

The Tukey procedure is a statistical test used to determine whether there are any significant variations between the mean values of different groups or samples. After an analysis of variance (ANOVA), this post hoc test can be performed to determine which groups are substantially different from one another. The grouping data in Table 3 demonstrate that there are notable variations in the samples’ mean air permeability values for each group as follows: 2.87, 0.74, 5.65, 10.23, 12.96, 15.20, 13.46, 7.43, 310.52, 32.90, and 71.39 for CTWRCU, CTWPCU, CTWRS, PNCST, CNU, PNCFT, PPCFT, PPCST, WKF, SL, and WCF, respectively. Based on their mean values, the samples are divided into categories A through J, with samples that belong to the same letter not significantly varying from one another. The sample WNF is distinguished from all the other examples in the table by the fact that it falls under category A. Except for WNF, the sample WCF is designated as belonging to group B, suggesting that it differs significantly from the others. Samples SL, PNCST, PPCFT, and CNU fall under the C, D, E, and E categories, respectively. This means that while they are not significantly different from one another, they are significantly different from the samples that performed better. The samples PNCST, PPCST, CTWRS, CTWRCU, and CTWPCU are classified as F, G, H, I, and J, indicating that they are very different from all the other samples in the table.

3.1.2. Water Vapor Permeability of Upper and Lining. Water vapor permeability is the amount of vapor transferred through a unit area of fabric in a unit of time and can be expressed as the ability of the leather or textile fabric to permit water vapor to pass through it. The water vapor permeability of the upper material reduces over a predefined period because of the reduction in pore size caused by the hygroscopic nature of the fiber. Further, the thinner upper
Material shows higher water vapor permeability than the thicker upper material; the water vapor permeability for both the lining and upper material is significant (P less than 0.05). Water vapor permeability is different for all upper and lining materials due to their different characteristics. The result shows that all the uppers and linings will be used for a specific purpose, which will be determined by the comfort index. The water vapor permeability of the upper and lining materials is shown in Figure 6.

The ability to transmit water vapor is one of the important properties of military combat boots’ upper and lining materials that make them so desirable for use in the construction of shoes. Figure 2 shows the water vapor permeability of different upper and lining materials. Upper and lining materials such as CTWRCU, CTWPCU, CTWRS, PNCST, CNU, PNCFT, PPCFT, PPCST, WKF, SL, and WCF have an average water vapor permeability of 1.05, 0.34, 1.44, 2.57, 3.68, 6.79, 4.85, 2.23, 67.41, 11.55, and 21.58 with a standard deviation of 0.15, 0.21, 0.14, 0.13, 0.54, 0.046, 0.092, 0.48, 0.19, 0.21, and 0.046, respectively. This average water vapor permeability in upper and lining materials is the amount of vapor transfer per unit area of upper and lining materials. The water vapor permeability of boot upper and lining materials is influenced by porosity, hydrophilicity, fiber density and alignment, thickness, and finishing processes. Materials with more pores and openings, as well as hydrophilic sites that attract moisture, tend to have higher permeability. Tightly packed fibers oriented in the same direction provide greater resistance to vapor diffusion compared to lose, random fibers. Thicker materials and sealed finishes like calendaring decrease permeability by blocking moisture passage. As shown in the data, tightly technical materials exhibit lower permeability, while more open absorbent structures result in high vapor transmission [17]. To compare the mean water vapor permeability of each material, the Tukey pairwise comparison method was used. The Tukey comparison is tabulated in Table 4.

