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Modelling thermal resistance of woven fabrics in wet state

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ABSTRACT – REZUMAT

Modelling thermal resistance of woven fabrics in wet state

In this study, a simple mathematical model based on conductive heat transfer is suggested for predicting the thermal resistance of wet woven fabric. For this purpose, cellulosic fabrics produced in two different weave types with different moisture content were investigated. Fabric is considered a system of a porous structure consisting of fibre, air and if present, water. The thermal resistance of fabric was calculated according to the proportion of these components. It was considered that the water's location could have changed the resistance values. The assumption was the capillary water was arranged serially with fibres and air when it was located in the yarns, and it was arranged parallel with the air when it was located between the yarns. Calculated values were compared with the measurement values obtained from ALAMBETA. When the results were evaluated, the obtained values were quite good except for the absolute dry fabric. Serial arrangement of fibre and air was better fitted for dry fabric. So, it is thought that the air acts as a single block in absolute dry fabrics. Additionally, for comparison, Maxwell-Eucken2 (ME-2) was also used. The new model's R^2 value is a little higher than *the other model as 0.9017. Furthermore, MSSD and MSAD values were 0.0000013 and 0.0007878 for this model, respectively. As a result of the study, it can be said that the suggested model is useful for predicting the thermal resistance of woven fabrics with different moisture content. Besides this, analyses of fabric porosity can be useful to manage the thermal resistance of wet fabrics.*

Keywords: *thermal resistance, woven fabric, weave type, modelling, wetting*

Modelarea rezistenței termice a țesăturilor în stare umedă

În acest studiu este prezentat un model simplu matematic bazat pe transferul de căldură conductiv, pentru preconizarea rezistenței termice a țesăturii în stare umedă. În acest scop, au fost investigate țesături celulozice produse cu două tipuri diferite de legături cu conținut diferit de umiditate. Țesătura este considerată ca un sistem de structură poroasă constând din fibre, aer și, dacă este prezentă, apă. Rezistența termică a țesăturii a fost calculată în funcție de proporția acestor componente. S-a considerat că locația apei ar fi putut modifica valorile rezistenței. S-a analizat apa supusă influenței capilare dispusă în serie cu fibrele și aerul atunci când este situată în fire și cea dispusă paralel cu aerul când se află între fire. Valorile calculate au fost comparate cu valorile măsurate obținute cu ALAMBETA. La evaluarea rezultatelor, valorile obținute au fost destul de bune, cu excepția țesăturii complet uscate. Aranjarea în serie a fibrei și aerului a fost mai potrivită pentru țesătura în stare uscată. Deci, se preconizează că aerul acționează ca un singur bloc în țesăturile complet uscate. În plus, pentru comparație, a fost utilizat și Maxwell-Eucken2 (ME-2). Valoarea R^2 a noului model este puțin mai mare decât cea a celuilalt model, cu 0,9017. În plus, valorile MSSD și MSAD au fost de 0,0000013 și, respectiv, de 0,0007878 pentru acest model. Ca rezultat al studiului, se poate spune că modelul sugerat este util pentru preconizarea rezistenței termice a țesăturilor cu conținut diferit de umiditate. Pe lângă aceasta, analizele porozității țesăturilor pot fi utile pentru a gestiona rezistența termică a țesăturilor în stare umedă.

Cuvinte-cheie: *rezistență termică, țesătură, tip de legătură, modelare, umezire*

INTRODUCTION

Clothing helps to keep the body temperature in the comfort zone by creating a thermal barrier between the human body and the environment. For this aim high thermal resistance is expected from clothing in cold weather, whereas in hot weather thermal resistance must be low. Thus, thermal resistance is considered one of the important comfort-related properties [1].

Fibre, yarn, and fabric parameters have a significant effect on the thermal properties of the fabrics. Many studies investigated the relationship between these parameters and the thermal characteristics of the fabrics. A high correlation between the thermal resistance of the fabric with thickness, weight, cover factor and porosity of the fabric was determined with these studies. The study by Cubric et al. indicates that the air enclosed in the fabric is a significant factor in thermal resistance [2]. Also, some researchers suggested prediction models for the thermal properties of the fabrics. For the prediction of thermal resistance of woven fabrics, Bhattacharjee & Kothari developed a mathematical model. Their model consists of heat transfer by conduction, radiation through air and radiation through yarns [3]. Matusiak developed a model of the thermal resistance of woven fabrics in the function of their structure [4]. Wei et al. established a structural model to predict the thermal resistance of fabrics [5]. Yang et al. described four different regions in fabric and suggested a predicting model using the arrangement of thermal resistance of yarn and thermal resistance of air serial, parallel or hybrid [6].

Due to sweat sorption in the fabric or due to rainy climate, the air enclosed in the fabric replaces with water although the proportion of water and air in the fabric will change. As a result, the thermal properties of the fabric change due to the moisture content of the fabric since the thermal conductivity of water is 25 times higher than the thermal conductivity of air. The thermal performance of fabric in wet conditions is more complex and it is affected by fabric thickness, porosity and fibre type [7]. Some researchers investigated the fabric's thermal properties in wet conditions [8–10]. Several studies used statistical models to investigate the relationship between fabric parameters and thermal properties [11–15].

Conduction, radiation, convection, and ventilation are dry heat transfer mechanisms, when wet heat transfer occurs evaporation, wicking, sorption and desorption, wet conduction (additional conductive heat transfer due to the clothing being wet), and condensation of moisture are added [16]. Modelling of the thermal properties of the fabrics in a wet state is investigated in some studies.

Dias and Delkumburewatte developed a mathematical model for the porosity of plain knitted fabrics based on the unit cell of stitch. Then they suggested a thermal conductivity model for wetted fabric. In this model, they assumed that the wet fabric consists of material, water, and air with different volume fractions. Their theoretical values were quite higher than the experimental values. However, theoretical values obtained from this model and experimental values have a similar pattern [17].

Hes and Loghin assumed that the thermal resistance of textiles is linked parallel to the thermal resistance of water, and they suggested a mathematical model for the thermal conductivity of wetted fabric [18]. Mangat et al. suggested a model for predicting the thermal resistance of wet denim fabrics by using mean porosity [19]. Mangat and Hes predicted the thermal resistance of denim fabrics at different moisture content. They considered wet fabric as a system of fibre, air, and water. They calculated the resistance values of wet fabric with eight different arrangements of the thermal resistance of fibre, air, and water. They suggested the model that gives the best results [20]. Similarly, Mangat et al. used this approach to predict the thermal resistance of selected fabrics in the wet state [21].

Mansoor et al. predicted the thermal resistance of wet socks by using the thermal conductivity of wet polymer. They have compared the models in the literature with the experimental data and developed two new mathematical models on modifications of the Maxwell Eucken-2 and Militky models for the prediction of thermal resistance of plain socks in the wet state [22]. Mansoor et al. also suggested another model with assumed that fabric density is changing with wetting [16]. Mansoor et al. used image analysis to obtain the porosity values of the socks and compared the experimental values of heat transfer of wet socks with theoretical values obtained from 3 different mathematical models [23].

Wu et al. improved the models based on Mangat's prediction models, by replacing the original moisture content with water content saturation. The results of their studies showed that air resistance and water resistance were connected in parallel, followed by serial arrangement with fibre resistance gave the best results with $R^2 \geq 0.955$. The modified model gave better results with R^2 values ranging from 0.95 to 0.99. [7]. Joshi et al. modelled both heat and mass transfer of layered fabrics [24]. Wu et al. classified into five levels of thermal absorptivity of wet fabrics with fuzzy comprehensive evaluation and compared with subjectively classified using participant evaluations [25].

Also, artificial intelligence is used for predicting the thermal properties of fabrics in wet states. Kanat and Özdil predicted the thermal resistance of knitted fabrics in the wet state by using an artificial neural network (ANN) [26]. Mandal et al. developed multiple linear regression and ANN models to predict the thermal protective and thermo-physiological comfort performances of fabrics used in firefighters' clothing [27]. Also, ANN was used by Li et al. to predict thermal resistance and water vapour resistance of wet knitted double jersey fabrics [28].

In this study thermal resistances of the woven fabrics with different moisture content are predicted from thermal resistances of fibre, air, and water. There are four different types of water held within fibres and fabrics as defined below [29].

- internal water, which is absorbed into fibres,
- capillary water, which is located in the capillary pores between fibres,
- surface water, which is located between the yarns,
- dripping water, which is located on the fabric and is transported downwards due to gravity.

This study aims to estimate the wet thermal resistance of woven fabrics using fabric geometric parameters. Different from the previous study, the suggested model uses the location of water, which existed in the fabric to calculate the thermal resistance of the fabric as well as volume fractions of fibre, air, and water. For this purpose, the porosity of the fabrics was analysed first, and the thermal resistance model was constituted by considering the position of water.

MATERIALS AND METHODS

Fabric properties

The proposed model to predict the thermal resistance of wetted woven fabric is experienced on three different cellulosic fibres cotton, viscose and Tencel™. 36 Ne yarns were used in all fabrics both for warp and weft. 3/1 (Z) twill fabrics were manufactured with all three yarns and with cotton yarns also plain fabrics were produced. Two different weft densities (23 and 27 picks/cm) were used for all fabrics [30].

In this study thermal resistance of wet woven fabrics is predicted by using their geometrical properties. For this purpose, warp and weft density, fabric weight and fabric thickness were determined experimentally. Other parameters used such as porosity and cover factor of the fabrics were calculated by using these measurement results.

All measurements were performed under the standard atmospheric conditions (20 ± 2°C temperature, 65% ± 4 relative humidity). The number of threads per unit length was determined according to TS 250 EN 1049-2. All fabric samples were dried at 105°C for 4 hours to obtain absolute dry fabrics. Fabric weights per unit area were determined according to TS EN 12127 at this stage. Fabric thicknesses were determined with the ALAMBETA instrument at thermal resistance measurement which is expressed in Testing Procedure. The measured properties of the fabrics are given in table 1.

The porosity and cover factor of the fabrics was calculated using equations 1 and 2 respectively [31, 32]:

$$\varepsilon = 1 - \frac{\rho_f}{\rho_{fb}} \quad (1)$$

$$CF = (P_1 \times d_1 + P_2 \times d_2 - d_1 \times d_2) / (P_1 \times P_2) \quad (2)$$

In equation 1, ρ_f is the fabric density (ρ_f = fabric weight per unit area/fabric thickness) (g/cm^3) and ρ_{fb} is the fibre density (g/cm^3). In equation 2, 1 and 2 are indices for warp and weft, respectively. *d* indicates the diameters of the yarns and *P* indicates the density of the yarns (figure 1).

To calculate the fabric cover factor firstly yarn densities were determined with Pierce's packing factor expressed as in equation 3 [33]:

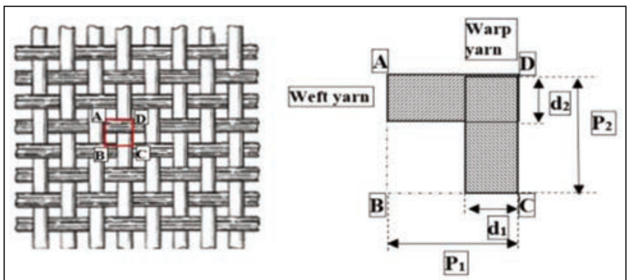


Fig. 1. Diagram of the weave structure

$$Packing\ factor = \frac{\rho_y}{\rho_{fb}} \quad (3)$$

In Pierce's equation, the packing factor is constant at 0.59 and ρ_y is the yarn density (g/cm^3) and ρ_{fb} is the fibre density (g/cm^3). According to the literature, fibre densities were taken as 1.55 g/cm^3 for cotton, 1.52 g/cm^3 for viscose [34] and 1.50 g/cm^3 for Tencel^{TM} [35] to calculate both porosity and packing factor. Also yarn diameter was calculated by using equations 4 and 5 is [33]:

$$V_y = \frac{1}{\rho_y} \quad (4)$$

$$V_y = \pi \frac{R^2}{4} Nm \cdot 100 \quad (5)$$

where *R* is the diameter of the yarn (cm), V_y is the specific volume of the yarn (cm^3/g), *Nm* is the yarn number (m/g).

Testing procedure

Thermal resistances of absolute dry fabrics were measured by using the ALAMBETA instrument at first (equivalent to ISO 8301). Fabrics were wetted with distilled water then the samples were left to dry at standard atmospheric conditions. At the drying stage, the wetted weight of the samples at 100%, 75%, 50% and 25 % moisture content according to dry weight was determined and the thermal resistance of the fabrics was measured at these conditions also.

When measuring thermal properties with ALAMBETA Instrument, the sample is placed on the measuring plate at 22°C and the measuring head at 32°C drops down and touches the sample. The thickness of the fabric is determined by measuring the difference between the levels of the measuring plate and the measuring head. Due to temperature difference heat flow occurs and the heat flow is processed on the computer and thermo-physical properties of the measured sample are evaluated [17, 36].

Since the water content of the fabric changes over time, the measurement time is important for this study. ALAMBETA Instrument was preferred in this study because the measurement is performed in a few minutes.

Table 1

FABRIC PROPERTIES

Fabric type	Warp density (ends/cm)	Weft density (picks/cm)	Thickness (mm)	Fabric weights (g/m^2)
Cotton/Plain/23	49	24	0,37	122.27
Cotton/Plain/27	50	28	0,34	130.99
Cotton/Twill/23	52	25	0,41	124.22
Cotton/Twill/27	53	28	0,37	132.03
Viscose/Twill/23	53	24	0,38	123.70
Viscose/Twill/27	53	28	0,34	130.73
Tencel^{TM}/Twill/23	50	24	0,37	121.88
Tencel^{TM}/Twill/27	51	28	0,34	129.17

The obtained resistance values from the suggested model are compared with the experimental values which are observed by using ALAMBETA Instrument.

Theoretical model

In this study, referring to the studies of Farnworth [37] and Hes and Stanek [38] heat transfer by convection and radiation was neglected. Farnworth [37] did not find any evidence of convection heat transfer through fabrics. Hes and Stanek [38] explained that the proportion of radiation heat transfer is less than 20% of the total heat transfer of the fabric. Therefore, only conducted heat transfer was considered.

The air gaps in the fabric were analysed at first, and then the thermal resistance values were calculated on this basis. The woven fabrics can be considered as a system consisting of fibre, air and if present, water. The thermal resistance of the wet fabric is calculated according to this system. Assumptions of this system are as follows:

- Thickness of the fabric does not change with wetting.
- Yarn diameter is constant throughout its length.

Dry fabric comprises two components fibre and air. Porosity expresses the air ratio in the fabric. So $(1-\varepsilon)$ is the fibre ratio within the fabric. Air gaps in the fabric are examined in two parts. One of these parts is the gap between yarns and the other is the gap between fibres in the yarns. Porosity consists of these two gaps. The covering factor refers to the part of the fabric covered with yarns. Thus $(1-CF)$ is the gap between yarns. Therefore, $\varepsilon-(1-CF)$ is the gap between fibres. The ratio of the gaps in the fabrics was calculated and the values were given in the following table.

By using these ratios and the thickness values of the fabrics; thicknesses of fibre in the yarn, air in the yarn and water in the yarn were calculated according to equations 6–8 [16]. The air and water thickness values change by water amount due to air being replaced with water. Since the wetting process was carried out according to the weight of the fabric, the water content was determined according to the volumes to calculate the thicknesses.

$$h_f = h \times p_f \tag{6}$$

$$h_w = h \times p_w \tag{7}$$

$$h_a = h \times p_a \tag{8}$$

In these equations, h indicates the thicknesses of the fabrics and p indicates the percentages of fibre, water, and air in the yarn. f, w indices refer to fibre, water and air, respectively (table 3).

According to literature, firstly small pores fill with wetting, and then the water moves to large pores [39]. Thus, the water molecules fill in the gaps between fibres, and the gaps between yarns, respectively. The thickness of the air between yarns is regarded as the thickness of the fabric since there was no water in these gaps in this study. Therefore, the resistance of the gaps of the fabric is calculated with equation 9.

$$R_{gaps} = \frac{h}{\lambda_a} \tag{9}$$

After that, the resistance of each part of the system in the yarn is calculated by using equations 10–12:

$$R_a = \frac{h \times p_a}{\lambda_a} \tag{10}$$

$$R_f = \frac{h \times p_f}{\lambda_f} \tag{11}$$

$$R_w = \frac{h \times p_w}{\lambda_w} \tag{12}$$

where R is the resistance of the material and λ is the conductivity of the material. The conductivity of fibre material is 71 $mWm^{-1}K^{-1}$ [37] of the air is 24 $mWm^{-1}K^{-1}$ and of the water is 600 $mWm^{-1}K^{-1}$ [19]. Since all fibres were cellulosic, the conductivities of the fibres were regarded the same as cotton fibre.

In this study, only the heat flow from the surfaces of the fabric was considered. While the yarn resistances were calculated, it was assumed that resistances of fibre, air and water were arranged serial (figure 2, *a*). Then the fabric resistances were calculated, and it was assumed that the resistance of yarn and air gaps were arranged parallel (figure 2, *b*).

With this assumption resistance of the yarn and fabric was calculated by using equations 13 and 14.

$$R_{yarn} = R_a + R_f + R_w \tag{13}$$

Table 2

FRACTION OF THE GAPS IN THE ABSOLUTE DRY FABRICS

Fabric type	CoverFactor (CF)	Porosity (ε)	1–CF	1–ε	ε–(1–CF)
Cotton/Plain/23	0.8304	0.7869	0.1696	0.2131	0.6173
Cotton/Plain/27	0.8550	0.7481	0.1450	0.2519	0.6031
Cotton/Twill/23	0.8625	0.8022	0.1375	0.1978	0.6647
Cotton/Twill/27	0.8811	0.7679	0.1189	0.2321	0.6490
Viscose/Twill/23	0.8765	0.7844	0.1235	0.2156	0.6609
Viscose/Twill/27	0.8883	0.7474	0.1117	0.2526	0.6357
Tencel™/Twill/23	0.8624	0.7821	0.1376	0.2179	0.6444
Tence™l/Twill/27	0.8849	0.7445	0.1151	0.2555	0.6294

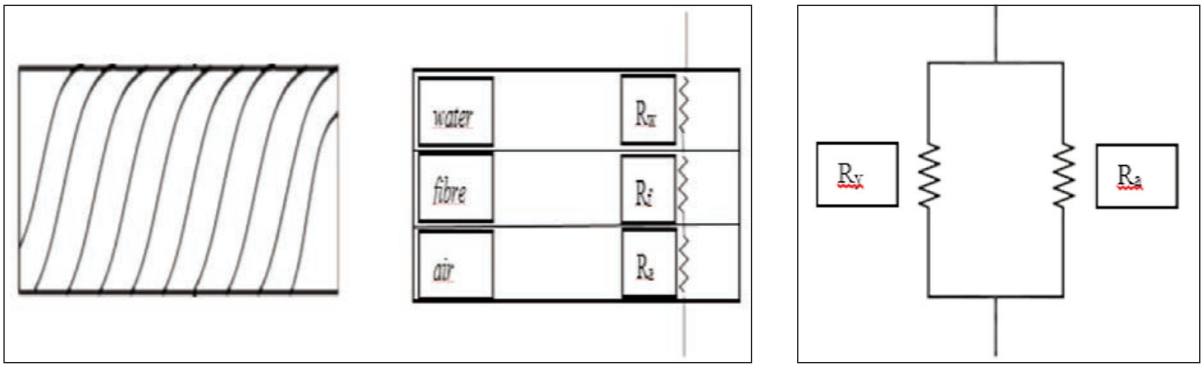


Fig. 2. Thermal resistance system of: *a* – yarn; *b* – fabric

Table 3

FIBRE, WATER, AND YARN THICKNESSES IN THE YARN ACCORDING TO WATER CONTENT (MM)

Water content acc. to weight	0%			25%			50%			75%			100%		
Fabric type	h_f	h_w	h_a	h_f	h_w	h_a	h_f	h_w	h_a	h_f	h_w	h_a	h_f	h_w	h_a
Cotton/Plain/23	0.0950	0	0.2751	0.0950	0.0368	0.2383	0.0950	0.0736	0.2015	0.0950	0.1104	0.1647	0.0950	0.1472	0.1279
Cotton/Plain/27	0.0988	0	0.2367	0.0988	0.0383	0.1984	0.0988	0.0766	0.1601	0.0988	0.1149	0.1218	0.0988	0.1532	0.0835
Cotton/Twill/23	0.0929	0	0.3122	0.0929	0.0360	0.2762	0.0929	0.0720	0.2402	0.0929	0.1080	0.2042	0.0929	0.1440	0.1682
Cotton/Twill/27	0.0967	0	0.2704	0.0967	0.0375	0.2329	0.0967	0.0749	0.1955	0.0967	0.1124	0.1580	0.0967	0.1498	0.1205
Viscose/Twill/23	0.0928	0	0.2846	0.0928	0.0353	0.2493	0.0928	0.0706	0.2140	0.0928	0.1058	0.1788	0.0928	0.1411	0.1435
Viscose/Twill/27	0.0968	0	0.2437	0.0968	0.0368	0.2069	0.0968	0.0736	0.1701	0.0968	0.1104	0.1333	0.0968	0.1472	0.0965
Tencel™/Twill/23	0.0942	0	0.2786	0.0942	0.0353	0.2433	0.0942	0.0707	0.2080	0.0942	0.1060	0.1726	0.0942	0.1413	0.1373
Tence™l/Twill/27	0.0973	0	0.2397	0.0973	0.0365	0.2032	0.0973	0.0730	0.1667	0.0973	0.1095	0.1302	0.0973	0.1460	0.0937

$$R_{fabric} = \frac{R_{gaps} \times R_{yarn}}{R_{gaps} + R_{yarn}} \quad (14)$$

For comparison, some of the models which gave good results in the literature were used. One of these models was the Modified Maxwell-Eucken2 (ME-2) model, which was expressed in Mansoor et al.'s study with best fitting. It was stated that this model can be convenient for the effective thermal conductivity of a two-component material with simple physical structures [22] (equations 15 and 16). In equation 15 λ_{fab}, λ_a and $\lambda_{wet\ polymer}$ are thermal conductivities of fabric, air and wet fibre, and F_a and $F_{wet\ polymer}$ are volume fractions of air and wet fibre, respectively.

$$\lambda_{fab} = \frac{\lambda_a F_a + \lambda_{wet\ polymer} F_{wet\ polymer} \frac{3\lambda_a}{2\lambda_a + \lambda_{wet\ polymer}}}{F_a + F_{wet\ polymer} \frac{3\lambda_a}{2\lambda_a + \lambda_{wet\ polymer}}} \quad (15)$$

$$R_{fab} = \frac{h_{fab}}{\lambda_{fab}} \quad (16)$$

Other two models Model 5 and Modified Model 5 were described in Wu et al.'s study. The saturation level was used instead of the ratio of water. In Model 5, water resistance and air resistance were connected parallel, fibre resistance was connected serial to them [7].