The mean water vapor permeability of eight upper and three lining materials, which were evaluated under the same circumstances, was compared using the Tukey pairwise comparison method. Table 4 shows the findings of this study and includes the mean, sample size, and grouping for each item. The materials’ average water vapor permeability ranged from 67.41 for WNF to 0.34 for CTWPCU. According to the Tukey comparison, the materials were grouped according to their mean water vapor permeability, with the highest mean materials being placed in Group A and the lowest mean materials being placed in Group I. Materials in various groups have significantly differing mean water vapor permeability, according to the Tukey comparison. Materials in Group A (WNF) had a mean water vapor permeability that was significantly higher than all other groups, whereas materials in Groups G, H, and I had a mean water vapor permeability that was significantly lower than all other groups. Materials in Groups B to F also differed significantly from other groups in terms of mean water vapor permeability. According to the analysis’s findings, CTWPCU is the least permeable material, whereas WNF and WCF are the most permeable. Groups A through F’s materials have high water vapor permeability and may be used in applications requiring strong breathability. Groups G through I’s materials may be better suited for applications requiring water resistance because of their relatively low water vapor permeability. Other elements, including fabric thickness, texture and structure, may also have an impact on water vapor permeability.

3.1.3. The Thermal Resistance of Upper and Lining Material. Thermal resistance is a measurement of an upper and lining material’s resistance to heat flow. A significant test for the thermal resistance of both the lining and upper material showed a p value of less than 0.05, which is a significant difference in material thermal resistance because of the difference in material thickness, fiber structure, breathability, and other factors. Depending on their thermal resistance properties, every material has its own application, but the specific application is determined by the integrated comfort index of the material. Thermally resistant footwear upper materials are specifically designed to provide insulation and conductivity against cold and hot temperatures [18]. The thermal resistance of the upper and lining materials is shown in Figure 7.

Thermal resistance is a measure of an upper and lining material’s ability to resist the flow of heat through it. Figure 3 shows the thermal resistance of different upper and lining materials such as CTWRCU, CTWPCU, CTWRS, PNCST, CNU, PNCFT, PPCFT, PPCST, WKF, SL, and WCF with a mean thermal resistance of 4.39, 6.17, 3.61, 2.17, 1.59, 0.67, 0.89, 2.79, 0.022, 0.17, and 0.083 with a standard deviation of 0.36, 0.26, 0.39, 0.073, 0.13, 0.065, 0.25, 0.037, 0.35, and 0.082, respectively. The thermal resistance of boot upper and lining materials is influenced by thickness, density, air pockets, fiber conductivity, coatings, and moisture content. Thicker and more compactly constructed fabrics impede heat flow and raise thermal resistance. Materials that trap air pockets and use low-conductivity fibers also resist heat transfer. Added polymer coatings further reduce heat penetration, while moisture content lowers thermal resistance. As the data show, thick, tightly technical materials exhibited higher resistance and thin, loose knits had very low resistivity [19]. To compare the thermal resistance of each material, the Tukey pairwise comparison method was used. The Tukey comparison is tabulated in Table 5.

From Table 5, the range of the materials’ average thermal resistance was 6.17 for CTWPCU to 0.022 for WNF. Based on their mean thermal resistance, the materials were divided into different groups using the Tukey comparison. Materials in group A, which included CTWPCU, had significantly higher mean thermal resistance compared to all other groups. Materials in group B, which included CTWRCU, had significantly higher mean thermal resistance compared to groups C, D, E, F, G, H, I, and J. Materials in group C had significantly higher mean thermal resistance compared to materials in groups D, E, F, G, H, I, and J. Materials in group D had significantly higher mean thermal resistance compared to materials in groups E, F, G, H, I, and J. Materials in group E had significantly higher mean thermal resistance
compared to materials in groups F, G, H, I, and J. Materials in group F had significantly higher mean thermal resistance compared to materials in groups G, H, I, and J. Materials in group G had significantly higher mean thermal resistance compared to materials in groups H, I, and J. Materials in group H had significantly higher mean thermal resistance compared to groups I and J. Materials in group I had significantly higher mean thermal resistance compared to group J. Materials in Group J, which included WCF and WNF, had significantly lower mean thermal resistance compared to all other groups. The results of this analysis suggest that CTWPCU and CTWRCU are the most thermally resistant materials, while WCF and WNF are the least thermally resistant. Materials in groups A to F had relatively high thermal resistance and were more suitable for applications that require insulation. Materials in groups G to I had relatively low thermal resistance and were more suitable for applications that required breathability and comfort. Additionally, other factors such as fabric density, thickness, and composition may also affect thermal resistance.
Table 5: Thermal resistance Tukey comparison for upper and lining material.