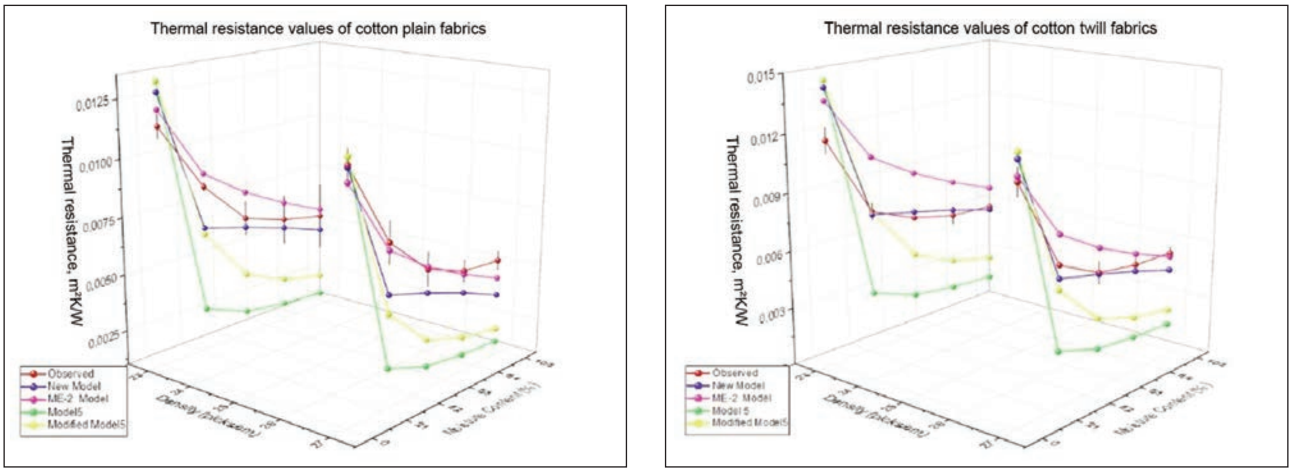
RESULTS AND DISCUSSION

The predicted values were quite good except for the values of absolute dry fabrics. For evaluating the predicted values, the sum of squares deviations (SSD) and the sum of absolute deviations (SAD) were used.

$$MSSD = \frac{1}{n} \sum_{i=1}^{n} (R_{tm,i} - R_t)^2 \quad (17)$$

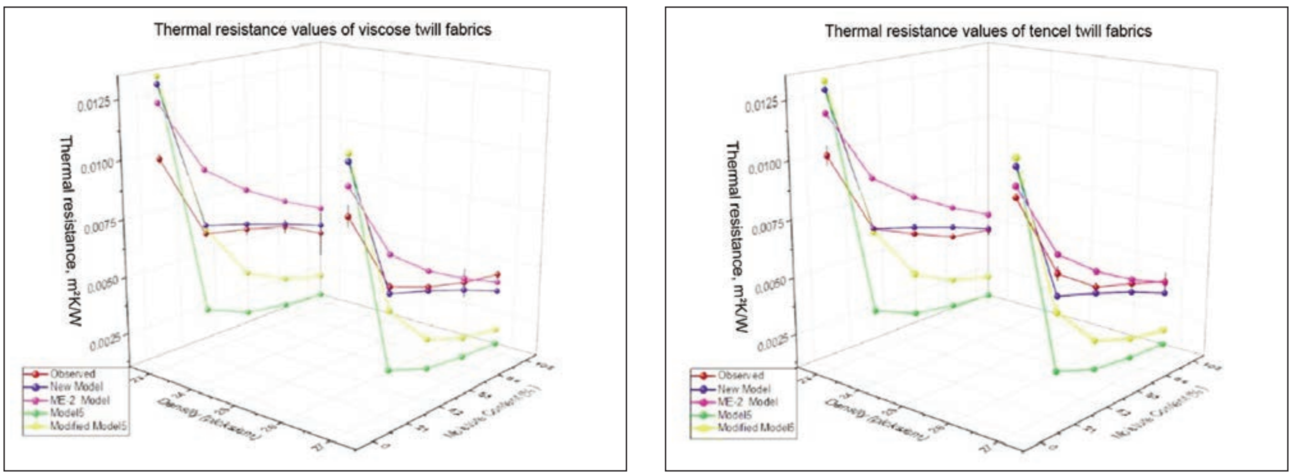
$$MSAD = \frac{1}{n} \sum_{i=1}^{n} |R_{tm,i} - R_t| \quad (18)$$

In these equations, R_{tm} is the measurement thermal resistance value and R_t is the calculated thermal resistance value. These mean values of SSD and SAD are 0.0000036 and 0.002007, respectively. These values are quite good but when compared with the literature [29] a little high. This difference



a *b*

Fig. 3. Comparison of predicted and observed resistance values of cotton fabrics with: *a* – plain; *b* – twill



a *b*

Fig. 4. Comparison of predicted and observed resistance values of: *a* – viscose twill fabrics; *b* – Tencel™ twill fabrics

results from the values of absolute dry fabrics deviations. If the absolute dry fabric values are left out of the calculations *MSSD* and *MSAD* values rise to 0.00000070 and 0.000631531, respectively. These values are better than the literature.

However, when the fibre and air resistances are arranged with serial for the absolute dry fabrics as suggested by Dias and Delkumburewatte the predicted values better fitted with measured values. This can be explained by the fact that the air in the fabric acts as a single block when there is no water in the structure. Furthermore, this block is broken with water molecules. *MSSD* and *MSAD* values were calculated with this approach and were obtained at 0.0000013 and 0.0007878, respectively.

The predicted values obtained from both the ME-2 model, Model 5, Modified Model 5 and new model vs. observed values of thermal resistance of the fabrics at different moisture content were shown in figures 3 and 4.

The coefficient of determination (R^2) and mean values of SSD and SAD values of these four models are given in table 4. All these models were quite good. Although modified Model 5 has the highest R^2 value, when considering SSD and SAD values new model was quite good also. It can be seen in the graphs that according to these results, using the location of water in predicting the thermal resistance of wet woven fabrics could give the closest values to actual resistance.

Table 4

R^2, MSSD AND MSAD VALUES OF THE MODELS

Model	R^2	MSSD	MSAD
New Model	0.902	0.00000130	0.00078780
ME-2 model	0.847	0.00000180	0.00109540
Model 5	0.885	0.00001307	0.00348515
Modified Model 5	0.930	0.00000541	0.00215592

CONCLUSION

Thermal resistance of fabrics is one of the most important properties of clothing comfort. Higher thermal resistance values provide better protection from cold. Steady air in textile structures increases thermal resistance and it is useful for cold-weather clothing. However, wetting the fabric means replacing the air in the fabric with water. Since the thermal conductivity of water is 25 times higher than the thermal conductivity of air, the resistance value of fabric decreases dramatically. Considering thermal comfort, predicting the thermal resistance of wet fabrics is crucial for textile designs.

In this study, the thermal resistances of wet woven fabrics were predicted with their geometrical properties. The location of water can be different in the textile structure such as internal, capillary, surface and dripping, and it was assumed that wetting of the structure comes into existence in this order.

It was considered that the location of the water could change the resistance values of the fabrics. For this reason, the air gap percentages between the yarns (surface gaps) and in the yarns i.e., between the fibres (capillary gaps) were calculated. The thermal resistances of the yarns were determined by assuming that resistances capillary water, fibres and air between the fibres arrange serial. The yarn resistance is arranged parallel with the resistance of air between the yarns.

In this study, there was no water between the yarns, although fabrics were wetted up to their own weight. In addition to this, in absolute dry fabrics air in the fabric acts as a single block and air and fibre arranged serial at this moment.

The predicted values were quite close to the actual values. R^2 was 0.9017 for this new model. MSSD and MSAD values were 0.0000013 and 0.0007878, respectively. Also, the results were compared with the obtained results from some of the models in the literature that gave good results. It was found that the new model's prediction is quite good. According to these results, it can be said that the distribution of fabric porosity is effective for managing the thermal resistance of wetted fabrics.

Also, this model can be applied easily since it uses only basic geometrical and physical parameters. Other fibre types and fabrics having different construction parameters and also higher moisture content could be examined in further studies.

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The effects of integrated Lean Six Sigma methodology with ergonomics principles in the garment industry

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ABSTRACT – REZUMAT

The effects of integrated Lean Six Sigma methodology with ergonomics principles in the garment industry

The present paper introduces an integrated model that combines the use of ergonomics with Lean Six Sigma (LSS) methodology based on the DMAIC (Define, Measure, Analyse, Improve, and Control) approach. In each DMAIC phase, an additional ergonomic perspective was integrated to improve the process both from the efficiency and ergonomic side. The present study was carried out in a textile industry specialized in the manufacture of articles for technical use. The study's aims are the following: achieving continuous improvement by eliminating waste, decreasing activities that are Non-Value Added, and preserving workers' health while focusing on external and internal productivity. It began with a defined stage intended to increase Value Added (VA) activities by reducing Non Value Added (NVA) through waste removal, to around 48.5%, increasing the cycle time to 4.6 %. The finding has led to the conclusion that an integrative approach has ultimately secured the workers' lives and boosted their operational performance.

Keywords: *Lean Six Sigma, ergonomics, clothing industry*

Efectele metodologiei Lean Six Sigma integrate în principiile de ergonomie din industria de îmbrăcăminte

Lucrarea de față introduce un model integrat care combină utilizarea ergonomiei cu metodologia Lean Six Sigma (LSS) bazată pe abordarea DMAIC (Definire, Măsurare, Analiză, Îmbunătățire și Control). În fiecare fază DMAIC, a fost integrată o perspectivă ergonomică suplimentară pentru a îmbunătăți procesul atât din punct de vedere al eficienței, cât și al ergonomiei. Acest studiu a fost realizat în industria textilă specializată în fabricarea articolelor de uz tehnic. Obiectivele studiului sunt următoarele: realizarea îmbunătățirii continue prin eliminarea deșeurilor, scăderea activităților care sunt fără valoarea adăugată și păstrarea sănătății lucrătorilor, concentrându-se în același timp pe productivitatea externă și internă. S-a început cu o etapă de definire menită să crească activitățile cu valoare adăugată (VA) prin reducerea celor fără valoare adăugată (NVA) prin eliminarea deșeurilor, la aproximativ 48,5%, mărind timpul ciclului la 4,6%. Analiza a condus la concluzia că o abordare integrativă a îmbunătățit în cele din urmă viața lucrătorilor și le-a sporit performanța operațională.

Cuvinte-cheie: *Lean Six Sigma, ergonomie, industria de îmbrăcăminte*

INTRODUCTION

Lean Management and Six Sigma philosophies are to be considered as the most promising initiatives in the continuous improvement of organizations [1, 2]. Indeed, this method is widely used by firms throughout the world in various industrial fields that include manufacturing [3–7], services [8, 9], commercial [10], health care [11, 12] and textile [13].

Ergonomics (or the study of human factors) is the scientific discipline that aims at a fundamental understanding of the interactions between human beings and the other components of the system. Ergonomics considers both the physical and psychological human aspects and is interested in looking for solutions in both the technical and organisational domains [14]. Several techniques have been used for the systematic and comprehensive assessment of a workstation [15].

The implementation of Lean Six Sigma (LSS) tools was beneficial. Yet, it can cause ergonomics problems, but with promising modifications. This failure occurs because several organizations focus only on implementing Lean Six Sigma (LSS) tools and do not consider the workers' security measures [16]. While trying to maximize productivity and improve working conditions, the interventions suggested by this methodology can compromise workers' health by reducing the high level of physiological and psychological stress [17–19]. The employment of ergonomics simultaneously with the LSS implementation process is consensual [20–22] and can easily miss the needs of the human factor in the production process. In addition, ergonomics must be integrated simultaneously with Lean to evaluate the effect of Lean improvements, for example, musculoskeletal disorder (MSD) risk factors associated with the job [23, 24].

To reach this goal, the current study presents the results of integrating ergonomics with Lean Six Sigma (LSS) implementation in the garment industry.

The remnant of this paper is as follows: the 2nd section explores the methods included in the different steps involved in this study. The 3rd section sets out the result and discussion which examines the case study and documents the results obtained from applications in the clothing industry. Then the 4th section includes a conclusion with future research.

METHODOLOGY

Our methodology was designed to help integrate the ergonomics and LSS implementation based on the DMAIC (Define, Measure, Analyse, Improve, and Control) approach. The DMAIC cycle was used because it is a standard method with clear consecutive phases: problem-solving and process continuous improvement [30]. Figure 1 shows the corresponding methodology.

In each DMAIC phase, an additional ergonomic perspective was integrated to improve the process both from efficiency and ergonomics as level follows:

• ***DEFINE PHASE***

In the define phase, we defined the objectives of the project and the current situation of the organization. In addition, Lean Six Sigma (LSS) and ergonomics metrics are selected with the relevant tools.

LSS and ergonomics are key indicators that would help standardize the identified measurements.

• ***MEASURE PHASE***

In the measure stage, data on measurable LSS and ergonomics indicators are collected to evaluate the status of performance metrics at the beginning of the improvement process.

• ***ANALYSE PHASE***

The analysis phase examines the collected data in order to generate a prioritized list of sources of variation. Using the result of the step "Measure", it's becoming possible to determine the root causes of variations and recognize the major problems of productivity and working conditions, revealed in the Define stage.

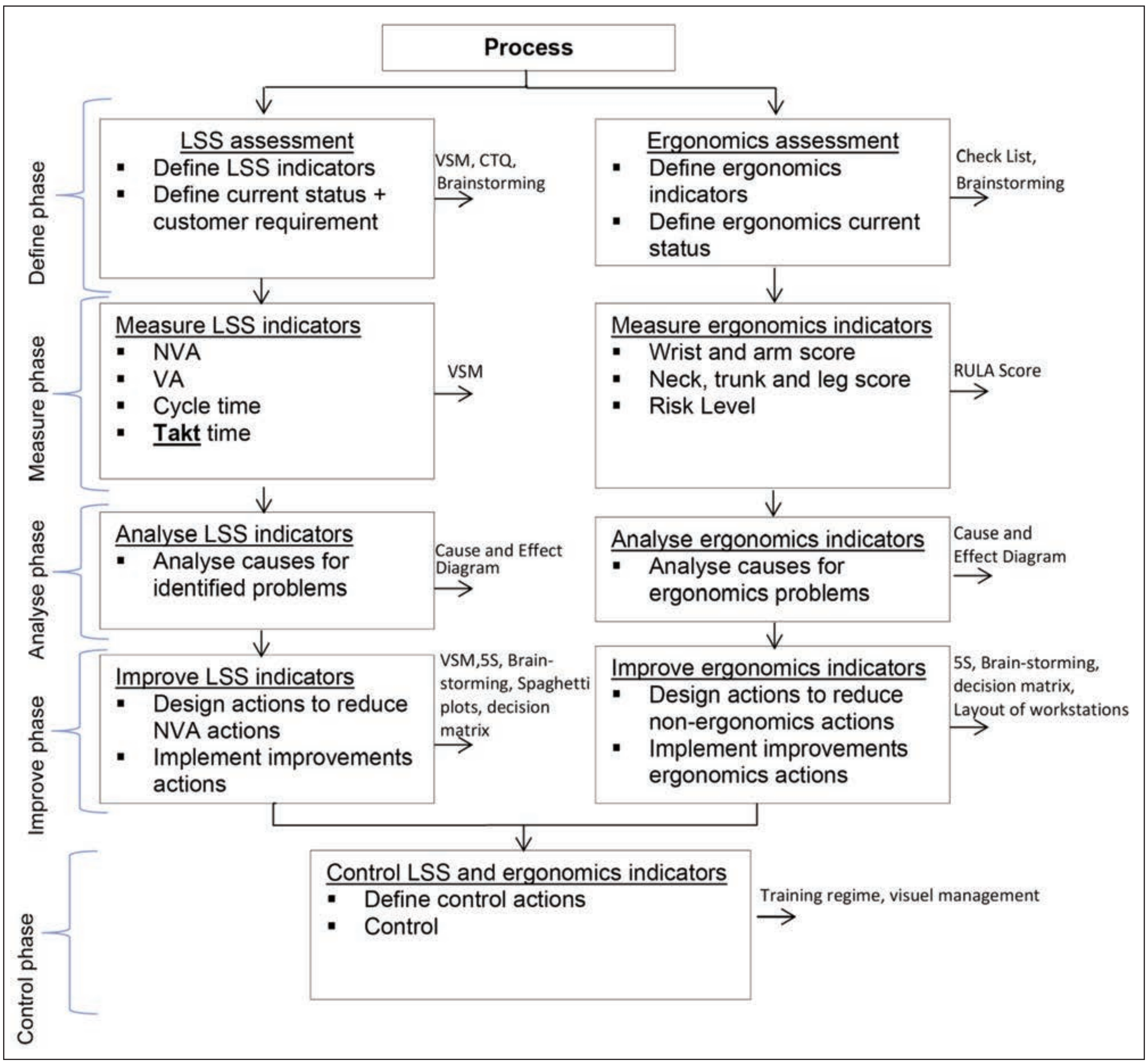

Fig. 1. Research methodology

• IMPROVE PHASE

In the improvement phase, we proposed and implemented some improvement measures to solve the LSS problems and improve the working conditions. Thus, the implementation of Lean Six Sigma (LSS) and ergonomics improvements would ensure the quality of organizational performance taking into account the safety of workers. Consequently, better results are realized, because the well-being of workers is significantly reflected on the efficiency level by reducing non-value-added activities, and increasing the productivity of the organization.

LSS tools such as Value Stream Mapping (VSM), the five S (5S): Sort, Set in order, Shine; Standardize, Systemize, kaizen, brainstorming, cause and effect diagrams are also used in studies of this type. Regarding ergonomic risk assessment methods, several methods were applied in the studies analysed, one of them is RULA. This method has a positive impact on process efficiency and at the same time it allows for reducing the risk level and decreasing the discomfort and fatigue that workers went through [25].

• CONTROL PHASE

The main purpose of this methodology is to improve process performance and working conditions and have the results that are obtained be sustained in the long run. The standardisation of the optimal solutions has been fully integrated into the training regime and the process documentation, and the information related to company performance was shared with its employees. A continued monitoring process and training are required.

CASE STUDY

The present study was carried out in the textile industry specialising in the manufacturing of articles for technical use. The objectives of the work are:

– reducing waste,
– increasing productivity and
– protecting workers and focus on external and internal productivity by integrating LSS and Ergonomics.

Given the complexity of the sewing process of technical products, there were higher demands for the human workforce. The success of this study requires leadership support, employee involvement, and employers' willingness to change and adapt.

• DEFINE PHASE

This phase consists of defining the problem and the customer requirements. The objective is to optimize the process by reducing NVA (Non-Value Added) and cycle time by improving the working conditions. The Critical to Quality (CTQ) essential elements are determined (figure 2).

• MEASURE PHASE

In this step, we will collect data on measurable indicators of production processes and ergonomics perspectives. As referred before, this will evaluate both ergonomic conditions and productivity parameters.

Productivity indicators

The activated VSM provides all details related to the company process as explained in figure 3. The outcomes of Cycle time, Lead time, VA and NAV are presented in the table.

In the current state, the data observed are collected through the VSM. The main indicators observed on the map are:

– Takt time = 5.82 min
– Lead time = 39.41 days + 19.92 minutes = 39.45 days
– Value Added time = 19.92 min
– Non-Added Value time = 39.41 days.

Observing the mapping of the current state we noticed that the sub-assembly process time is greater than the takt time (figure 4), in this situation the production process generates a bottleneck problem, so it becomes necessary to intervene to adapt the rhythm takt time production.

After a close observation, we concluded that the priority problems regarding the previous waste definition are waiting time, transportation, over-processing, motion and excessive inventory.