<table>
<thead>
<tr>
<th>Sample</th>
<th>N</th>
<th>Mean</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTWPCU</td>
<td>5</td>
<td>6.17</td>
<td>A</td>
</tr>
<tr>
<td>CTWR CU</td>
<td>5</td>
<td>4.39</td>
<td>B</td>
</tr>
<tr>
<td>CTWR S</td>
<td>5</td>
<td>3.61</td>
<td>C</td>
</tr>
<tr>
<td>PPCST</td>
<td>5</td>
<td>2.79</td>
<td>D</td>
</tr>
<tr>
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<td>5</td>
<td>2.17</td>
<td>E</td>
</tr>
<tr>
<td>CNU</td>
<td>5</td>
<td>1.59</td>
<td>F</td>
</tr>
<tr>
<td>PPCFT</td>
<td>5</td>
<td>0.89</td>
<td>G</td>
</tr>
<tr>
<td>PNCFT</td>
<td>5</td>
<td>0.67</td>
<td>H</td>
</tr>
<tr>
<td>SL</td>
<td>5</td>
<td>0.17</td>
<td>I</td>
</tr>
<tr>
<td>WCF</td>
<td>5</td>
<td>0.083</td>
<td>J</td>
</tr>
<tr>
<td>WNF</td>
<td>5</td>
<td>0.022</td>
<td></td>
</tr>
</tbody>
</table>

3.2. Integrated Combat Boot Material Comfort Index

Thermo-physiological comfort index of military combat boots’ material for both hot and cold climatic conditions is determined as shown in Table 6.

The integrated thermo-physiological comfort index of combat boots is specially designed to determine the maximum comfort index of the material in the harshest and most demanding climatic conditions. The materials used to manufacture these boots are selected based on various properties, including air resistance, water vapor permeability, and thermal conductivity. As shown in Table 6, different materials have different thermo-physiological comfort indexes. Leather is a natural material that offers an excellent thermo-physiological comfort index in cold climates compared to textile materials. CTWRCU, CTWPCU, CTWR S, and SL have 19.32, 33.33, 12.09, and 24.18 thermo-physiological comfort indexes, respectively. This result indicates that leather provides excellent thermo-physiological comfort in cold climates relative to textiles because of its low air permeability, vapor transmission, and wicking, coupled with its high thermal resistance and moisture absorption, to help retain body heat. The tight, non-breathable structure of leather prevents air circulation and sweat evaporation, which allows insulation of warmth. Its dense construction also provides superior thermal resistance to the cold. By readily absorbing and holding moisture close to the foot, leather maintains humidity levels that further conserve heat. These same properties that restrict ventilation and dissipate heat and dampness to create discomfort in hot conditions enable leather to excel at insulating feet in the cold. The data show that leather’s higher integrated comfort index reflects its strengths in maintaining thermal protection in cold climatic conditions compared to textiles [20]. This confirms that leather for cold wearers provides personalized comfort and support.