Transportation and unnecessary motion are the significant types of waste detected in our case study. Even, according to Shigeo Shingo in Peter & Taylor "Excessive movement of people, information or goods resulting in wasted time, effort and cost" [36]. In addition, unnecessary motion can cause twisting, lifting, reaching and walking. Therefore, this may lead to health problems and could endanger the safety of workers.

These types of waste can be reduced by implementing ergonomics perspectives. Once the wastes are eliminated, productivity and ergonomics conditions can be improved simultaneously.

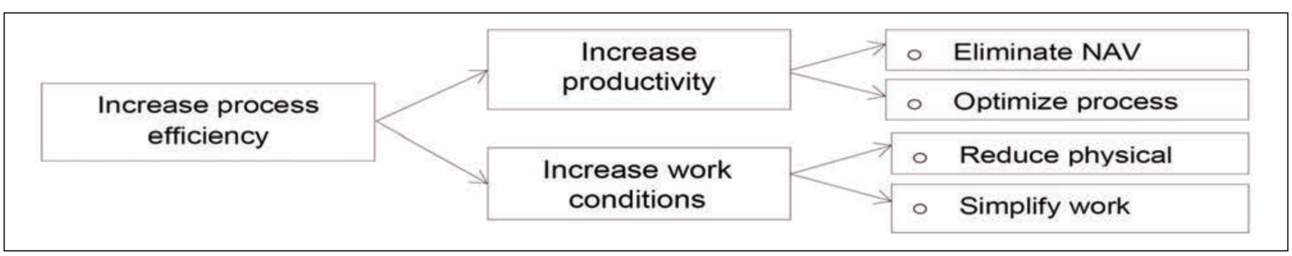

Fig. 2. The Critical to Quality (CTQ)

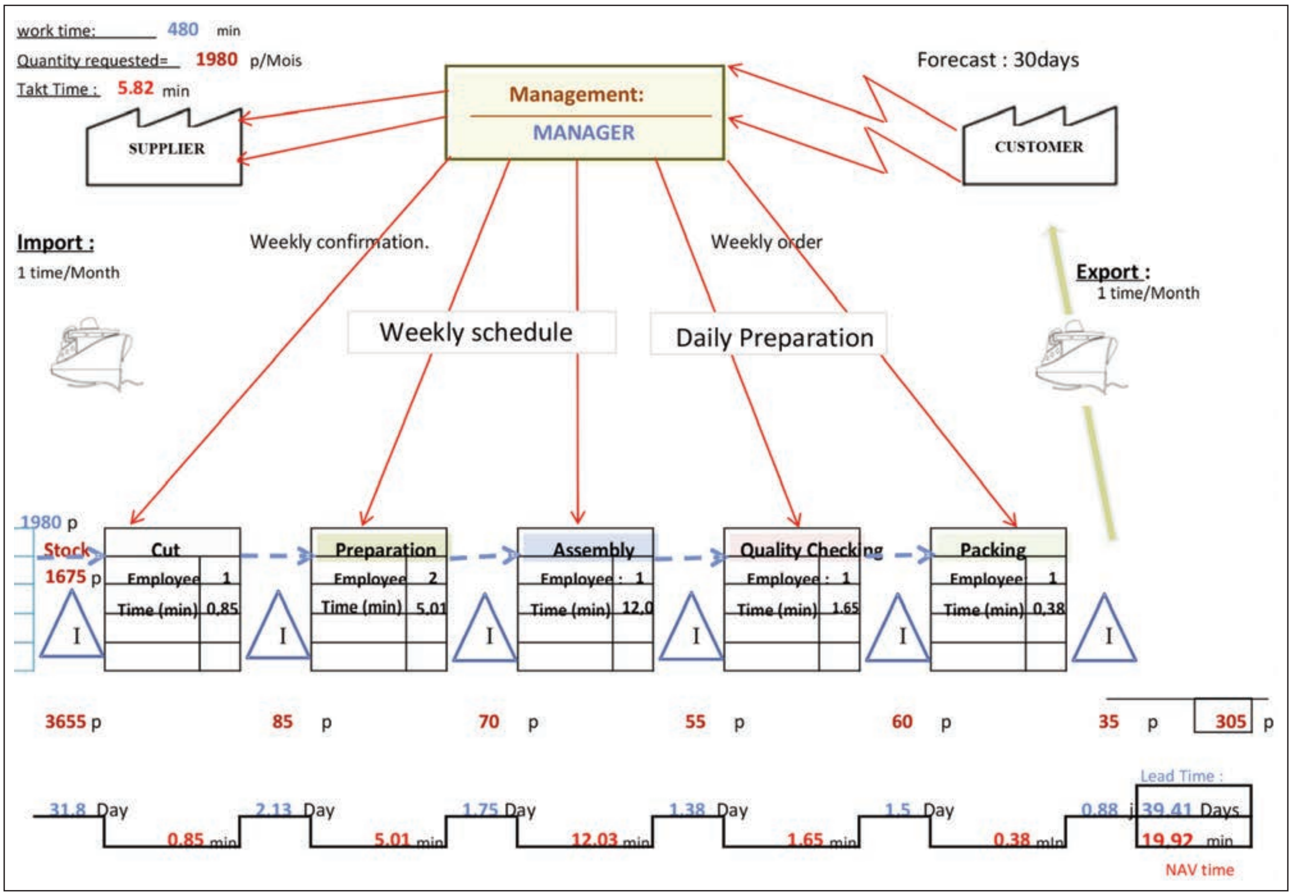

Fig. 3. Activated VSM

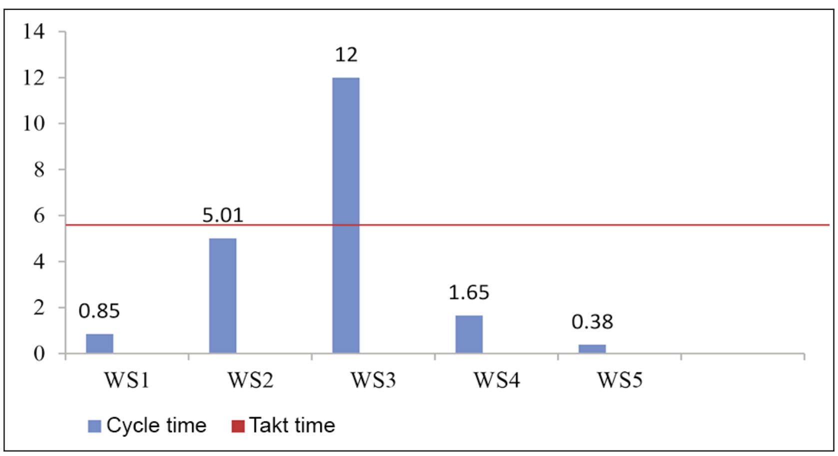

Fig. 4. Cycle times vs. takt time

Work and ergonomic conditions indicators

The three main risks that workers may face are related to musculoskeletal disorders: (WRMSDs) high force, awkward posture, and excessive repetition [37].

To conclude this research, data have been collected through a rapid upper limb assessment (RULA) worksheet. The different postures of workers have been closely observed from the viewpoint of RULA. This observation has been assessed by the RULA score. Also, the various scores have been compiled according to the RULA worksheet to get the RULA grand score. Table 1 presents the different categories of the risk levels of occupational tasks obtained after analysing the posture.

Since the RULA score of WS3 is in the medium risk zone, the working posture needs an immediate investigation. Training for proper sitting as well as standing posture is essential to reduce work-related musculoskeletal disorders (WMSDs) and improve the health condition of workers.

• ***ANALYZE PHASE***

The analysis phase examines the collected data to come up with a prioritized list of sources of variation [28] to identify the root causes of these sources and analyse the problems of variation process inefficiency, by using the result of the "Measure" step. At this stage, the causes of non-value-added activities were determined.

Analysis of different types of process waste

In this step, a real vision of the progress and deviations of the processes is carried out to analyse the flow and to determine through an in-depth study, the different types of the most repetitive waste. Also, possible root causes of problems are identified (figure 5). The causes of Ergonomics risk in the identified workplace are also determined (figure 6).

Table 1

RULA SCORE						
No.	Part of body	Work Station				
		WS1	WS2	WS3	WS4	WS5
Body Part A						
1	Upper Arm	2	2	1	1	2
2	Lower Arm	2	2	3	1	2
3	Wrist	2	2	4	1	2
4	Wrist twist	1	1	1	1	1
	Score A	3	3	4	1	3
5	Muscle use score	1	1	1	1	1
6	Force/load score	0	0	0	0	0
	Wrist and arm score	4	4	5	2	4
Body Part B						
1	Neck	2	2	3	1	2
2	Trunk	1	3	4	1	3
3	Legs	1	1	1	1	1
	Score B	2	4	5	1	4
4	Muscle use score	1	1	1	1	1
5	Force/load score	0	0	0	0	0
	Neck, trunk and leg score	3	5	6	2	5
	Final Score	3	5	7	2	5
	Level Risk	Low-risk Change may be needed	Medium risk Further investigation, Change soon	High Risk Investigate posture and change needed immediate	Low-risk Change may be needed	Medium risk Further investigation, Change soon

• ***IMPROVE PHASE***

Improve phase of the project has begun with brainstorming to ensure the success of the research and the choice of appropriate improvements to reduce NAV and resolve the problems that were identified in the previous phase.

The development of the action plan necessitates the employment of 10 actions, the Lean Six Sigma project team decided to classify the actions according to their importance. A selection graph allows you to quickly and simply identify the difficulty of implementing an action in comparison to the impact of the expected result.

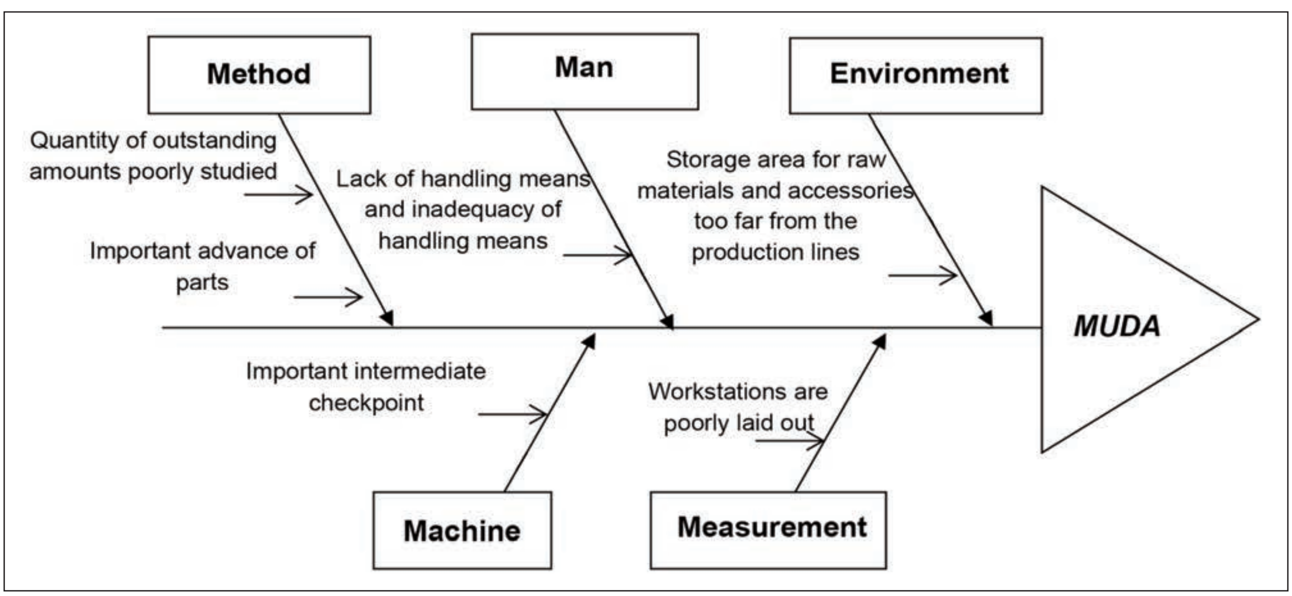

Fig. 5. Cause-effect diagram of MUDA

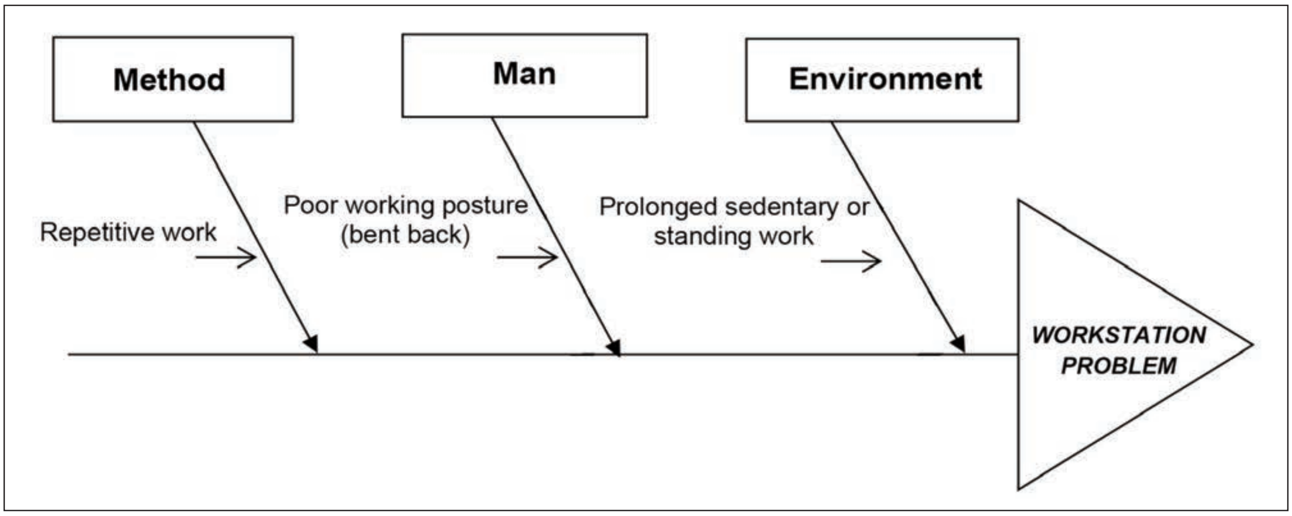

Fig. 6. Cause-effect diagram of work-station problem

Table 2 presents the decision-making matrix for the actions implemented with the following indications:

– The green box presents the actions that will be carried out;
– The red box presents the actions that will not be carried out; and
– The yellow box presents the actions that will be discussed.

Therefore, we will select the predefined actions in the action plan using the decision matrix presented in table 2.

Thus, we have developed an action plan which summarizes the actions implemented in order to reduce or eliminate the different types of Muda that have been encountered. The proposed corrective solutions are presented in table 3.

Table 2

DECISION MATRIX			
Strong	*Review the production schedule	*Minimize the quantity per batch launched	*Modify the supply system
Average	*Modify layouts	*Eliminate intermediate check *Establish an FMEA method	*Change the handling equipment *Study and arrange key workstations
Low	*Establish the follow-up sheet	*Minimize the transport distance by implementing of storage area in the production chain	*Install the machine with a table frame
Implementation difficulty / Impact	Low	Average	Strong

Table 3

PROPOSED CORRECTIVE SOLUTIONS	
Problem	**Corrective Solutions**
Motion	Minimize the transport distance by implementing of storage area in the production chain
Unnecessary inventory	Minimize the quantity per batch launched
Over-processing	Change the handling equipment Study and arrange key workstations
Unnecessary gestures	Change the handling equipment

Table 4

THE DISTANCE BEFORE AND AFTER IMPROVEMENTS	
Parameter	**Value**
Distance (m): before	255
Distance (m): after	123
Gain (m)	132
	51%

Table 5

THE RESULTS BEFORE AND AFTER IMPROVEMENTS			
Parameter	**Before improvements**	**After improvements**	**Gain**
Cycle Time	19.92 mn	19 mn	4,6 %
NAV	39.41 days	20,3 days	48,5 %
Distance	255 m	123 m	51 %

The proposed advancements were implemented on the ground to improve the stability of production processes to the extent of eliminating all types of waste such as unnecessary transport, unnecessary gestures, the excessive stock to stabilize the workstations henceforth, improving the performance of production processes from productivity and ergonomics point of view.

The current facility was improved. When setting up a new facility and applying 5S construction sites in the storage area, the distance travelled to the import/export area and the raw materials store is reduced. We achieved a 51% distance gain in manufacturing processes. The distance gains are presented in table 4. In addition, we have improved the layout of the work area. This eliminates handling tasks that require leaning posture or torsion.

The following table shows significant improvements after implementing the Lean Six Sigma-ergonomics process methodology.

• ***CONTROL PHASE***

The main objective of the Lean Six Sigma methodology is not only to improve process performance but also to achieve greater results in the long term [29]. The improvements that have been made were fully integrated into the training curriculum and process documentation. Information about the company's performance was shared with its employees. A regular audit of the settings was carried out. Once the project is completed, visual management, total productive maintenance and FMEA processes should be implemented to provide a visual aid to control the corresponding key input and output variables and ensure that the team can't go back to old habits.

CONCLUSION

The integration of ergonomics in continuous improvement activities gives the potential to obtain substantial gains in productivity and improve the working conditions of workers at the same time.

This study presents a model regarding the integration of ergonomics and LSS based on the DMAIC cycle. Indeed, in each phase of the DMAIC method, ergonomic tools and methodologies have introduced an additional ergonomic perspective.

The Present study was conducted in the textile industry specialising in the manufacturing of articles for technical use.

It began with a defined stage intended to increase VA activities by reducing NVA through waste removal, to around 48.5%, increasing the cycle time to 4.6 %. This was done by improving Ergo conditions by reducing workers' fatigue and discomfort.

The key finding of this work shows that the company needs to improve its ergonomics conditions and Lean Six by communicating and stressing the importance of the integration of those methods. Hence, the function of every clothing SME is to focus on these parameters.

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A study of types of silhouettes in women's clothing

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ABSTRACT – REZUMAT

A study of types of silhouettes in women's clothing

This research focuses on reviewing fashion trends from the past decade, with a particular emphasis on identifying unique silhouettes that deviate from traditional classifications. These new silhouettes often combine two existing shapes, straight and A-line, or feature unusual combinations like fitted and colourful styles. The study seeks to expand the classification of women's fashion silhouettes by introducing new combined shapes that reflect modern trends and consumer preferences. By integrating traditional and contemporary designs with qualitative and quantitative analysis, the research enhances statistical reliability and supports designers and retailers in creating and presenting more stylish, tailored garments.

The study enhances silhouette classification for dresses and skirts by identifying four distinct groups of dresses and three groups of skirts using Principal Component Analysis (PCA). Combined with an advanced system that integrates both qualitative and quantitative analyses, this approach provides deeper insights into consumer preferences and emerging trends. The use of aspect-based form factors offers an efficient method for classifying silhouettes and contributes to improving upon previous research in this area.

The findings of this study have practical applications for fashion designers, enabling them to create garments that more effectively express consumer tastes and better showcase clothing and decorations. Additionally, retailers can utilize these insights to improve the arrangement of merchandise in stores, thereby personalizing the shopping experience and boosting sales.

Keywords: *principal component analysis, dress silhouettes, skirt silhouettes, algorithm, sketches*

Studiu asupra tipurilor de siluete în îmbrăcămintea pentru femei

Această cercetare reprezintă o trecere în revistă a tendințelor modei din ultimul deceniu, punând un accent deosebit pe identificarea siluetelor unice care se abat de la clasificările tradiționale. Aceste siluete noi combină adesea două forme existente, cum ar fi linia dreaptă și linia A, sau includ combinații neobișnuite, precum stiluri mulate și colorate. Studiul își propune să extindă clasificarea siluetelor din moda feminină prin introducerea unor forme combinate noi, care reflectă tendințele moderne și preferințele consumatorilor. Prin integrarea design-urilor tradiționale și contemporane cu analize calitative și cantitative, cercetarea îmbunătățește validitatea statistică și sprijină designerii și retailerii în crearea și prezentarea unor articole de îmbrăcăminte mai stilate și personalizate.

Studiul îmbunătățește clasificarea siluetelor pentru rochii și fuste, identificând patru grupuri distincte de rochii și trei grupuri de fuste, utilizând Analiza Componentelor Principale (PCA). Combinată cu un sistem avansat ce integrează atât analize calitative, cât și cantitative, această abordare oferă perspective mai profunde asupra preferințelor consumatorilor și tendințelor emergente. Utilizarea factorilor de formă bazați pe aspect asigură o metodă eficientă de clasificare a siluetelor și contribuie la îmbunătățirea cercetărilor anterioare din acest domeniu.

Rezultatele acestui studiu au aplicații practice pentru designerii de modă, ajutându-i să creeze articole care exprimă mai bine gusturile consumatorilor și pun în valoare îmbrăcămintea și elementele decorative. În plus, retailerii pot utiliza aceste informații pentru a îmbunătăți aranjarea produselor în magazine, personalizând experiența de shopping și crescând vânzările.

Cuvinte-cheie: *Analiza Componentelor Principale, siluete de rochii, siluete de fuste, algoritm, schițe*

INTRODUCTION

The design elements are shape, colour and material. The shape can be viewed from the perspective of silhouette, contour, colour, type of textile fabric and detail [1]. Online shopping platforms pose a challenge for consumers and designers to make decisions when choosing clothing. Quickly identifying the apparel product will greatly improve the efficiency of both the shopping and design experience. Online platforms are a convenient way to find information about clothing, usually through images. While displaying an image is convenient for browsing, the information conveyed is limited and each user may perceive different features of the same image. If the clothing features in the images can be extracted objectively, these methods can provide consumers with a more convenient service.

The silhouette is a key element in conveying clothing style and aesthetics. There are five types of silhouettes known in modern women's fashion (A, H, X, T and O) [2]. Traditionally, defining the silhouette of a garment has depended on a visual, subjective assessment, with no explicit connection between subjective assessments and objective measurements.

Through the data analysis, Stangerup et al. [3] investigated and identified six silhouettes: A, H, O, T, X, and S. These became the main silhouettes: A, H, O, T, and X, with a special category of S. Although the technique has a useful way of predicting clothing trends, it is relatively less relevant for online clothing shopping.

Some classifications complement the basic silhouettes, such as "tunic", "balloon", and "hourglass" [4].

It is known that the silhouette of clothing has been used to establish, maintain, or even mask certain defects in the human body [5]. However, it remains unclear whether clothing styles can establish multiple identities determined by a particular culture. In the study by Zou et al. [6], the authors identify research limitations while providing a general, comprehensive literature review, as there are still challenges in this area: increased international collaboration, multilingualism of publishing platforms, and innovative approaches where historical perspectives can be presented within modern digital technologies and virtual fashion. The approach is aimed at academics, designers and practitioners interested in the development of this area of fashion design. Many researchers have shown interest in silhouette extraction and recognition.

According to Jiang et al. [7] Research is currently underway on intelligent silhouette recognition of pants to improve efficiency for both designers and consumers using online shopping platforms. The methodology uses DeepLabV3+ semantic segmentation with deep separable convolution, mainly to accelerate the computational speed and accurately detect H-shaped silhouettes. This can be seen in improvements in recognition accuracy and efficiency through the analysis and redefinition of pant silhouettes, more specifically in the optimization of dataset labels. Key findings include that improved recall rates, IoU, and PA metrics were achieved for various silhouettes. This means that overall classification and prediction accuracy for silhouette categories improves.

However, some limitations are also noted, particularly related to the fact that the dataset focuses on pants in standing poses and therefore generalizations are limited to other clothing poses only. Therefore, the goal of future research is to expand this dataset and improve these models for real-world applications in different clothing configurations.

Kumari's [8] research is based on the interrelationship between fashion and architecture, based primarily on the architectural monuments of India's Mughals and their influence on the silhouettes and motifs of clothing. By analysing the motifs and silhouettes – Monul monuments, Humayun's Tomb, Buland Darwaza, Itimad-ud-Daulah's Tomb, Taj Mahal and Badshahi Masjid – fashion designers developed contemporary Mughal clothing designs that reflect the same geometric, botanical and symmetrical motifs in these monuments. Other functional aspects, such as thermal comfort, also combine the curved architectural element with the bell-shaped silhouette of the garments, thus allowing free air circulation. This would therefore mean that some kind of standardized model for cross-cultural and trans-historical comparisons between architectural structure and clothing silhouette is likely to be developed, suggesting ways in which heritage conservation and modern fashion design can come together in this research.

At the end of his book, Lee [9] examines the relationship between clothing silhouettes through a theoretical framework that explains how clothing shapes and authenticates social identities. She applies modern clothing theory to ancient Greek evidence by analysing individual garments and their silhouettes in terms of how they were used to express aspects of identity such as gender, status, and cultural norms. The studies by Jalil et al. [10] and Atanasova et al. [11] suggest several advantages and limitations of silhouette analysis in children's clothing sizing. Benefits include solving problems with inconsistent sizing by producing garments tailored to both the garment type and the child's exact body characteristics and body shape. By using higher cutting techniques and 3D virtual fitting software such as CLO3D, sufficient precision is achieved in garment evaluation and construction. Variations in the shapes of children's silhouettes are identified that do not correspond to standard market sizes. Therefore, the fit is mainly affected by non-standard silhouettes such as spoons or oval shapes. This discrepancy highlights the need to design revised sizing charts and pattern-making techniques for the different body shapes of children to minimize fit and post-use waste in the production of children's clothing. Further research into international variations in silhouette shapes could ultimately help develop a more comprehensive sizing standard that would benefit consumers worldwide.

Online resources such as Treasury [12] and SewGuide [13] via resources that provide very detailed guidance on different dress silhouettes, such as A-line, sheath-line, and trumpet, and discuss how these shapes can accentuate or complement different body types. As Lee explains, part of this idea is to reveal social status and identity in ancient Greece through forms of clothing. Contemporary fashion trends like those on Byrdie [14] recognize the asymmetry of fashion dress silhouettes - for example, maxi dresses, mini dresses and drop waists – while shaping them to reflect personal identity and taste. Of course, the information presented in online resources is subject to further research in the available scientific literature.

Zhang et al. [15] achieved automatic measurement of traditional Chinese suits with A-line silhouettes based on the fuzzy C-means clustering method and key point positioning algorithm. Although this approach is efficient and flexible enough to measure the A-line of traditional Chinese costumes, it typically requires pattern adjustment for specific silhouettes.

According to Kazlacheva [16], fashion design theorists define silhouettes in four ways: depending on the degree of fit in the waist area, designation with letters, designation with geometric figures or comparison with a specific object. The analysis of silhouette types shows that there is no complete overlap between the four types of designations and the whole variety of silhouettes in modern clothing can be represented not only by the degree of fit in the waist area but only by letter designations, geometric shape designations and comparison with a specific subject. A match can only be found between the literal meaning and the similarity to a geometric figure. For example, A-shaped and trapezoidal, U-shaped and rectangular silhouettes are the same. Based on the study and analysis of the geometric shape and depending on the degree of fit of the product in three of the main areas of the female body (chest, waist and hips), a classification of silhouettes can be made (the S-shaped silhouette is not included in the classification, as it hardly finds a place in modern clothing): Close-fitting: Close-fitting on the chest, waist and hips, with a straight cut, no seam and a small opening at the bottom. Fitted: Cut lower at the waist, with a straight, small or no slit at the bottom. Semi-Fitted: Very slightly fitted, straight and with little or no slit at the bottom. Straight: This means that the fit from the waist down is very slight or non-existent. The cut is straight and typically features minimal or no slit at the bottom of the garment. Y-Shape: The bottom is straight but with very little or no cleavage, the top is visually enlarged with flared shoulders, including the collar and sleeve details. Inverted Y: fitted above the waist, cropped hem that starts below the hip line. X-shaped: Visually enlarged top with flared shoulders, details such as collar and sleeves and flared hem. Inverted V-waist: fitted cut with domed hem. O-Waist: Tapered at the waist with a flared, balloon-shaped hem [17]. A-Line: No tightness at the waist with flared A-line hem. O-line: Extra wide waist and hips, rounded shoulders and narrower hem. V-shaped – wide at the shoulders and then narrow at the bottom.

This classification is quite complete and includes the types of silhouettes introduced by great fashion designers such as Christian Dior and Yves Saint Laurent, as well as all the silhouettes included in the publications of other authors. Qin et al. [18] studied the silhouettes of a women's jacket. The authors identify waist, length, and hemlines as critical design elements in consumer perceptions of women's suit silhouettes and quantitatively demonstrate how variations in these elements affect consumers' fashion evaluations.

Hadija et al. [19] point out that qualitative methods – observation, interview and documentation – enable an in-depth study of clothing forms and their constructive details. Only this methodological approach enabled the development of a comprehensive and in-depth understanding of the characteristics and fit issues of the dresses studied by the authors. A disadvantage of this research is that qualitative methods allow deeper level insights; Reliance solely on observations, interviews, and documentation may have missed quantitative data that would have allowed for statistical validity or more comprehensive trend analysis.

According to McCoy [20], who examines Norman Norell's combined silhouette, the historical understanding of fashion and its relationship to societal norms, particularly misogyny, the idea here is to contextualize how fashion's creations reflect and perpetuate cultural attitudes towards women. Tsuru et al. [21] investigate the clusterability of dress silhouettes. The authors use principal component analysis, mean square shift and cluster analysis methods to group. The authors suggest dividing the silhouettes into three categories. A limitation of this study is that only dress silhouettes are considered.

Nie et al. [22] use region of interest and analysis of variance to quantify the factors corresponding to the X-shaped silhouette. Although the study measures the waist, chest, hem, hips and shoulders, it is not clear enough how these features are perceived and prioritized by a person when choosing clothing.

According to Radieva [23], who studies the relationships between the shapes of the lower part of the garments and the silhouettes developed by Christian Dior and Cristobal Balenciaga. The author uses the correspondence analysis method. A disadvantage of this development is that only the silhouettes and shapes of the two designers mentioned are analysed. Lee et al. [24] analysed 1389 photos of wedding dresses. Key elements are identified by ranking and categorizing 15 top designs, 11 sleeve designs and eight skirt silhouettes that are most popular and sought after by consumers. The results are useful for designers and manufacturers who want to create modern and aesthetically pleasing wedding dresses. A limitation of the study is that it is limited to wedding dresses published in a specific magazine over a specific period. The analysis of available literary sources shows that it is necessary to look for methods of quantitative analysis to ensure sufficient accuracy of results in the study of clothing silhouettes, the results of which can be effectively used in the design and identification of consumer preferences. It is necessary to leverage elements of artificial intelligence and machine learning to more accurately predict trends and group silhouettes and shapes, compared to traditional methods that use qualitative analysis and basic statistical techniques. In most cases, a specific type of silhouette and shape is examined. A more comprehensive analysis of silhouette and clothing types is required. Dress silhouettes are one of the most studied elements. Few studies were found on other clothing items such as skirts. It is necessary to find a sufficiently effective method of grouping the silhouettes of women's clothing. This grouping should be suitable for online applications where silhouettes are used in consumer clothing selection. The study of fashion trends of the last decade (2014–2024) shows that the following silhouettes can be found in the collections of fashion designers: fitted, semi-fitted, Y-shaped, Y-shaped reverse, X-shaped and U-shaped below the waist, as well as silhouettes that cannot be called one of the most complete of the studied classifications, the 12-silhouette classification of Kazlacheva [16, 17]. These silhouettes, presented in the last fashion season, cannot be labelled in any of four possible ways: by the fit in the waist area, by the letter designation, by being identified by a geometric figure or an object. Some of these silhouettes are extremely asymmetrical, which again contradicts the idea of silhouette representation. However, these silhouettes can be presented as a combination of several existing silhouettes, for example, a silhouette that combines straight and A-shaped, or a silhouette that combines fitted and floral. Therefore, the classification of the twelve silhouettes can be supplemented by another combined silhouette.

The purpose of the study is to develop and expand the classification of silhouettes in women's clothing by identifying and introducing new combined silhouettes that meet the requirements of modern design trends and consumer tastes. This development adds more completeness and sophistication to the categorization system by including not only the classic but also the more modern silhouette shapes that would be suitable for the dress and skirt design trends. It is also expected to bring together qualitative and quantitative analysis, increasing the statistical validity and utility of silhouette classifications to help designers and retailers design and present more fashionable, tailored garments.

MATERIAL AND METHODS

29 silhouettes of dresses were analysed in the work. Also, 40 silhouettes of skirts and 19 necklines are available in the available literature [25, 26]. A total of 24 basic formulas were used to determine silhouette shape coefficients [27]. They have the following form:

$$K_1 = \frac{P^2}{A} \tag{1}$$

$$K_2 = \frac{D}{d} \cdot 100,\ \% \tag{2}$$

$$K_3 = \frac{P^2}{4\pi A} \tag{3}$$

$$K_4 = \frac{1}{K_3} \tag{4}$$

$$K_5 = \frac{A}{A_{ideal}} \tag{5}$$

$$K_6 = \frac{A}{A_{mr}} \tag{6}$$

$$K_7 = \left(\sqrt{\frac{D}{2}} + \sqrt{\frac{d}{2}}\right)\frac{\sqrt{\frac{D}{2}}}{d} - 1 \tag{7}$$

$$K_8 = \frac{\frac{d}{2}}{\frac{D}{2}} \tag{8}$$

$$K_9 = \left(\frac{D}{2} - \frac{d}{2}\right)\frac{D}{d^2} \tag{9}$$

$$K_{10} = \frac{d}{D} - 1 \tag{10}$$

$$K_{11} = \frac{\frac{D}{2} - \frac{d}{2}}{d} \tag{11}$$

$$K_{12} = \frac{D - d}{D} \tag{12}$$

$$K_{13} = \frac{dD}{2} - 1 \tag{13}$$

$$K_{14} = \frac{(D + 2)(d + 2)}{2D^2(-dD + D + 2)} \tag{14}$$

$$K_{15} = \frac{P^2}{4\pi A} - 1 \tag{15}$$

$$K_{16} = \frac{d}{D} \tag{16}$$

$$K_{17} = \frac{D}{d} - 1 \tag{17}$$

$$K_{18} = \frac{D}{d} \tag{18}$$

$$K_{19} = \frac{dD}{2} \tag{19}$$

$$K_{20} = \frac{D - d}{2d} \tag{20}$$

$$K_{21} = \frac{P}{D} \tag{21}$$

$$V = \frac{4}{3}\pi\,\frac{D}{2}\left(\frac{d}{2}\right)^2 \qquad K_{22} = \frac{3V}{4\pi D d^2} \tag{22}$$

$$K_{23} = \frac{P}{D - P} \tag{23}$$

$$K_{24} = \frac{D}{D - P} \tag{24}$$

where d is a minor axis of the silhouette; D is a major axis of the silhouette; P is the perimeter; A is the area; A_{ideal} is the ideal area calculated along the major and minor axis of the silhouette; A_{mr} is the area of the rectangle enclosing the silhouette; V is volume calculated along the major and minor axis.

The silhouettes of dresses are presented in figure 1. They are not grouped but presented in the order of the literary sources listed above. The silhouettes of the dresses with their serial numbers are marked Dx. Dress silhouettes range from fitted D1 and sheath D3 to loose including tent D7 and peasant dress D19. Functional and versatile styles like the shirt dress and wrap dress provide comfort without sacrificing style, so they can be worn for any occasion. The ball gown and empire are formal silhouettes that exude classic elegance for special occasions. The innovative and

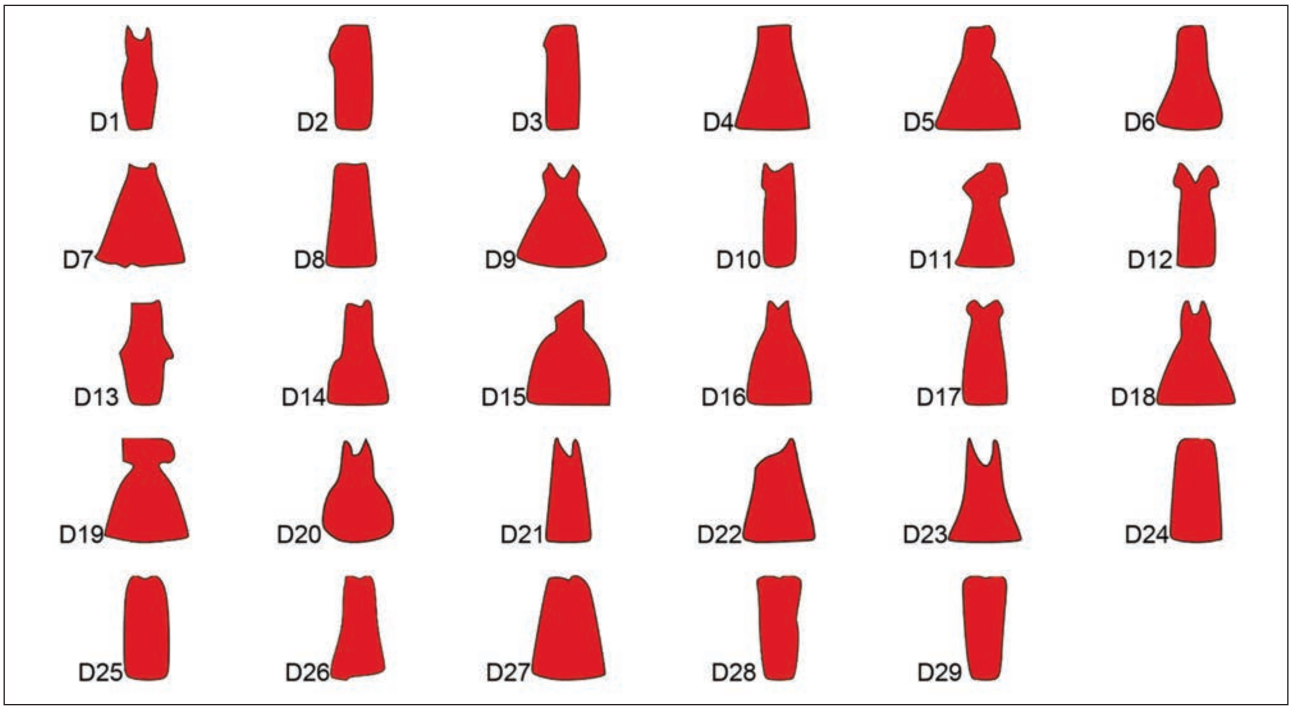

Fig. 1. Dress silhouettes

modern contours are the low waist and trapeze models that refresh the modern fashion look. Peplums and bouffants are silhouettes that pay more attention to structural elements for their visual impact. Casual clothing consists of a sheath dress and a tunic, which emphasizes freedom of movement and calm. In addition, nostalgic and charming dresses reflect themes related to history and culture. Different silhouettes suit different tastes, occasions and body types. They embody timeless and innovative fashion.

Table 1 shows the names of the used silhouettes of dresses.

Skirt silhouettes are shown in figure 2. They are not grouped but presented in the order of the literary sources listed above. The silhouettes of the skirts with their serial numbers are marked Sx. Skirt silhouettes range from some of the all-time classics such as Pleated (S1), A-line (S9) and Straight (S3) to later innovations such as Asymmetrical (S27) and Trumpet (S28). The silhouettes have different lengths and different cuts, suitable for many occasions and tastes. Some styles emphasize textural and textural elements such as accordion (S17 or rustle (S18) and introduce practical elements into their design such as wrap (S11). Gypsy (S15) and sarong (S21) represent cultural inspirations, where Complicated constructions are visible Fix Box Pleat, S23. Variations suit taste, occasion and different body types – all classic and contemporary trends.

Table 2 shows the names of the skirt silhouettes used.