Another material commonly used in military combat boots is technical textile fabric. These materials show an excellent thermo-physiological comfort index in hot conditions compared to leather. PNCFT, PPCFT, CNU, and WNF have an 8.15, 4.83, 2.15, and 119.5 thermo-physiological comfort index, respectively. This indicates that textiles exhibit a higher integrated thermo-physiological comfort index versus leather in hot conditions owing to their high breathability, moisture vapor transmission, wicking, and lightweight flexibility. The porous and absorbent nature of textile fibers enhances air circulation, sweat evaporation, and heat dissipation from the foot. This prevents moisture build-up and overheating. The loose construction and low mass of textiles further aid cooling while providing minimal insulation. In contrast, leather’s non-breathable properties lead to heat and dampness entrapment. The data show that textiles’ much higher comfort index reflects their inherent advantages in heat and moisture management through structural ventilation, capillary actions, and conformability. This demonstrates why textiles outperform leather for hot-weather footwear applications [21]. They are suitable for use in warmer environments where breathability is essential to prevent foot sweating and ensure comfort. The thermo-physiological comfort index of all upper and lining materials is shown in Figure 8.

The selection of appropriate material for construction boots plays a significant role in regulating foot temperature. Quality leathers and textile blends are optimal materials for combat boots due to their ability to regulate foot temperature in both hot and cold conditions. Their moisture vapor permeability allows sweat evaporation to prevent overheating, while adaptive insulation retains some warmth when needed without excessive heat build-up. High-performance leathers and textiles also maintain breathability, flexibility, and abrasion resistance over the boots’ lifetime to provide consistent temperature control and comfort in varying conditions. The balance of ventilation, insulation, durability, and conformability makes these materials well-suited for combat applications requiring effective thermo-physiological regulation from hot to cold environments over prolonged use. Their ability to manage moisture and modulate insulation in response to climate makes leathers and textiles ideal for the rigorous thermo-regulation demands of military footwear [22]. For hot climatic conditions, a plain nylon canvas four-thread upper and warp-knitted fabric lining were selected due to higher air permeability, water vapor permeability, low airflow resistance, and thermal resistance that induce a higher thermo-physiological comfort index of 8.5 and 119.5, respectively. These materials have the characteristics of moisture wicking that eliminate sweat and keep feet dry in hot climates, enhance comfort, and reduce the risk of blistering and bacteria. Whereas in the case of cold climatic conditions, a chrome-tanned waterproof cow upper and sheep lining were selected due to low air permeability, water vapor permeability, and
higher airflow resistance and thermal resistance that induce a higher thermo-physiological comfort index of 33.33 and 24.18, respectively. These materials keep heat inside the shoe to reduce heat conduction from outside to inside. Overall, integrated combat boots are designed with comfort in mind and the materials used are selected to ensure that the wearer is comfortable at all times during long hours of use in harsh environments [23].

3.3. Strength Property of Selected Material. To guarantee the safety, dependability, comfort, and performance of the boots, it is crucial to measure the strength attributes of the materials. Materials that are overly soft or rigid might be uncomfortable or impede movement, while materials that are weak or readily destroyed can result in accidents or frequent replacements. Strong and long-lasting materials can give the wearer superior support and protection, which is crucial for activities like trekking, building projects, or military operations. Generally, evaluating the strength characteristics of boot materials aids in injury prevention, user happiness, and extended boot life. In this study, based on the thermo-physical comfort index, CTWPCU, PPCFT, SL, and WNF were selected as the main materials for the hot and cold climatic conditions in military combat boot development. The best military combat boot material is one that balances durability, weight, insulation, and protection [3]. Different materials have their own unique strengths and it is up to the wearer to choose the material that meets their needs best. One of the key elements affecting the durability of military combat boots is their strength. Military combat boots are made of durable materials such as leather, nylon, or other synthetic materials. This material is selected to withstand various types of terrain and harsh environments, providing durability and protection to the foot. The strength property of the selected material is shown in Table 7.