A basic image analysis algorithm was used [28–30]. It consists of the following steps: the RGB (Red, Green and Blue) image is loaded; it can be converted into an HSV (Hue, Saturation, Value) model; The colour component S (HSV) is taken and the data in this matrix is normalized to the range [0, 1]. The image is converted to black and white with a binarization threshold of T = 0.22. The Region Props feature defines the major and minor axes, area and perimeter based on the object (silhouette) in the image. These features were used in the calculation of 24 silhouette form factors. Figure 3 shows the steps of the algorithm used. First, the original RGB image is presented, followed by conversion to S(HSV) colour space. A black-and-white image was then cre-

Table 1

NAMES OF DRESS SILHOUETTES									
№	**Name**	**№**	**Name**	**№**	**Name**	**№**	**Name**	**№**	**Name**
D1	Body-con	**D7**	Tent	**D13**	Peplum	**D19**	Peasant	**D25**	Tunic
D2	Shift	**D8**	Blouson	**D14**	Drop waist	**D20**	Balloon	**D26**	Princess
D3	Sheath	**D9**	Halter	**D15**	One shoulder	**D21**	Baby-doll	**D27**	Trapezoid
D4	Strapless	**D10**	Slip	**D16**	Ball gown	**D22**	Jumper	**D28**	Pegged
D5	Bouffant	**D11**	Shirt	**D17**	Empire	**D23**	Sun	**D29**	V-Line
D6	A-Line	**D12**	Wrap	**D18**	Apron	**D24**	Yoke	-	-

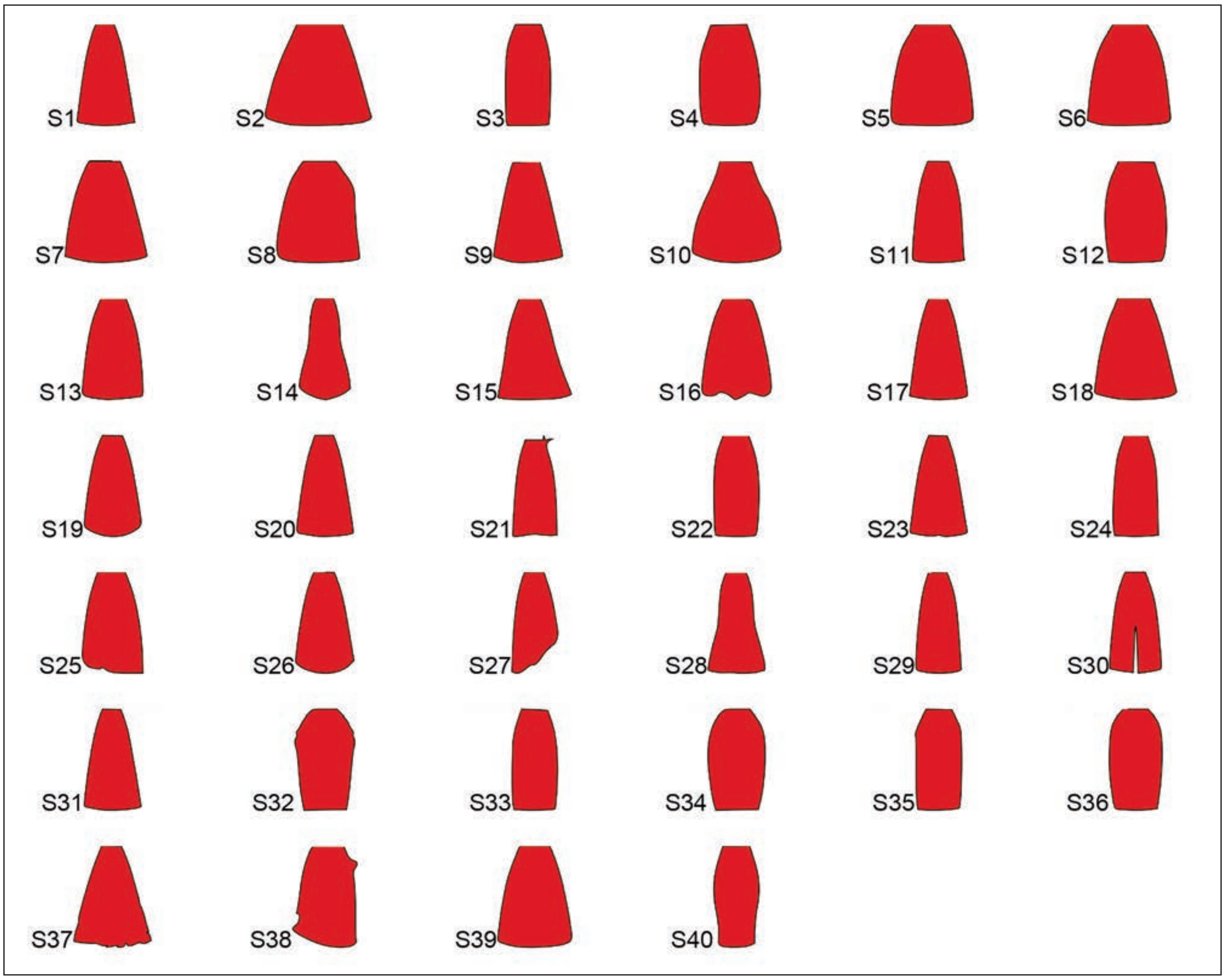

Fig. 2. Skirt silhouettes

Table 2

NAMES OF SKIRT SILHOUETTES

№	Name	№	Name	№	Name	№	Name	№	Name
S1	Pleated	**S9**	A-Line	**S17**	Accordion	**S25**	Layered	**S33**	Fall
S2	Short	**S10**	Bell-Shaped	**S18**	Ruffled	**S26**	Panelled	**S34**	Sheath
S3	Straight	**S11**	Wrap	**S19**	Full	**S27**	Asymmetrical	**S35**	Peplum
S4	Underskirt	**S12**	Mini	**S20**	Gored	**S28**	Trumpet	**S36**	Pegged
S5	Bubble	**S13**	Wraparound	**S21**	Sarong	**S29**	Circle	**S37**	Tulle
S6	Tulip	**S14**	Mermaid	**S22**	Fly	**S30**	Culottes divided	**S38**	Ruffled
S7	Knife pleated	**S15**	Gypsy	**S23**	Fix box peat	**S31**	Fixed box pleat	**S39**	Inverted pleated
S8	Draped	**S16**	Godet	**S24**	Buttoned straight	**S32**	Cowl	**S40**	Pencil

ated with only the silhouette isolated for easier analysis. Basic dimensions are then extracted from the black-and-white image to identify and measure the properties of the regions present. Finally, the calculated shape coefficients describing the properties of the silhouette shapes are displayed for further study and classification.

The selection of meaningful shape indices was carried out using the ReliefF method [31]. This method solves the problem of dividing data into classes. Essentially, the data set is repeatedly sampled and then the relevance of the features is assessed in terms of their ability to distinguish between instances that are close to each other, within the same class, or across classes. The important steps by which the method works are: A random sample is taken from the data set; the nearest neighbours of the same class and different classes are found; and the weights of the data are analysed based on how well they could distinguish the sampled instance from its neighbours. The ReliefF method captures relationships between features and has the advantage of

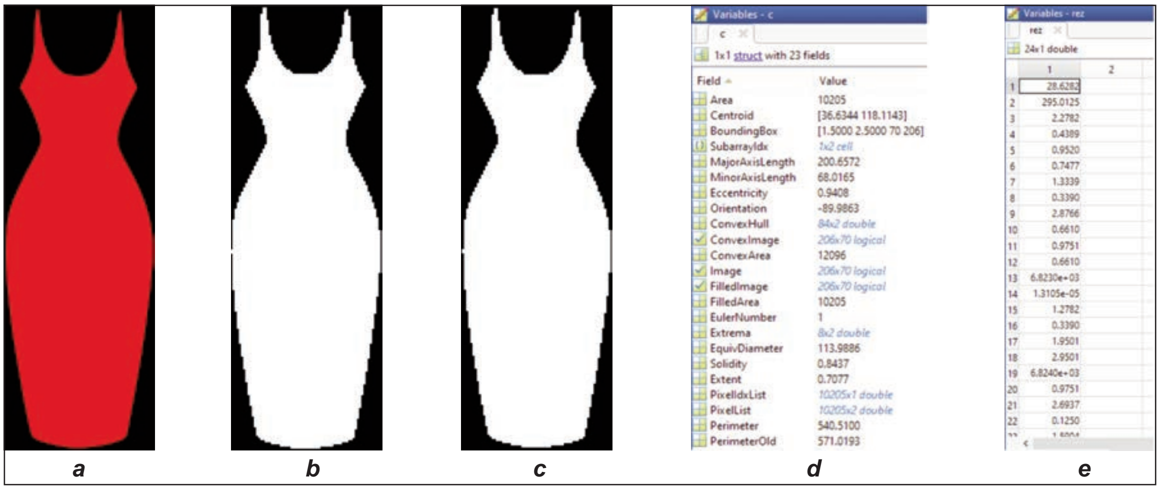

Fig. 3. Stages of the algorithm for calculation of silhouettes form coefficients: *a* – original RGB image; *b* – S(HSV) image; *c* – black and white image; *d* – results from the implementation of *region props* function; *e* – calculated coefficients of the form

being robust to noise. Shape indices whose weight coefficients have a value greater than 0.6 are considered meaningful [32].

Feature vectors are defined from the selected shape coefficients. The principal component analysis (PCA) method [33] was used to group silhouette types based on reduced data from the selected feature vectors. It is a statistical dimensionality reduction technique that preserves as much variability as possible in the data set. PCA basically does the following: the data set is standardized to a mean of zero and a standard deviation of one for each feature. The covariance matrix was calculated, thereby determining the relationship between the different features. The eigenvalues and eigenvectors of the covariance matrix were calculated. The eigenvectors of the selected principal components (PC) are identified as those corresponding to the directions of maximum variance consistent with the eigenvalues; The data is projected onto a new subspace containing the selected principal components. PCA converts the input data into a new coordinate system, reducing the number of dimensions in the data and preserving the important information.

The software products Matlab 2017a (The Mathworks Inc., Natick, MA, USA) and MS Office 2016 (Microsoft Corp., Washington, USA) were used for data processing.

RESULTS

A selection of meaningful shape coefficients was made. The results are shown in figure 4. Those features whose weighting coefficients have a value above 0.6 are significant. In the figure, this limit is marked "0.6 Circle". For the silhouettes of dresses and necklines, 5 features are informative, while for skirts there are 4 features. This shows that the silhouettes of skirts can be described with a smaller

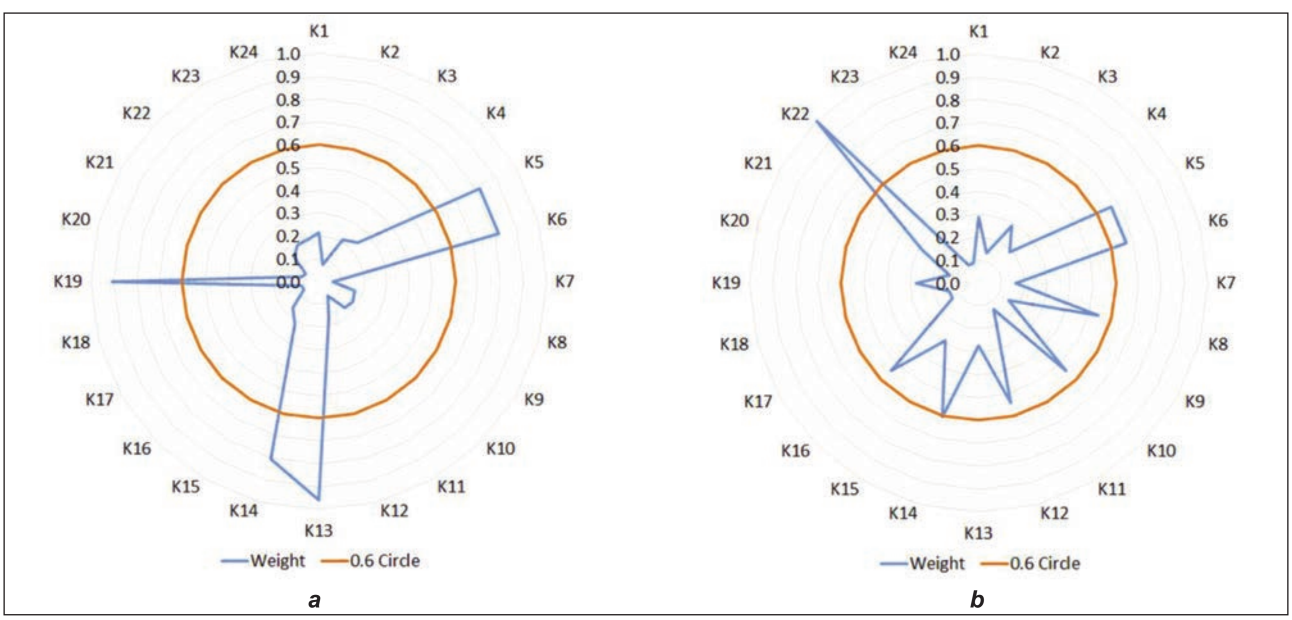

Fig. 4. Selection of informative coefficients of form for silhouettes: *a* – dress; *b* – skirt

number of features. The 24 features are analysed and then only informative are used. There are two feature vectors. FVD contains 5 informative features of dresses, and FVS contains 4 features for skirts. These feature vectors are reduced to 2 principal components.

After selection, vectors of the most meaningful shape coefficients of the object groups under consideration were obtained. Feature vectors for dress silhouettes (FVD) and skirts (FVS) each consist of five informative shape coefficients. The silhouettes of skirts and dresses have in common the coefficients K5, K6 and K14. In summary, there is a sufficiently large agreement in the information coefficients for skirts and dresses.

The vectors of informative shape coefficients have the form:

$$FVD = [K5\ K6\ K13\ K14\ K19] \quad (25)$$

$$FVS = [K5\ K6\ K14\ K22] \quad (26)$$

The feature vectors were reduced to two principal components using the PCA method. The two principal components for all cases describe over 95% of the variance in the data. The obtained results are visualized together with the resulting groups of silhouettes in figure 5.

With the silhouettes of the dresses, four groups can be formed, which are located in the four quadrants of the diagram. In the first quadrant (+PC1, +PC2), a group of X-shaped silhouettes is formed, which have a more modern look. In the second quadrant (–PC1, +PC2), a group of A- and I-shaped silhouettes is formed. In the third quadrant (–PC1,–PC2) again, the group mainly consists of A- and I-shaped silhouettes, which embody the traditional and minimalist style. X- and Y-shaped silhouettes are grouped in the fourth quadrant (+PC1,–PC2).

In skirt graphics, three groups of silhouettes are formed. The first group covers the first and fourth quadrants. This group includes silhouettes with an innovative, practical, and flexible design. The second group is in the second quadrant, covering silhouettes with a structured formal design, and the third group is in the third quadrant, containing classic and conservative silhouettes. The first group covers the most silhouettes.

When analysing combined silhouettes, several main types can be distinguished: Combined symmetrical silhouette; combined asymmetrical silhouette; combined silhouette of two or more parts; Combined silhouette transformer; and A combined silhouette of two or more basic silhouettes. If you look at the silhouette trends of the last few years, you'll notice how difficult it is to define the silhouette of women's clothing. This is due to the increasing consumer demand for clothing with an unusual and different appearance as well as a unique and memorable effect. The design of women's clothing in a combined silhouette is shown in figure 6. The silhouettes consist of a combination of a Y-shape above the waist and an O-shape below the waist. The combination of V shape, asymmetrical Y shape at the top and O shape below the waist. A combination of a Y-shaped bodice above the waist with a fitted peplum and a separate straight skirt. A combination of a bustier dress in a fitted silhouette and a detachable peplum. A combination of fitted and X-shaped.

To visualize how the combined silhouette designs will look in the finished garments (figure 7), the AI art generation tool NewArc.ai [34] was used. The software allows us to transform our sketches into stunning images. NewArc.ai is transforming design education in fashion, textiles, products and architecture through its AI-driven rendering technology. Users can create high-quality renderings by providing initial images and prompts and viewing a range of fabrics and styles. This innovation allows designers to effectively explore different fabrics and materials, increasing creativity and learning outcomes. In the fashion and textile sector, NewArc.ai stands out for its clear representation of various fabrics such as satin, velvet, silk and cotton. This tool is invaluable for designers as it allows them to visualize their designs in different materials without the need for physical prototypes.

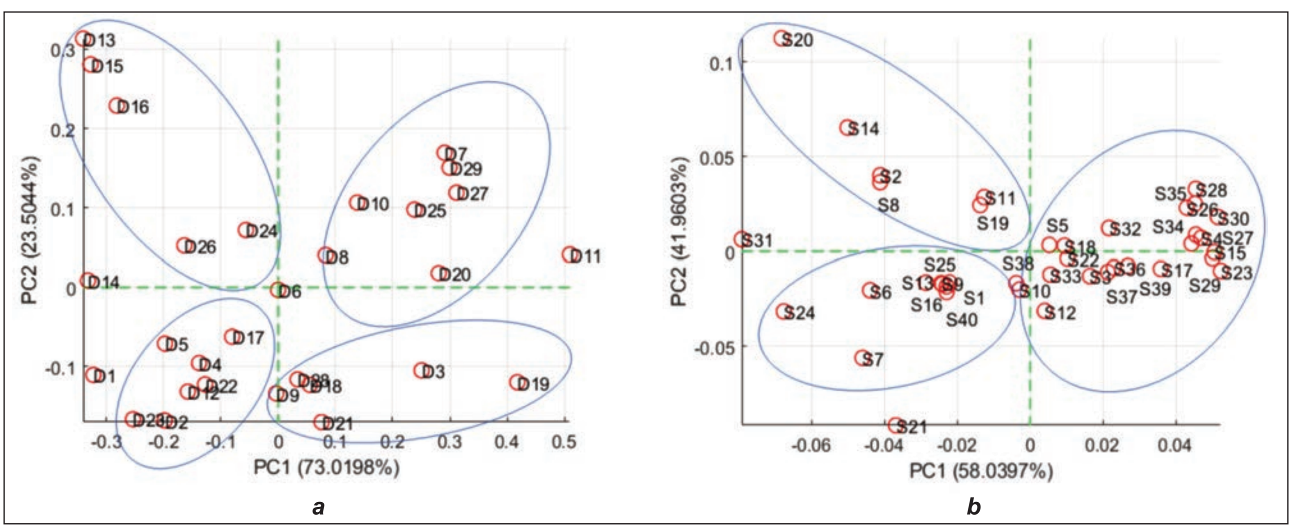

Fig. 5. PCA for grouping of silhouettes: *a* – dress; *b* – skirt

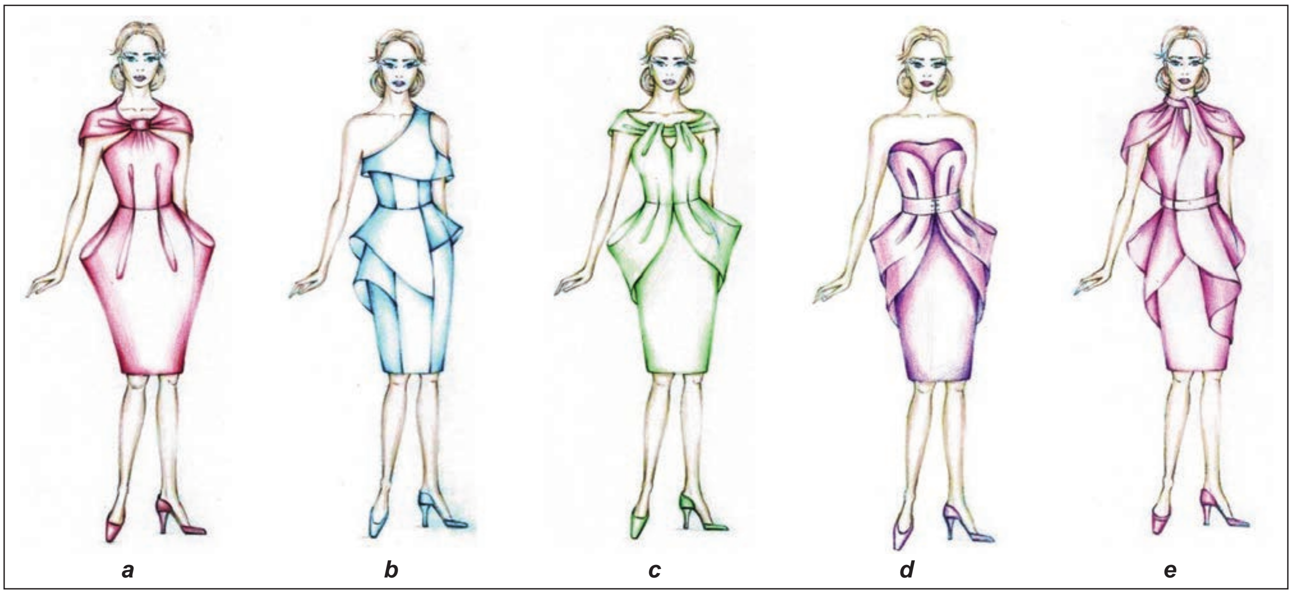

Fig. 6. Results from the design of combined silhouettes: *a* – combined symmetrical silhouette; *b* – combined asymmetric silhouette; *c* – combined silhouette of two parts; *d* – combined silhouette transformer; *e* – combined silhouette of two basic silhouettes

Fig. 7. The combined silhouettes generated in NewArc.ai

DISCUSSION

The results of Tsuru et al. [18] have been supplemented and refined. The authors only analyse the silhouettes of dresses. They use PCA, MSD (Mean Squared Displacement) and cluster analysis. The four clothing groups obtained in this work directly solve the MSD grouping problem. Using PCA-reduced form factors, four groups of dresses were directly obtained in this work, while Tsuru et al. [18] obtained this after processing the data using cluster analysis. This shows that using form factors that represent ratios is a better option than using "raw" measurements. Compared to MSD, PCA applies dimensionality reduction, variance maximization to include significant differences, and noise filtering for clear clustering. Its multivariate approach – considering multiple variables simultaneously – uncovers complex relationships and interactions that MSD may miss entirely. In addition, PCA allows interpretability through the visualization of the main components, which supports an intuitive understanding of the data structure itself, whereas MSD lacks this. Additionally, PCA's scalability and flexibility put it at the forefront of various datasets and analyses, thereby expanding its applicability compared to MSD, a dimensionality reduction technique whose uses tend to be extremely limited. In this way, PCA provides a solid framework for grouping objects, captures the underlying variations in the data, and improves clarity throughout the analysis so that it remains reliable.

Qin et al. [18] studied variations in the silhouette of women's jackets and found that waist, length, and hems are important design elements in consumers' perceptions of fashion. Our research contributes to their findings by better categorizing silhouettes, examining different types of silhouettes, and proposing new silhouettes that further advance knowledge of consumer preferences and perceptions in fashion design. Hadija et al. [19] used qualitative methods that examined the shapes and construction details of the garments in-depth, providing valuable insights into the fit and performance of the garments. However, our approach complements this by using qualitative analysis supported by quantitative analysis for statistical validity and comprehensive trend analysis, thus addressing the potential limitations of purely qualitative methods. Nie et al. [22] quantified the factors affecting X-shape, including waist, chest, hem, hip, and shoulder measurements; However, more knowledge is needed about how these factors influence clothing choices. This deeper analysis was done in this work.

CONCLUSIONS

An analysis of fashion trends for the subglacial decade shows that there are silhouettes that cannot be assigned to any of the most comprehensive of the studied classifications, the 12-silhouette classification. Some of these silhouettes are extremely asymmetrical, which again contradicts the idea of silhouette representation. However, these silhouettes can be presented as a combination of several existing silhouettes, for example, a straight and A-shaped silhouette or a fitted and colourful silhouette. Therefore, the classification of the twelve silhouettes can be supplemented by another combined silhouette. The presented author's analysis distinguishes several types of combined silhouettes, including symmetrical, asymmetrical, multifaceted, transforming and mixtures of the basic silhouettes. Such detailed categorization will help meet consumers' growing needs for originality and memorable designs in their clothing. In women's clothing silhouettes, the trend is developing to create designs that are non-standard but have a great visual impact.

The results obtained in this development help to improve the knowledge and classification of silhouettes for dresses and skirts, allowing us to identify specific, highly distinguishable groups and establish new silhouettes. Dress silhouettes are divided into four groups, each located in a different quadrant of the PCA diagram: modern X-shaped silhouettes in the first quadrant; A- and I-shaped silhouettes in the second and third quadrants for traditional and minimalist styles, respectively; and finally, the X and Y shaped silhouettes occupy the fourth quadrant. Three groups of skirts can be quickly identified: the first and fourth quadrants with innovative, flexible designs; structured, formal designs in the second quadrant; and classic, conservative silhouettes in the third quadrant.

Compared to previous research, our study offers a more sophisticated classification system and new silhouettes that reveal additional insights into consumer preferences. Our mixed silhouette approach combines in-depth qualitative and quantitative analysis for statistical validity and comprehensive trend analysis. This article explores proportion-based form factors to provide an efficient method for classifying silhouettes – a system that better solves the grouping problems of previous studies and provides a clearer understanding of dress and skirt design trends.

The results obtained in this study are suitable for practical application. Through better categorization and the development of new silhouettes, designers can make clothing more presentable and fashionable so that they are closer to consumer tastes and thus improve fashion. Clear delineation of silhouettes forms the basis for how designers can effectively implement the visual and functional impact of different clothing styles. This is particularly valuable when designing specialized collections to meet consumers' diverse needs for specific, unique and memorable clothing.

Furthermore, identifying combined silhouettes and studying them for functional aspects, air circulation and thermal comfort would be helpful in developing a much more comfortable and practical garment. Fashion brands can use these insights to improve garment fit and performance, reduce returns and increase customer satisfaction. The results achieved in this development allow retailers to better organize goods in shop windows and make it easier for consumers to find suitable clothing according to their tastes and shape preferences. Personalization can increase sales and improve customer satisfaction throughout the entire shopping experience.

The limitations of the current work are recruiting dress and skirt silhouettes that do not truly represent the global market. The sample size cannot capture this enormous diversity of consumer perceptions and preference variables. Additionally, reliance on certain analytics technologies may impact applicability for some designers and brands. Such future studies should be expanded to a wider range of garments with greater sample diversity, followed by extensive consumer surveys to identify perceptions with demographic-specific knowledge. Combining new technologies such as AI and machine learning to further fine-tune silhouette analysis; Exploring functional and sustainable elements of silhouettes for improved material utilization, garment durability and sustainable environmental impact.

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Investigation of thermal insulation of cold protective clothing under different underwear and ambient conditions

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ABSTRACT – REZUMAT

Investigation of thermal insulation of cold protective clothing under different underwear and ambient conditions

In this study, the thermal insulation of cold protective outerwear under various clothing combinations and ambient conditions was estimated using a thermal manikin. A series of cold protective outerwear, worn with various types of underwear, were evaluated in a conditioned room to explore the dependence of outerwear thermal insulation on the underwear. Besides, statistical studies were utilized to study the effect of ambient temperature on the thermal insulation performance of cold protective clothing ensembles. The thermal insulation of outerwear was observed to be different when it was measured with various fit styles, thicknesses and combinations of underwear. These discrepancies can be attributed to the variation in the air gap between clothing layers and the presence of stagnant air within the porous clothing. Furthermore, the ambient temperature was found to be a dominant factor affecting the thermal insulation performance of the clothing ensembles with high air content, as the airflow inside the porous material may be aggravated by the larger temperature difference between the clothing and the environment. Based on this study, ambient conditions for the assessments of different kinds of clothing can be divided into five groups, simulating the actual-used scenarios. The findings of this study are anticipated to enhance the comprehensiveness of thermal insulation evaluations for clothing systems and assist in the identification of optimal clothing choices for diverse ambient conditions.

Keywords: *clothing thermal insulation, underwear, cold protective outerwear, fit, ambient conditions*

Investigarea izolației termice a îmbrăcămintei de protecție exterioară pentru diferite tipuri de lenjerie de corp și condiții ambientale

În acest studiu, izolația termică a îmbrăcămintei de protecție exterioară în diferite combinații de articole și condiții ambientale a fost estimată folosind un manechin termic. O serie de articole de îmbrăcăminte de protecție exterioară, purtate cu diferite tipuri de lenjerie de corp, au fost evaluate într-o cameră condiționată pentru a explora dependența izolației termice a îmbrăcămintei exterioare asupra lenjeriei de corp. În plus, studii statistice au fost utilizate pentru a studia efectul temperaturii ambientale asupra performanței de izolare termică a ansamblurilor de îmbrăcăminte de protecție exterioară. S-a observat că izolația termică a îmbrăcămintei exterioare este diferită atunci când a fost măsurată cu diferite stiluri de ajustare pe corp, grosimi și combinații de lenjerie de corp. Aceste discrepanțe pot fi atribuite variației spațiului de aer dintre straturile de îmbrăcăminte și prezența aerului stagnant în interiorul îmbrăcămintei poroase. Mai mult, s-a constatat că temperatura mediului ambiant este un factor dominant care afectează performanța de izolare termică a ansamblurilor de îmbrăcăminte cu conținut ridicat de aer, deoarece fluxul de aer din interiorul materialului poros poate fi afectat de diferența mai mare de temperatură dintre îmbrăcăminte și mediul exterior. Pe baza acestui studiu, condițiile ambientale pentru evaluările diferitelor tipuri de îmbrăcăminte pot fi împărțite în cinci grupuri, simulând scenariile utilizate în mod real. Se anticipează că rezultatele acestui studiu vor spori exhaustivitatea evaluărilor de izolare termică pentru sistemele de îmbrăcăminte și vor ajuta la identificarea alegerilor optime de îmbrăcăminte pentru diverse condiții ambientale.

Cuvinte-cheie*: izolație termică a îmbrăcămintei, lenjerie de corp, îmbrăcăminte de protecție exterioară, corespondență, condiții ambientale*

INTRODUCTION

Clothing thermal insulation property is an important factor affecting human thermal comfort [1, 2]. In some extremely cold conditions, the physiological function of humans gradually diminishes when the clothing cannot provide sufficient thermal insulation [3]. Therefore, the thermal property of clothing should be accurately measured to keep human thermal comfort in various ambient conditions.

Some researchers worked on the clothing thermal insulation performance by perceptual assessment [4, 5]. Although such subjective assessment is meaningful to understand the perceptions of subjects, it tends to be less reproducible and can expose the subjects to dangerous conditions. Therefore, objective methods were developed to measure clothing thermal insulation. The guarded hotplate method is widely adopted to estimate the thermal insulation of fabric [6, 7]. As it is limited to measuring the thermal properties of clothing, thermal manikins are further adapted to estimate the thermal insulation of the whole clothing system [8, 9]

Thermal manikins are considered the most effective tools to estimate clothing thermal insulation. Several standards have addressed the measurement specification of the thermal insulation using a thermal manikin, since clothing thickness, size, fit and test conditions can influence the thermal insulation performance of the clothing system [10–13]. Cold protective outerwear is always worn with underwear to keep human thermal comfort. The fit styles, combinations and structure of underwear may cause differences in the thermal insulation of outerwear, while the influence introduced by underwear on the deduced outerwear thermal insulation was rarely studied. In addition, testing conditions, such as ambient temperature and relative humidity, are usually kept constant for different kinds of clothing. However, it was reported that the clothing thermal insulation performance can be influenced by the ambient conditions as the airflow in the porous clothing can be enhanced due to the higher temperature difference between human skin and ambient conditions [7].

In the present work, a series of studies was employed to estimate the effect of underwear on the thermal insulation of cold protective outerwear. Besides, the dependence of thermal insulation performance of clothing on the ambient temperature was also investigated. Based on the statistical analysis of winter temperature and humidity of 298 major cities in China, ambient conditions for the assessments of various clothing ensembles were further proposed to simulate the actual-used scenarios. The obtained results could be useful for more accurately evaluating the thermal insulation of clothing systems and help to choose the most suitable clothing for various ambient conditions.

MATERIALS AND METHODS

Samples

A total of seven underwear and nine outerwear (manufactured by K-Boxing Co., Ltd, China) with the same clothing size L were selected in this study. The size of the experimental samples fitted the dimension of the thermal manikin appropriately. Table 1 presents the detailed characteristics of samples, including manufacturing method, structure, colour, fit, material, mass density, thickness and porosity. Samples U1~U7 are underwear and samples O1~O9 are outerwear. Softening finishing was applied to all underwear samples. All samples were dark-coloured to minimize the influence of colour on radiative heat transfer.

Method

The thermal insulation performance of clothing was measured using a thermal manikin (LD-1, Laizhou Electronic Instrument Co., Ltd., China) [8,14]. As shown in figure 1, the front and back of the testers are two independent curved elements. Different sizes of clothes can be measured by adjusting the chest, waist and hem circumferences. The middle parts are testing plates encircled by the guarded plates at the

Table 1

CHARACTERISTICS OF TESTING ENSEMBLES

No.	Product name	Manufacturing method/colour/structure	Material	Density (g/m^2)	Thickness (mm)	Porosity (%)
U1	V-neck sweater	Knitting; Navy; Regular fit	48^S/2/S 100% W	231.4	0.86	79.62%
U2	Round-neck sweater	Knitting; Black; Regular fit	30^S/2/S 100% C	228.6	0.81	81.67%
U3	Crewneck thick cardigan	Knitting; Black; Regular fit	30^S/2/S 100% W	318.2	1.22	80.24%
U4	Crewneck thin cardigan	Knitting; Black; Regular fit	48^S/2/S 100% W	239.2	0.84	78.43%
U5	Turtleneck sweater	Knitting; Black; Regular fit	30^S/2/S 100% W	332.9	1.21	79.16%
U6	Shirt	Woven; Black; Tight fit	120^S/2/S 70% C/26% N/4% SP	187.3	0.27	51.27%
U7	Crewneck thick sweater	Knitting; Black; Loose fit	30^S/2/S 84.5% C/15.5% T	427.9	1.54	81.66%
O1	Medium-long jacket	Navy; Loose fit	100% Cotton	434.7	0.36	-
O2	Suit	Black; Low collar; Tight fit	80% C/20% V;	758.5	1.13	-
O3	Medium-long down coat	Navy; Thick; Regular fit	Surface: 100% T; Filling: 90% Duck down	540.0	16.40	-
O4	Medium-long down coat	Navy; Thick; Loose fit		523.6	16.72	-
O5	Short down coat	Navy; Thick; Regular fit	Surface: 100% T; Filling: 80% Duck down	532.7	12.33	-
O6	Short down coat	Navy; Thick; Loose fit		521.6	12.73	-
O7	Short wadded jacket	Black; Thick; Regular fit	Surface: 100% T; Filling: 100% Cotton	446.8	11.75	-
O8	Short wadded jacket	Black; Thick; Loose fit		418.3	11.92	-
O9	Tweed coat	Navy; Low collar; Tight fit	54.8% W/45.2% T	855.3	7.12	-

Note: C: Cotton; N: Nylon; SP: Spendex; T: Polyester; V: Viscose; W: wool

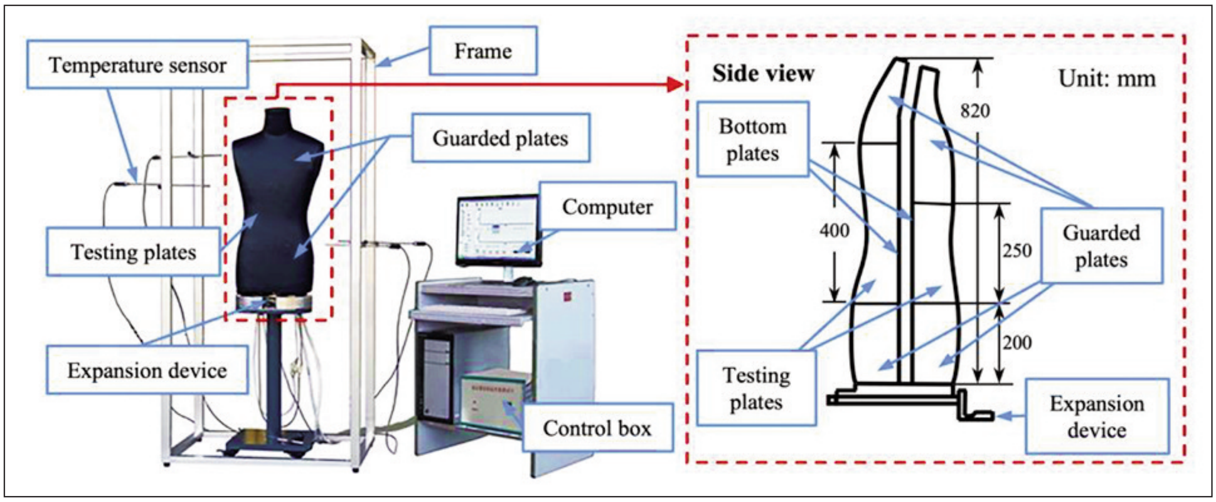

Fig. 1. The structure of LD-1 thermal manikin

neck and waist and the inside surfaces between the front and back elements are bottom plates. The temperature of all plates is controlled at 33±0.2°C to simulate the temperature of the human skin surface. The guarded and bottom plates can effectively reduce the heat dissipation from the collar and low hem of clothing. Moreover, four temperature sensors are fixed 15~30 cm away from the tester to measure the ambient temperature. During the experiment, the generated heat flux of the testing area and associated temperatures are recorded at given intervals.

Measurements for the outerwear thermal insulation with various underwear

According to the clothing thickness, styles and combinations, the outerwear samples were divided into thin outerwear used in cool areas or in spring/autumn (such as sample O1 and O2) and thick outerwear used in cold areas or in winter (such as sample O3), and separately worn with the single thin underwear and two combined underwear to simulate the actual-used scenarios. Three types of outerwear (sample O1~O3) with different thicknesses and styles were selected as typical samples to investigate the dependence of thermal insulation of various outerwear on underwear. The combinations of outerwear and corresponding underwear are shown in table 2.

Table 2

THE CORRESPONDING UNDERWEAR FOR DIFFERENT KINDS OF OUTERWEAR

Case	Outerwear	Underwear
Cool area or spring/autumn	O1/O2	U1, U2, U4, U6, U7
Cold area or winter	O3	U6U1, U2U3, U2U5, U2U7

Clothing ensembles used in cold area and cool areas were conducted in a room with temperatures of 15°C and 55% RH and 22°C and 65% RH, respectively, simulating the indoor conditions of winter and spring/autumn in Yangtze River Delta of China. The ambient temperature and relative humidity in each test were kept constant within ±1°C and ±4%, respectively.

The total thermal insulation I_T (m^2·°C/W), effective insulation I_{clu} (m^2·°C/W) and intrinsic insulation I_{cl} (m^2·°C/W) are determined as follows:

$$I_T = \frac{A_s\,(T_s - T_a)}{H} \tag{1}$$

$$I_{clu} = I_T - I_a \tag{2}$$

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \tag{3}$$

where T_s and T_a are the mean temperature of skin and environment (°C), respectively; H is heat generated from the testing plates (W); A_s is the total surface area of test plates (m^2); I_a is thermal insulation of the air layer on the surface of the nude thermal manikin; f_{cl} is clothing area factor.

Intrinsic insulation of clothing ensemble I_{cl_e} (m^2·°C/W) can be estimated based on the insulation of individual clothing as [11]:

$$I_{cl\_e} = I_{clu\_o} + I_{clu\_u} \tag{4}$$

where I_{clu_o} and I_{clu_u} are intrinsic insulation of outerwear and underwear (m^2·°C/W), respectively.

Measurements for the clothing thermal insulation under various ambient conditions

Seven kinds of cold protective outerwear (O3~O9) worn with underwear ensemble U2U3 were selected to study the effect of ambient temperature on the clothing's thermal insulation performance. Four types of temperature (–10°C, 0°C, 10°C and 20°C) were adopted to simulate various environmental conditions. It was found that although the relative humidity was set at a constant level (65±4%), the actual value was measured at 57±4% for –10±1°C, 61±4% for 0±1°C, 72±4% for 10±1°C and 65±4% for 20±1°C, respectively, as relative humidity cannot be controlled under 10°C. Consequently, winter conditions of 298 major cities in China for 30 years were further investigated to analyse suitable testing environments including temperature and relative humidity for different clothing.

RESULTS AND DISCUSSION

Effect of underwear on thermal insulation performance

Thermal insulation of underwear

Five types of single underwear and four types of underwear ensembles (table 2) were selected to estimate the influence of underwear clothing properties on outerwear thermal insulation. The fit styles of underwear were different, such as tight fit, regular fit and loose fit. Table 3 shows the intrinsic insulation of nine different underwear. The intrinsic insulation of four underwear ensembles was closed with a maximum difference of 9.0%. The insulation of single underwear was different, with the minimum and maximum values 0.0397 $m^2 \cdot °C/W$ (sample U6) and 0.0716 $m^2 \cdot °C/W$ (sample U7), respectively. This was mainly due to different clothing fit and thickness. Sample U6 was the thinnest sample with the tightest fit and sample U7 was the thickest sample with the loosest fit.

Thermal insulation of cold protective outerwear used in cool area

Two kinds of spring/autumn outerwear, loose fit (sample O1) and tight fit (sample O2), were measured with the corresponding underwear (table 2) to obtain its intrinsic thermal insulation. The thermal insulation was plotted as shown in figure 2, respectively.

In the case of loose-fitting sample O1, as shown in figure 2, *a*, the I_{cl_e} of various clothing ensembles shows similar values, with the minimum value 0.185 $m^2 \cdot °C/W$ and maximum value 0.191 $m^2 \cdot °C/W$. It was interesting that although the I_{cl_u} of tight-fitting underwear U6 was lower and the I_{cl_u} of loose-fitting underwear U7 was higher than that of other single underwear (table 3), the thermal insulation of their corresponding clothing ensembles was close to other combinations. This is due to that the thickness of the air gap between the tight-fitting underwear U6 and loose-fitting outerwear O1 was wider than that of other ensembles, leading to additional thermal insulation [15]. Besides, the thickness of the air gap between underwear U7 and O1 was thinner due to the loose-fitting structure of sample U7, and thus the I_{cl_e} of U7+O1 was similar to other ensembles. It suggested that the underwear fit exerted little influence on the thermal insulation of clothing ensembles when outerwear was loose-fitting.

However, the intrinsic insulation (I_{cl_o}) of outerwear O1 measured with different underwear was slightly different, with a maximum difference of 18.3%. Statistic significant test (ANOVA) was further adapted to observe the difference among the I_{cl_o} of outerwear O1 measured with five kinds of underwear. The results indicated that the I_{cl_o} of outerwear O1 measured with U6 and U7 was significantly different from the insulation measured by other underwear at a 95% confidence level. Besides, no significant difference was found in regular-fitting underwear U1, U2 and U4. The results implied that the combination way affected the thermal insulation of outerwear. This significant difference was mainly caused by the obvious difference in thickness and fit styles of U6 and U7.

In the case of tight-fitting sample O2, the thickness of the microclimate air gap among clothing layers was much thinner due to the tight structure of outerwear.

Table 3

THE THERMAL INSULATION OF UNDERWEAR

Parameters	Underwear ensembles				Single underwear				
	U2U3	U2U5	U6U1	U2U7	U1	U2	U4	U6	U7
I_{cl_u} ×10^{-2} ($m^2 \cdot °C/W$)	9.00	9.56	9.74	9.89	6.40	5.90	5.93	3.97	7.16
CV (%)	5.1	3.5	2.9	5.0	6.6	8.8	7.1	5.5	7.0

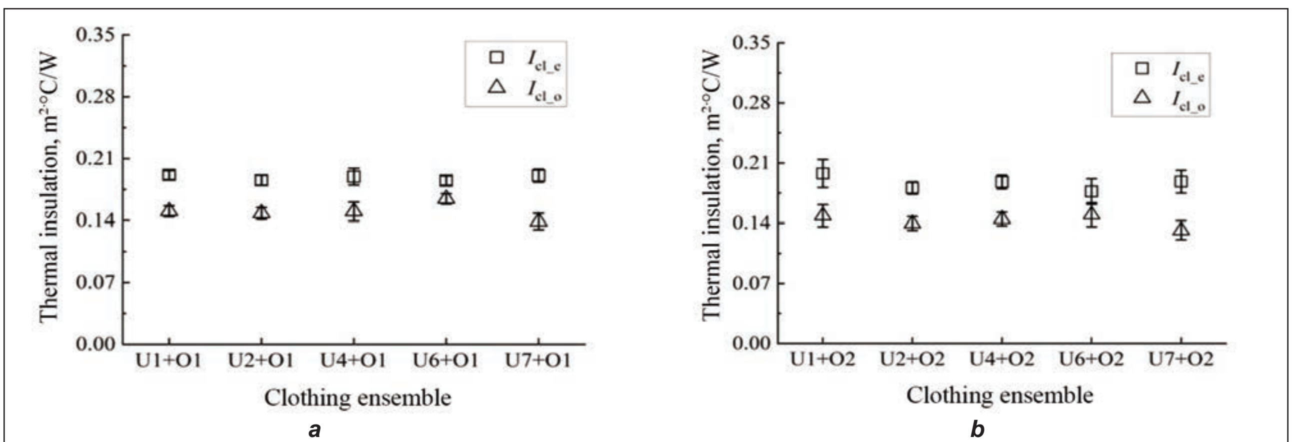

Fig. 2. The thermal insulation of the outerwear sample and its clothing ensembles for sample: *a* – O1; *b* – O2

The results showed that only the I_{cl_o} of outerwear O2 measured with underwear U7 was significantly different from the insulation measured by other single underwear at a 95% confidence level. This was because the thermal insulation of underwear U7 was higher as the presence of a thick air gap between the skin and underwear caused by the loose-fitting structure [16]. While the loose-fitting underwear U7 was in close contact with the skin when it was worn with tight-fitting outerwear, and thus the I_{cl_o} of outerwear O2 deduced from the thermal insulation of underwear U7 was lower, as shown in figure 2, *b*.