The strength property of the upper material in military combat boots’ development is crucial in determining the durability and resilience of the shoe against tearing. From Table 7, chrome-tanned waterproof cow upper leather and plain nylon canvas four-thread upper material have an average tensile strength of 42.82 ± 1.21 and 33.62 ± 0.78, tear...
strength of 98.25 ± 5.23 and 74.65 ± 1.54, and ball burst strength of 1245.26 ± 6.25 and 1132.05 ± 1.36, respectively. The difference in tensile strength is due to the type of material used for the upper material, which can significantly affect its strength. For instance, leather is a common material used for shoe uppers as it is strong and durable [24]. Textile materials such as nylon, polyester, and mesh are also used, but they are not as strong or long-lasting as leather [25]. The construction method of the boots can also affect their strength. Shoes that are made using processes such as cementing or direct injection moulding tend to be stronger than those made using other methods like stitching [26]. The thickness and quality of materials used for the upper can also affect its strength. Thin, low-quality materials are more prone to tearing and wear than thicker, high-quality materials. The flexibility of the upper material is also a factor that can affect its strength [27]. Shoes that are too flexible or too rigid can be prone to tearing, whereas appropriately flexible shoes can withstand more significant stress and last longer. In a general way, the type of material, construction method, thickness, quality, and flexibility of the upper material are all factors that can affect the strength properties of military combat boots’ upper and lining materials.

3.4. Thermal Comfort Property of Military Combat Boot Upper. The upper part of combat boots is the section that covers the foot and ankle, extending up to the midcalf or higher, depending on the design. It is typically made from upper and lining materials or a combination of both and is designed to provide protection and support to the foot and ankle. The upper part of combat boots designed for hot temperatures must be breathable, comfortable, and durable while also protecting against moisture and other environmental hazards. In hot climates or during rigorous activities, military combat boots mostly utilize ventilation features such as perforations, padding, and mesh materials to enhance airflow and heat dissipation. This combat boot upper features a layer of plain nylon canvas four-thread, padding foam, and warp-knitted fabric. This layer allows the foot to breathe and release moisture, reducing the generation of sweat. Whereas in cold weather, military combat boot uppers must have an insulation layer built into the upper to help retain the body’s natural heat, keeping the feet warm in colder temperatures. Insulation layers can be made of chrome-tanned, waterproof cow-upper leather, padding foam, or sheep lining. The prepared military combat boots for the thermal comfort test are shown in Figure 9. The upper of a military combat boot is designed to provide comfort and protection to the foot and ankle during strenuous military activities.

The thermal comfort property of a military combat boot upper refers to its ability to regulate the temperature of the foot, keeping it within a comfortable range at varying ambient temperatures. The thermal comfort properties of the boot upper are shown in Table 8.

Thermal comfort is a vital consideration in the design and manufacture of military combat boots’ uppers. An ideal military combat boot upper enables ventilation, allows sweat to evaporate, retains the natural heat of the feet, and utilizes breathable materials to regulate foot temperature, ensuring that the user’s feet remain comfortable in varying environmental temperatures. From Table 8, it shows that the upper component of hot military combat boots has an average of 14.15 ± 0.52, 5.37 ± 2.01, 1.59 ± 0.62, and 0.87 ± 0.04 air permeability, water vapor permeability, thermal conductivity, and thermal resistance, respectively, whereas cold-weather military combat boots have a mean of 0.21 ± 0.08, 0.094 ± 0.02, 0.083 ± 0.03, and 9.61 ± 0.95 air permeability, water vapor permeability, thermal conductivity, and thermal resistance, respectively. Hot military combat boots have higher air permeability, water vapor permeability, and thermal conductivity with low thermal resistance, which indicates that they enable breathability, moisture-wicking, and airflow to prevent heat-related injuries, evaporate quickly, and provide the necessary protection and support for soldiers to perform their duties effectively [4]. Cold-weather military combat boots show higher thermal resistance and low air permeability, water vapor permeability, and thermal conductivity; this reveals that they provide insulation and cold resistance to warmth to the feet of military personnel and protect against frostbite, hypothermia, and other cold-weather injuries while providing support and comfort for the feet during extended periods of use [28].