Thermal insulation of cold protective outerwear used in cold areas

Outerwear O3 was down clothing used in cold conditions. As presented in figure 3, it was found that the I_{cl_o} deduced from the thermal insulation of various underwear ensembles was similar, with a maximum difference of 3.4%. It was found that the difference between the I_{cl_o} measured with underwear ensembles U2U5 and U2U7 was significantly different at a 95% confidence level. Besides, no significant difference can be detected in the I_{cl_o} of sample O3 measured with other underwear ensembles. I_{cl_u} of underwear U2U7 was higher than that of other underwear ensembles, while the I_{cl_e} of clothing ensemble U2U7+O3 was lower (table 4). This implied that the thickness of down outerwear O3 was compressed when it was worn with sample U2U7 due to the loose-fitting structure of underwear U7, thus resulting in a reduction of still air content in the filling material of sample O3.

The above results indicated that the estimated thermal insulation of the outerwear worn with different fit styles (tight fit, regular fit, and loose fit) and thickness of underwear may exhibit variations. These variations were attributed to differences in the air gap between clothing layers and the presence of stagnant air within the porous clothing, even when the size of the underwear closely matched that of the thermal manikin. Therefore, it is crucial to take into account not only the size but also the fit style and thickness of the underwear during the thermal insulation testing for outerwear.

Testing conditions for various clothing

Effect of ambient temperature on thermal insulation performance

Humans will perceive different thermal sensations when they wear the same clothing ensemble in different ambient conditions. Four different temperature conditions were adopted to examine the influence of ambient temperature on clothing thermal insulation. Outerwear with different thicknesses and fit styles was selected. Sample U2U3 was used as underwear worn with outerwear.

Figure 4 shows the dependence of clothing total thermal insulation (I_T) on the ambient temperature. The I_T of ensembles with filling material (U2U3+O1~O8) was at least 25.0% higher than that of without filling material (sample U2U3+O9) due to the high still air content inside the filling material, as it was reported that the thermal conductivity of air in relative static state was much smaller than that of fibres [17]. Besides, it was found that the I_T of each ensemble kept an approximately constant value when the ambient temperature increased from –10°C to 10°C, after which it slightly rose and the value of I_T increased up to 17.2% when the ambient temperature increased to 20°C except for the ensemble sample U2U3+O9. It is of interest to note that the clothing's porous structure and fit influenced the clothing's thermal insulation in diverse ambient conditions The outerwear O9 was the only one tight fit and without filling material and its fibres contacted closely with each other. The microclimate air gap in ensemble sample U2U3+O9 was thin. The chest circumference of sample O9 was 1.079 m, slightly wider than that of the thermal manikin (0.960 m). While the chest circumferences of the other outerwear ranged from 1.141 m to 1.194 m, representing a 0.062 m to 0.115 m increase compared to sample O9. Therefore, the air content within the clothing system of ensemble sample U2U3+O9 was low. The results implied that the heat flux transferred through ensemble U2U3+O9 in different temperature conditions was mainly by conduction and the ambient temperature exerted little influence on the thermal insulation, which was in agreement with

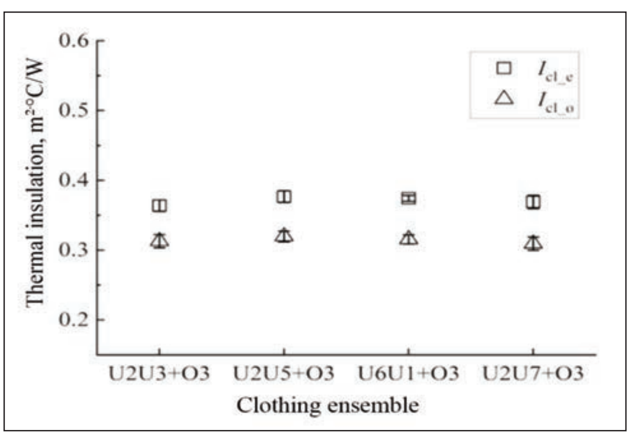

Fig. 3. The thermal insulation of outerwear sample O3 and its clothing ensembles

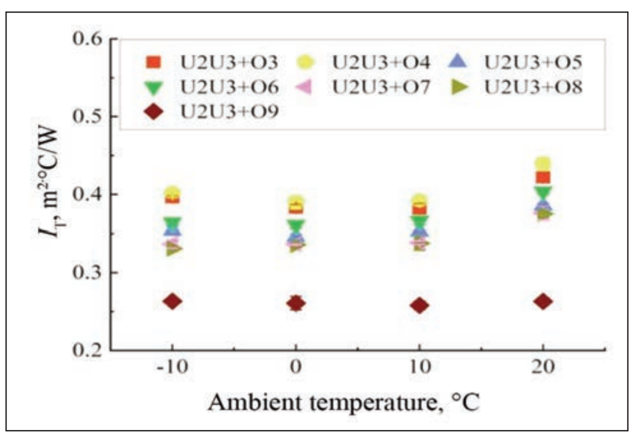

Fig. 4. Clothing total thermal insulation under various temperature conditions

Table 4

RECOMMENDED TESTING CONDITIONS FOR DIFFERENT KINDS OF CLOTHING						
Clothing type	**I_T**		**Winter condition**		**Testing condition**	
	(clo)	**(m^2·K/W)**	***T* (°C)**	**RH (%)**	***T* (°C)**	**RH (%)**
Clothing used in extremely cold conditions	4.8~5.9	0.739~0.911	$-20 \le T \le -10$ (42 cities)	24 cities > 60% RH	–15±2	-
Thick down coat, thickly wadded jacket, etc	3.7~4.8	0.567~0.739	$-10 < T \le 0$ (87 cities)	59 cities 40~60% RH	–5±2	-
Wadded jacket, thin down coat, etc	2.5~3.7	0.395~0.567	$0 < T \le 10$ (119 cities)	110 cities > 60% RH, in which 64.5% of cities 75~85% RH	5±2	80±4
Jacket, suit, tweed coat, etc (without filling material)	1.4~2.5	0.223~0.395	$10 < T < 20$ (41 cities)	40 cities > 60% RH, in which 80% of the city 70~80% RH	12±2	75±4
Thermal underwear	<1.4	<0.223	Common conditioned room		20±2	65±4

the previous work [7]. The increasing thermal insulation of other ensembles was believed to be associated with decreasing convection inside the filling material and microclimate air gap as the temperature difference decreased, leading to smaller equivalent conductivity [18].

Recommended testing conditions for clothing

Ambient temperature has a major influence on the clothing's thermal insulation performance according to the previous section. Besides, as the relative humidity cannot be controlled in low-temperature conditions, the influence of the relative humidity on the thermal insulation performance was not experimentally investigated. The relative humidity may affect the clothing's thermal properties, especially for the textile with a high moisture regain [19].

To determine the testing conditions for various kinds of clothing, the average winter temperature and relative humidity of 298 major cities in China during the 30 years were analysed [20], as illustrated in figure 5. In addition, the winter temperature represents the average temperature of the coldest month in one year. Besides, it was reported that the most comfortable and healthy relative humidity for the human body was 40%~60% [21], the environmental relative humidity was divided into three levels, dry feeling (less than 40%), comfortable feeling and healthy (40%~60%) as well as wet feeling (more than 60%). The classification of ambient temperature and humidity for various kinds of clothes was developed according to the temperature-humidity distribution, as shown in table 4. The total thermal insulation of the clothing ensemble was (I_T) calculated by equation 1 and the heat dissipation per unit area was set to be 1 MET (58.2 W/m^2). It means that when a human is exposed to different conditions, the heat dissipation of the body surface is maintained at about 58.2 W/m^2 to keep comfortable by wearing clothes with different thermal properties [22]. As a result, the testing condition was developed for various clothing as shown in table 4.

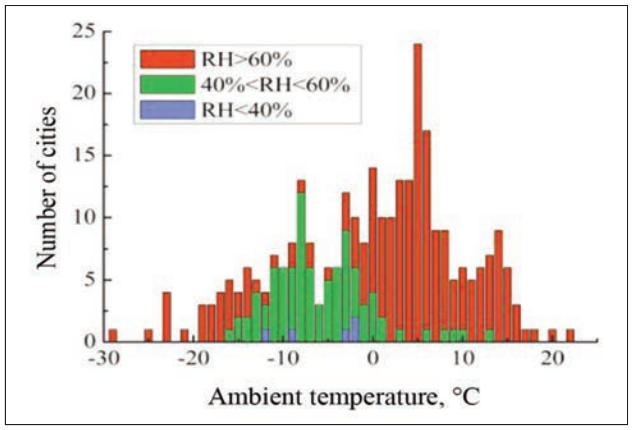

Fig. 5. Temperature-humidity distribution in China

CONCLUSIONS

A series of tests were carried out to investigate the influence of underwear on the measurements of clothing insulation of cold protective outerwear. The study reveals that even when the size of the underwear was suitable for the thermal manikin, variations in the thermal insulation of the outerwear may still occur. These fluctuations were caused by the discrepancy in the air gap between clothing layers and variations in the stagnant air within the porous fabric, as the fit styles and thicknesses of corresponding underwear were different. Consequently, in thermal insulation testing for outerwear, it is crucial to consider not only the size of underwear but also appropriate styles and thickness.

We also examined the influence of ambient temperature on the thermal insulation of clothing ensembles. Thermal insulation of clothing with filling material was observed to increase with ambient temperature from 10°C to 20°C since the convection inside the clothing system was decreased. Thermal insulation of a tight-structure clothing system was observed nearly unchanged, as the fibres of such clothing contacted closely with each other. Then testing ambient conditions for various clothing was divided into 5 groups according to the analysis of winter environment.

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Investigation of the factors affecting the insulation properties of down-filled clothing

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ABSTRACT – REZUMAT

Investigation of the factors affecting the insulation properties of down-filled clothing

Goose down is an ideal raw material used in producing many products because it is light and bulky, has low thermal conductivity, and has the best thermal insulation properties. Due to its light, soft and warm-feeling structure, these feathers are considered a superior and luxurious filling material for bedding and clothing against the cold climate.

Nowadays, goose down is used in the production of some items such as souvenirs or ornaments, in the production of pillows and quilts, in the production of winter alpinist and ski clothes, sleeping bags, and seat production.

Goose down is an excellent insulation material and its performance can be improved by the appropriate design and production method. Clothes or sleeping bags made from goose down are usually made of baffles. Feathers are filled by hand or machine to these baffles which can be produced in different constructions. Several factors influence the thermal insulation of a goose-down-filled product. The most important factors are fill power, goose down weight and goose down rate. In this study, the production of goose down products and the factors affecting the thermal insulation properties of these products were investigated.

Keywords: *goose down, clothing, filling fibres, thermal resistance, thermal insulation*

Investigarea factorilor care influențează proprietățile de izolare ale îmbrăcămintei umplute cu puf

Puful de gâscă este o materie primă ideală folosită în fabricarea multor produse, deoarece are o masă redusă și este voluminos, are conductivitate termică scăzută și, prin urmare, are cele mai bune proprietăți de izolare termică. Datorită structurii lor ușoare, moi și care oferă căldură, aceste pene sunt considerate un material de umplutură superior și de lux pentru așternuturi și îmbrăcămintea de protecție la frig.

În prezent, puful de gâscă este utilizat în producția unor articole precum suveniruri sau ornamente, în producția de perne și cuverturi, în producția de îmbrăcăminte pentru iarnă pentru alpinism și schi, saci de dormit și în producția de scaune.

Puful de gâscă este un material de izolare excelent și performanța acestuia poate fi îmbunătățită prin proiectare și metoda de producție adecvată. Articolele de îmbrăcăminte sau sacii de dormit cu puf de gâscă sunt, de obicei, fabricați din buzunare despărțitoare cu aer (”baffles”). Penele sunt umplute manual sau mecanic în acestea, putând fi produse în diferite tipuri de construcții. Există mai mulți factori care influențează izolarea termică a unui produs umplut cu puf de gâscă. Cei mai importanți factori sunt puterea de umplere, greutatea pufului de gâscă și cantitatea pufului de gâscă. În acest studiu au fost investigate fabricarea de produse din puf de gâscă și factorii care influențează proprietățile de izolare termică ale acestor produse.

Cuvinte-cheie: *puf de gâscă, îmbrăcăminte, fibre de umplutură, rezistență termică, izolare termică*

INTRODUCTION

Human beings have benefited from waterfowl in various ways for thousands of years. During domestication, humans consumed the meat of wild birds, used their fat for lighting and heating, and their feathers for warmth [1].

Feather is a tissue in all poultry animals and covers the body. Feathers are a necessary structure for many purposes in poultry, such as flight, heat insulation, giving shape and colour to the body,
and preventing injuries [2, 3]. Like human hair and nails, feathers of poultry are made of keratin [4]. Feather is also a type of raw material used especially in the textile industry.

Among poultry, waterfowl feathers are the most valuable. The underparts and body feathers of water birds have a wide range of uses for humans. These feathers have important features.

The main features of these are natural insulation, ability to hug the body, breathability and low allergenic level (hypoallergenic) [5]. For this reason, waterfowl feathers are used as a natural filling and insulation material in the production of high-quality products [6]. Assuring the thermal stability of the human body is one of the most important functions of clothing. Its thermal insulation properties play a crucial role in a human's heat maintenance, especially in winter conditions [7–10]. Filling materials are generally used for trapping air and providing insulation. The insulation and comfort levels mainly depend on the type and amount of filling material as well as on the filling method [11]. Goose down is the most common natural filling raw material.

Goose down has been used to fill pillows and duvets for more than 2000 years. Today, goose down is used in furniture as well as in quilts, winter clothes, sleeping bags [12], bedding, and winter mountaineering and ski clothes [13–15]. Goose feathers are also used in the production of various ornaments and quality badminton balls [6]. Goose down is an ideal raw material for the production of many products with its lightness and unique insulation properties [16].

Properties of goose down

Goose down, each feather set consists of multiple branches extending outward from a central point. Each of these branches has fine fibres with knots on it [17]. Their structure is three-dimensional and since their clusters are composed of interlocking fine barbs, they attach and thus create millions of tiny air spaces trapping air. Due to the characteristics of lightweight, soft touch and warm feeling, the downs have long been considered superior and luxurious as a filling material for bedding and outerwear against cold climates [18].

The factors affecting the insulation properties

In the outdoor industry, down quality is usually assessed and sold using two main measurements: The down to feather ratio, and the fill power and garment structure [19].

Down-to-feather ratio: The down-to-feather ratio calculates the percentage of down to the percentage of feathers in the product. The blends are generally 70/30, 80/20, or 90/10 of which the first blend amount represents the percentage of down, and the second one represents the percentage of feathers.

Fill power: Fill power is the universal rating system for goose down [20]. Down fill power is a measure of the loft or 'fluffiness' of the down and its insulating properties. The higher the fill power, the more air pockets in the down and the more insulating the jacket will be for its weight. Fill power is calculated in laboratory conditions and is measured in cubic inches per ounce. To test fill power, an ounce of down is compressed by weight in a glass cylinder. Its ability to bounce back and 'loft' is calculated as the fill power. Fill power is also an indication of the quality of the down used. The better the quality of down the higher the fill power. As less down is required to provide the same amount of warmth, jackets with a higher fill power tend to be lighter and more compressible [21]. Down jacket fill power ratings are given in the following:

Fill Power	Rating
400 – 450	Medium
500 – 550	Good
550 – 750	Very Good
750 – 900	Excellent

For down outerwear ratings will generally fall between 600 and 800.

Filling quantity: Filling is carried out by machine. Filled materials come to the sewing department for joining.

Fig. 1. Goose down filling machine

In garments with box-shaped components, the different width of the compartments allows the goose feathers in different proportions. Different filling rates are available in different parts according to the environmental conditions in which the garment will be used. A larger amount of fluff is usually applied to the compartments in the chest and back section of the garment. This rate is lower in the arms and shoulders. This is because the use of more feathers on the shoulders disrupts the overall appearance of the garment.

Garment structure: The construction of the garment is another factor affecting the insulation properties.

Baffles: Down jackets are usually constructed by using a series of compartments called "baffles". Baffles are the pockets of space that are created between two layers of fabric which then hold the goose or duck down that is in the jacket. The size and construction of the baffles have an impact on the effectiveness of the insulation. The compartments eliminate the possibility of goose down movement, ensure that the insulation is equal and minimize the areas that can get cold. The dimensions of these compartments may be different from each other. It is the form of these compartments that give its appearance to many of the clothes. These compartments are formed by quilting. These may be box-shaped or have different patterns.

There are two main types of construction using baffles; box wall and stitch-through.

Box wall: The jacket or sleeping bag's filling is formed into channels with box wall construction each baffle

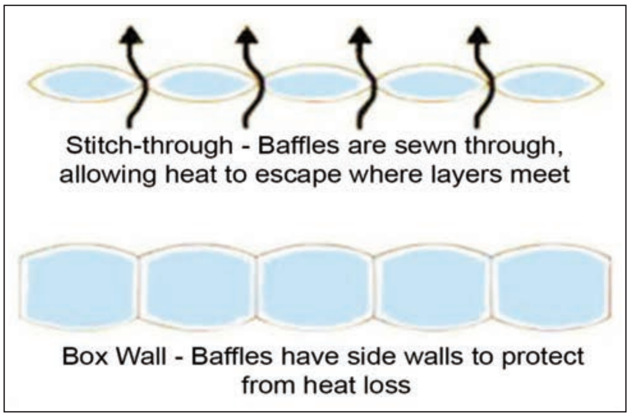

Fig. 2. Types of the baffles

has side walls. These horizontal compartments are designed to hold the down in place around the body and maximize the performance of the jacket [22]. There are nearly every size or pattern (midi, micro, square or zig-zag) baffles. Wider baffles offer better warmth, as they contain more grams of down and can be constructed with fewer seams, so less heat is lost. However, wider baffles make the jacket more bulky and less compressible. Conversely, narrow or micro baffle jackets work best for warmth in spring or autumn, or as technical mid-layers, but compress excellently to be packed away when not needed.

Stitch-through: This method is the most common. It is easier, less time-consuming, and therefore cheaper for manufacturers than other forms of baffle construction. The outer material is stitched directly into the inner lining, separating the down in different baffles, which are horizontally oriented.

This method uses less fabric is lighter than more complicated box baffle construction, and is less costly. Because of weight, simplicity, and cost, most lightweight jackets, and many of the heavier ones utilize this construction. Although stitch-through construction saves weight via the use of less material, it is less warm than box baffle construction because the down is pinched at the seams of the stitch-through baffles and thus loft is reduced to zero at each point of baffle stitching. The stitch-through baffling prevents the migration of the down, but due to the simple construction, it also reduces the optimum loft of the down, creating "cold spots" at each baffle seam. The benefits of using stitch-through baffles are that this method uses less fabric overall and is lighter than more complicated box baffle construction, it helps keep the price of the down jacket low too. Depending on the innovations in sewing technology, welded or bonded baffles are also being produced in addition to stitch-through.

Welded or bonded baffles: This construction technique fuses the inner and outer pieces of fabric to create a baffle that holds them down using heat, chemicals, glue, or a combination of all three. There is one major benefit to these techniques: since there are no holes in the outer fabric from sewing the baffles they are more wind impermeable and water resistant or proof.

Model properties: It's also important to look at possible routes for cold air to enter the jacket, starting with zips. Because of their structure, zips are air-permeable and cold will find its way in wherever possible, so zips should preferably have a protective, insulated, baffle mounted on either the outside or inside of the zip, hood, hem and cuffs are also important because of each provides a possible route for cold air to enter. Zips are one of the areas where heat loss can occur, particularly the main front zip, so it's essential to look at features which can reduce or prevent this. Baffles can be placed either inside or outside the zip to prevent heat loss through the zip. An internal baffle will generally sit naturally behind the zip, whereas a baffle on the outside will need holding in place using velcro or snaps.

There is little point in wearing an insulated jacket if cold air gives easy access to the extremities, so hem and drawcord adjustment is essential. While elasticated cuffs can give a good fit the velcro fastening is generally preferable, giving both a better fit and allowing the wearer to adjust the gap to regulate airflow [23].

The collar is one of the most important areas of an insulated jacket. With warm air naturally rising the area around the neck provides the easiest escape so needs special attention. A lined collar with a soft face and a baffle that encircles the wearer's neck should be used.

In this study, it was aimed to find out the factors affecting the thermal insulation properties of goose down clothing. Since goose down is often used in jacket production, the properties of jackets have been investigated.

MATERIAL AND METHOD

Materials are supplied from Hungary. The down-to-feather ratio of samples used in this study is 80/20 and 90/10. For filling goose down, nonwoven bags of 30 cm × 30 cm were prepared. The weight of the nonwoven fabric is 65 g/m^2 and it is produced from 100% cotton. These bags were sewn with 100% polyester sewing thread. The stitch length was kept constant at 3.5 stitches/cm for all sewing applications. Fiber samples were placed into nonwoven bags. Filling materials weighing 10, 15, and 20 g were placed into each bag respectively.