3.5. Development of Shoe Upper. Combat boots’ upper refers to the part of a shoe that covers the foot, including the top, sides, and back. Typically, a range of materials, such as mesh, leather, or synthetic fabrics, are used to develop military combat boots, which may also incorporate features such as laces, straps, or zippers to secure the shoe to the wearer’s foot. The design and construction of the shoe upper can greatly affect the fit, comfort, and style of a shoe. A combat boot’s upper construction involves assembling the different components of the shoe’s upper, which may vary depending on the style and design of the shoe. Typically, the upper is composed of several layers, including padding, lining, and the outer layer material. In this study, a sample of combat boots’ uppers is developed from selected upper, lining, and padding foam to determine comfort properties such as thermal resistance, water vapor permeability, and air permeability. Figure 10 shows images of the military combat
boot samples that were developed using the selected materials. Two boot samples were produced, each one fabricated from a different textile or leather material chosen for testing. The images provide a visual representation of how the various candidate upper and lining materials look when made into combat boots.

4. Conclusion

The general objective of the research was to analyze the thermo-physiological comfort properties of military combat boot material for hot and cold climatic conditions in the development of military combat boots. After materials were collected from a different manufacturer, a one-way ANOVA and Tukey pairwise comparison significant test for the wear comfort properties of the upper and lining materials were determined. The $p$ value for the significant test is less than 0.05, which indicates that there was a significant difference between materials in air permeability, thermal resistance, and water vapor permeability properties.

The thermo-physiological comfort index for hot and cold climate conditions was determined based on wear comfort properties. The sample materials showed different amounts of thermo-physiological comfort index, but the highest was selected based on the three relationships of wear properties for each climatic condition. For hot climatic conditions, a plain nylon canvas four-thread upper and warp-knitted fabric lining were selected due to their higher thermo-physiological comfort indexes of 8.5 and 119.5, respectively. These materials have higher breathability and intermediate strength, which eliminate sweat and keep feet dry in hot climates. Whereas in the case of cold climatic conditions, chrome-tanned waterproof cow upper leather and sheep lining were selected due to a higher thermo-physiological comfort index of 33.33 and 24.18, respectively, with higher strength properties. These materials keep heat inside the shoe to reduce heat convection from outside to inside due to their low thermal conductivity and higher thermal resistance. After the selection of appropriate material for the appropriate climatic conditions, a sample boot upper was developed and underwent the wear property test. The sample upper for hot and cold climatic conditions shows air permeability of $14.15 \pm 0.52$ and $0.21 \pm 0.08$, water vapor permeability of $5.37 \pm 2.01$ and $0.094 \pm 0.02$, thermal conductivity of $1.59 \pm 0.62$ and $0.083 \pm 0.03$, and thermal resistance of $0.87 \pm 0.04$ and $9.61 \pm 0.95$, respectively. Thermo-physiological comfort index analysis is a method used to evaluate materials’ comfort in a particular environment based on the combination of temperature, humidity, and air movement. This analysis is particularly useful in selecting materials for combat boots, clothing, and other textiles that will be used in specific climatic conditions. By using this method, military combat boot designers and manufacturers

<table>
<thead>
<tr>
<th>Boots upper</th>
<th>Average air permeability ($m^3/m^2 \cdot min$)</th>
<th>Average water vapor permeability ($g/cm^2 \cdot hr$)</th>
<th>Average thermal conductivity ($W/m^2K$)</th>
<th>Average thermal resistance ($m^2K/W$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-climate military combat boots</td>
<td>$14.15 \pm 0.52$</td>
<td>$5.37 \pm 2.01$</td>
<td>$1.59 \pm 0.62$</td>
<td>$0.87 \pm 0.04$</td>
</tr>
<tr>
<td>Cold-climate military combat boots</td>
<td>$0.21 \pm 0.08$</td>
<td>$0.094 \pm 0.02$</td>
<td>$0.083 \pm 0.03$</td>
<td>$9.61 \pm 0.95$</td>
</tr>
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References