Before testing, all samples were conditioned for 24 hours under the standard atmospheric conditions (20 ± 2°C temperatures, 65% ± 5% relative humidity).

The first step of the study was monitoring the down structure under a scanning electron microscope (Thermo Scientific Apreo S).

The thermal resistance of goose down filled test samples was tested according to ISO 11092 (British Standards Institute 1993) using an SDL ATLAS M259B Hot Plate Tester. Clo values were calculated with the following formula by using the obtained thermal resistance values. Clo values were calculated by using 1 clo = 0.155 m^2K/W.

Air permeability tests of the samples were carried out by using a Textest-FX 3300 testing machine (pressure difference was 100 Pa, measured area was 20 cm^2) in accordance with ISO 9237 standard specifications [20]. The thickness of the samples was measured according to the relevant standards [21].

RESULTS AND DISCUSSION

The morphological structure of down feather

The first step was to determine the morphological study of the down structure under a scanning electron microscope (SEM). Figure 3 shows SEM pictures of down samples with a magnification of 1000. Figure 4 indicates the SEM pictures of gooseneck feathers magnified by 2500 times.

Air permeability

As shown in figure 5, the air permeability values of the nonwoven materials filled with 90/10 and 80/20 ratio blended down feathers were close to each other. However, when the amount of filling was examined, it was observed that the air permeability decreased as the filling amount increased. The air permeability of the sample filled with 20 g was the highest value.

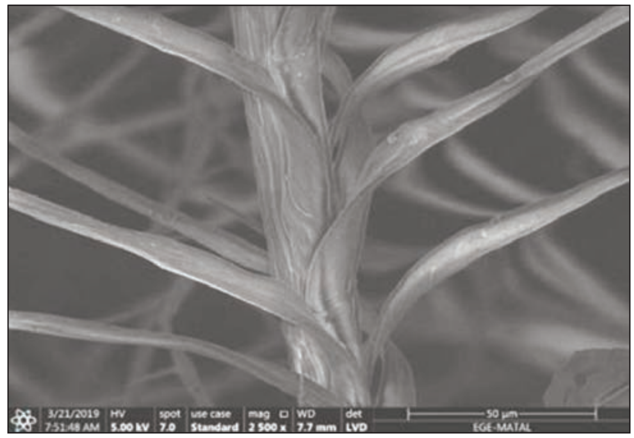

Fig. 4. SEM photo of gooseneck feathers

Thermal resistance

Figure 6 shows the thermal resistance values of the samples. The thermal resistance values were close to each other with the down ratios of 90/10 and 80/20. When the amount of filling is examined, it is seen that both the 90/10 and 80/20 ratios increase the amount of thermal resistance.

The concept of the 'clo' is a unit to measure the thermal resistance of clothing, which is called 'clothing insulation' [22]. Clo values were obtained by using the conversion equation of 1 clo = 0.155 m^2K/W. Figure 7 shows clo values of the samples.

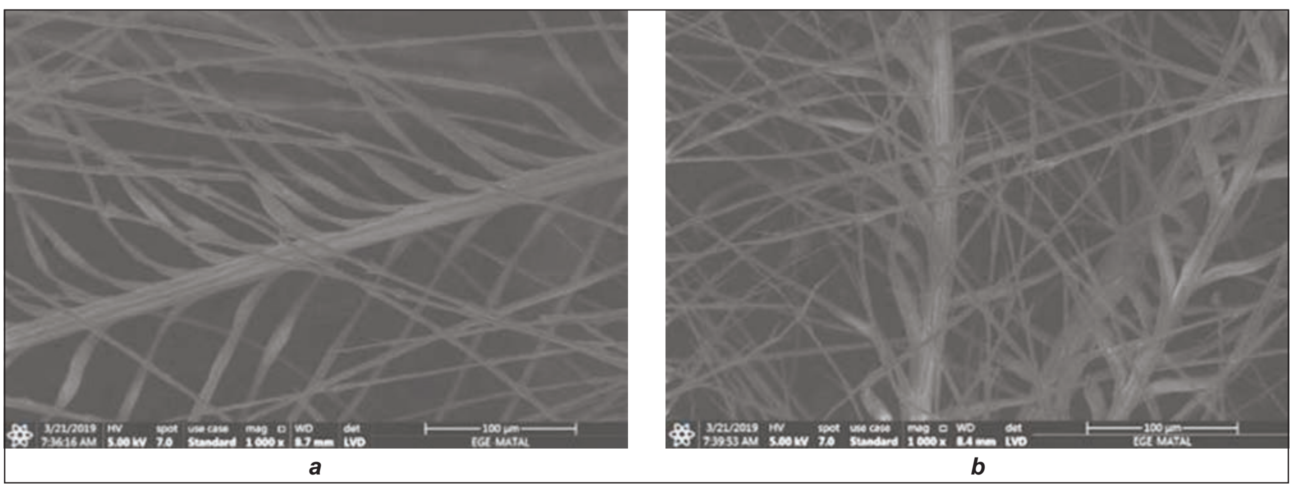

Fig. 3. SEM photos of goose down feathers: *a* – the down feather with 80/2; *b* – the down feather with 90/10

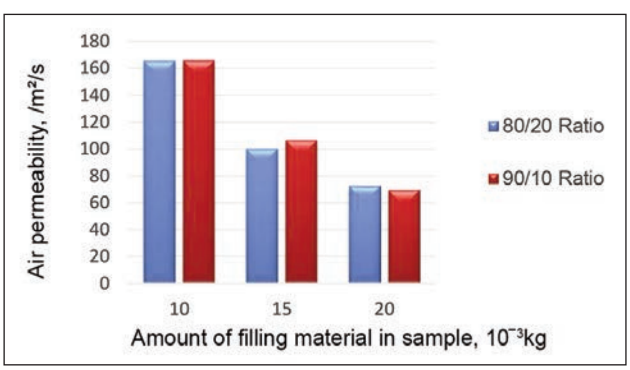

Fig. 5. Air permeability values of the samples

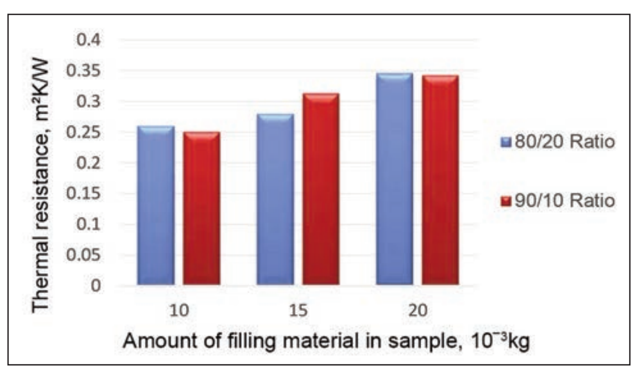

Fig. 6. Thermal resistance values of the samples

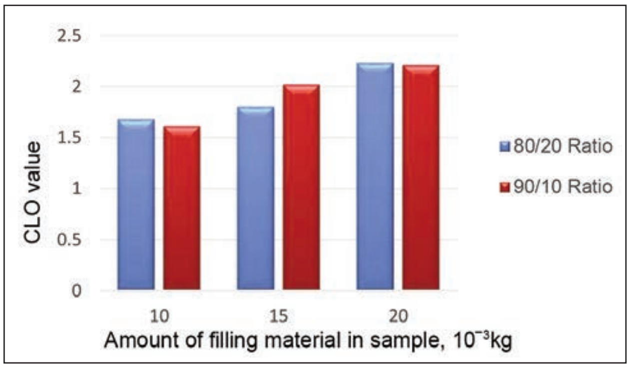

Fig. 7. Thermal insulation values of the samples in clo unit

CONCLUSIONS

The living organisms in nature have undergone various physiological changes depending on the climate and living conditions of their region. Animal fibres that support the preservation of the body temperature of the organisms living in the regions where the ambient temperature is very low contribute to the improvement of the thermal properties when used in the clothing.

In the study, goose down was used in the 90/10 and 80/20 ratios. The ratio of 90/10 indicates that softer and higher quality down are used more in the gooseneck feather. The 80/20 ratio indicates that the use of gooseneck feathers is reduced and the rate of use of wing feathers increases. The thermal resistance test of the goose down was used in the study with 90/10 and 80/20 ratios and 10 grams, 15 grams and 20 grams filling rates.

The ratios of 90/10 and 80/20 were close to each other in terms of thermal resistance and clo values. The reason for this is that they both show similar feather characteristics. However, the major disadvantage is that the end portions of the wing feathers are more pointed and that during usage they can penetrate from both the stitches and the fabric, however, the gooseneck feathers are not pointed. For this reason, although they are more expensive, customers can prefer 90/10 due to this usage comfort.

When the amount of filling is examined, it can be seen that both the 90/10 and 80/20 ratios increase the amount of thermal resistance and clo value as the filling amount increases. This can be achieved by increasing the filling quantities in the regions where different heat retention values are desired in different garment sections or the ambient temperature is too low.

As can be seen from SEM images, down clusters were made of a large number of subunits each with appropriate orientation and crotches and triangle nodes. This structure provides thermal insulation of goose feathers.

As the air permeability of the samples increases, the amount of air entering the samples also increases. This results in faster heat and moisture transfer. Therefore, the fabric with low air permeability has the highest thermal resistance. When the air permeability results of the samples were examined, it was seen that the air permeability values were close to each other filled with both 90/10 and 80/20 ratios down feathers. However, when the amount of filling was examined, it was observed that the air permeability decreased as the filling amount increased. The air permeability is inversely proportional to the amount of down. This is indicative of the insulating property of the goose down.

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Knitted linings for protective equipment against vibrations

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ABSTRACT – REZUMAT

Knitted linings for protective equipment against vibrations

Vibrations can affect the human body during everyday activities or in the workplace through various tools. It can occur at any point that comes into contact with a vibrating surface, including the hands (hand-arm vibration, HAV), the feet (foot-transmitted vibration, FTV) or the buttocks and back (whole-body vibration, WBV). The paper presents a group of knitted fabrics that could be used as linings for footwear or gloves, designed for personal protective equipment (PPE) in vibration environments. These fabrics have a single jersey tubular structure and were produced on a circular knitting machine with a small diameter and three stitch depths, made from functional yarns with good comfort properties. The knitted materials were tested using the free vibration method to measure their natural frequencies (Hz), as knowing these values helps to avoid resonance phenomena between the materials and the external vibrating system. The natural frequencies were measured in three directions (course, wale, perpendicular) and the results show that, for all variants, the natural frequencies measured in the perpendicular direction are four times higher than in the other two test directions. The fabrics made from Outlast natural fibre yarns have 30% lower natural frequency values than those made from synthetic yarns (Coolpass, Coolmax) or from natural-synthetic blended yarns (Dri-Release), which confirms the influence of the yarn type on the vibration behaviour of the materials. Coolpass, Coolmax and Dri-Release knits have comparable values of the natural frequencies, both in the course and wale test direction (41–48) Hz and (182–189) Hz in the perpendicular test direction. This type of knitted fabric, with low thickness and good extensibility, is suitable for anti-vibration equipment, e.g. in the field of dentistry, where it should be combined with a suitable antimicrobial and antibacterial treatment and a high level of comfort.

***Keywords**: tubular single jersey, footwear linings, functional yarns, circular knitting machines, natural frequencies, vibrations*

Căptușeli tricotate pentru echipamente de protecție împotriva vibrațiilor

Vibrațiile pot afecta corpul uman atât în timpul activităților zilnice, cât și la locul de muncă, prin utilizarea diferitelor instrumente de lucru. Vibrațiile pot apărea în orice parte a corpului aflată în contact cu o suprafață care vibrează, inclusiv la nivelul mâinilor (vibrații mână-braț), al picioarelor (vibrații ale piciorului) sau al feselor și spatelui (vibrații ale întregului corp). Lucrarea prezintă un grup de tricoturi destinate căptușelilor pentru încălțămintea sau mănușile de protecție în medii vibratorii. Aceste tricoturi au structura glat tubular și au fost produse pe o mașină de tricotat circulară cu diametru mic, cu trei trepte de desime, realizate din fire funcționale cu proprietăți de confort superioare. Materialele au fost testate prin metoda vibrațiilor libere pentru măsurarea frecvențelor lor naturale (Hz), deoarece cunoașterea acestor valori contribuie la evitarea fenomenelor de rezonanță între materiale și sistemul de vibrații externe. Frecvențele naturale au fost măsurate în trei direcții (rând, șir, perpendicular), iar rezultatele arată că, pentru toate variantele, frecvențele naturale măsurate în direcția perpendiculară sunt de patru ori mai mari decât în celelalte două direcții de testare. Tricoturile obținute din fire din fibre naturale Outlast au frecvențe naturale cu 30% mai mici decât cele realizate din fire sintetice (Coolpass, Coolmax) sau fire în amestec naturale-sintetice (Dri-Release), confirmându-se astfel influența tipului de fir asupra comportării materialelor la vibrații. Tricoturile din firele Coolpass, Coolmax și Dri-Release au valori comparabile ale frecvențelor naturale, în direcția rândurilor și a șirurilor (41–48) Hz și valori de (182–189) Hz în direcție perpendiculară. Acest tip de tricot, cu grosime redusă și extensibilitate bună, este recomandat produselor antivibrații, de exemplu în domeniul stomatologiei, împreună cu un tratament antimicrobian și antibacterian adecvat și cu un nivel ridicat de confort.

***Cuvinte-cheie:** glat tubular, căptușeli încălțăminte, fire funcționale, mașini circulare de tricotat, frecvențe naturale, vibrații*

INTRODUCTION

Vibration, regardless of its industrial origin, affects the human body, causes discomfort, impairs performance and can lead to various health problems [1]. Three main types of vibration are distinguished for workers who are exposed to aggressive vibration over a prolonged period: hand-arm vibration (HAV), foot-transmitted vibration (FTV) and whole-body vibration (WBV) [2–5]. From a clinical point of view, vibrations cause different manifestations that can be grouped into syndromes depending on the mode of action and degree of occupational exposure. In whole-body vibration exposure, very low-frequency vibrations 0–2 Hz can cause kinetosis, low-frequency vibrations 2–20 Hz cause rhythmic movements of organs in the pelvic and abdominal cavities and medium-frequency vibrations 20–200 Hz cause osteo-musculoarticular syndrome [6–9]. When workers are exposed to FTV by standing on platforms or equipment that vibrates, white feet/toes are observed, resulting in whiteness of the toes and tingling and numbness in the feet. Discomfort, pain or soreness is most severe when exposed to FTV in the range of 28–40 Hz and least severe below 10 Hz [5], [10]. In the case of HAV, the frequency range of 5.6–1400 Hz mainly affects the hand-arm system and leads to vascular disorders such as Raynaud's syndrome, which was first mentioned in 1862 by the physician Maurice Raynaud [11]. In addition, neurological disorders such as numbness, reduced tactile or thermal sensitivity and musculoskeletal disorders such as joint pain in the hand, elbow or shoulder, muscle weakness in the arm, tendonitis and reduced grip strength are also observed [12]. These negative effects can be mitigated by the use of personal protective equipment (PPE). However, a large proportion of these commercially available anti-vibration products contain insulating layers of materials such as polyurethane foam, air cushions, polymer gels and rubber which, despite their excellent anti-vibration properties, often offer low comfort due to poor moisture wicking, high stiffness or obvious thickness [13–20]. Alternatively, textile knitted structures offer several advantages, such as high flexibility, better comfort, and an optimal mass-to-volume ratio and have also proven to be superior in terms of comfort and environmental friendliness.

LITERATURE REVIEW

The international standard EN ISO 13753. Mechanical vibration and shock – Hand-arm vibration – Method for measuring the vibration transmission of elastic materials under loading by the hand-arm system, defines the resilient material used for the development of anti-vibration products as a material consisting mainly of foam with elastic properties or rubber and occasionally of a textile material [21]. Based on this framework recommendation, the well-demonstrated drawbacks of common elastic materials used for vibration-damping PPE [22–27] and the previous remarkable results obtained with spacer fabrics in technical applications such as seat cushions, anti-decubitus blankets or various industrial composites, several research groups have focused over the last decade on investigating the vibration-damping capacity of textile materials and the structural properties that correlate with this functionality. It has been shown that several raw material properties and process parameters must be met to develop a knitted fabric designed for a specific purpose. Many of these studies focused on identifying the parameters that define the functionality of the tested material, namely the damping capacity, but very few of them investigated the comfort requirements of anti-vibration PPE. The novelty of this ground-breaking research is the linking of these two areas, starting from the existing knowledge on functionality with a new focus on the comfort of PPE.

The comfort performance of anti-vibration materials should be considered in terms of the environmental conditions in which the PPE is used. Since cold is the main factor that increases the negative effects of vibrations on the human body, special attention must be paid to the *raw materials* selected to minimize these risks, starting with the analysis of the materials previously used. Natural fibres, such as cotton, are often used in anti-vibration gloves. There are several patents for them, but very few studies on their ability to reduce vibration transmission [22, 26, 28]. Synthetic fibres are the most commonly used raw material for knitted anti-vibration structures. Their damping performance has been investigated in numerous experiments, but the influence of the raw material on the vibration behaviour has rarely been analysed [23, 29–32]. For artificial fibres such as polyacrylonitrile and polypropylene, there are very few studies that have investigated their influence on the ability to dampen vibrations [29]. High-performance fibres such as Kevlar or Dyneema have been used in the development of anti-vibration gloves for specific applications where cut-resistant and fire-resistant properties are required [33]. In some models of anti-vibration gloves, para-aramid yarns or high-density polyethylene have also been used for the outer layer and various types of elastic yarns for the wrist band or backhand areas [22, 26–27, 34].

Fabric thickness is an important parameter for both cushioning capacity and comfort properties. Based on the fundamental theory of mechanics that for good vibration isolation it is necessary to reduce the dynamic stiffness of the isolator material for low resonant frequency values during vibration, it has been deduced that the use of thicker materials is highly recommended for this purpose. To achieve a relatively high thickness without compromising flexibility, dexterity and tactile sensitivity, some research has focused on achieving an optimal thickness for specific vibration isolation applications [23, 31, 35]. The influence of *fabric mass* per square meter on the natural frequencies of the vibration damping material is investigated for the first time by the authors in this paper, and no other studies on the influence of this parameter were found in the literature.

The damping performance of protection materials has been widely studied in the literature. Particular attention has been paid to *knitting technology*, especially spacer fabrics, which are frequently used in the manufacture of vibration-damping materials [35–37]. Recent tests with spacer fabrics specifically designed for vehicle driver seats showed good vibration isolation in the frequency range of 0–35 Hz, as it is known that low and medium frequencies have the strongest negative effects on human health [9, 38]. The *test direction* has a certain influence on the natural frequencies measured in all three directions: transverse, longitudinal and perpendicular. In most cases, the highest values were recorded in the vertical direction [29–30, 39, 40]. This was confirmed by testing seven commercially available anti-vibration gloves, which proved to be more effective against vibrations transmitted to the palm in the forearm direction (z-axis) than in the x- and y-directions [41]. It has been shown that the *tightness of the fabric*, a property of knitted fabrics that correlates with the machine stitch depth parameter, influences the natural frequency of the fabric. In particular, increasing stitch depth is associated with decreasing natural frequency values, which is reflected in a lower stiffness of the fabric [39].

MATERIALS AND METHOD

Knitted materials

A tubular single jersey structure was created from two types of 100% synthetic yarns, 150 den, with superior moisture transport, drying properties and prolonged heat retention on the body (Coolpass and Coolmax), one blended yarn of synthetic and natural fibres, 30/1 Ne, characterized by optimized moisture transport, drying, soft feel and comfort (Dri-Release) and one artificial yarn made from natural fibres, 30/1Ne, which offers temperature regulation through micro-encapsulated phase change materials embedded at fibre level (Outlast).

The knitting process was carried out on the circular knitting machine "Lab Knitter" 24E (Mesdan-Lab), with a diameter of 3¾ inches, 1 knitting system, 240 working needles, a negative feed system and a cylinder speed of 0 to 450 rpm. The knitting conditions were set by adjusting the stitch depths at three levels, while the yarn feed tension, take-down tension and cylinder speed were kept constant. The minimum and maximum values of the stitch cam division were determined in correlation with the machine gauge and the fabrics were defined as tight (3.0), medium (9.0) and loose (15.0). The fabrics were relaxed in dry condition and finished according to the standard EN ISO 6330 for textile testing. The mass per square meter (g/m^2) was determined according to EN 12127 and the fabric thickness according to ISO 5084 [42].

In this study, materials were tested against vibrations to characterize them as linings in protective footwear. The yarns used for these knitted fabrics are efficient in terms of moisture and thermoregulation, as the negative effects of vibrations on the human body are enhanced in cold environments [43, 44].

Testing method

A Piezotronics impact hammer was used as the dynamic exciter of the knitted material and the vibrations were measured with a PCB B52 Piezotronics accelerometer (figure 1, *a*). The signal was processed with a 6023 National Instruments data acquisition card (figure 1, *b*). To determine the natural frequencies of the system, Fast Fourier Transformation (FFT) was applied and the Spectrum Analyzer application of LabView 8.2 software was used (figure 1, *c*).

Weft knitted fabrics behave differently in horizontal and vertical directions due to the particular way in which the needles, which knit the yarn across the width of the fabric, form the stitches. For this reason, the knitted fabrics were tested in the wale and course directions, as well as, in the perpendicular direction. Each measurement was repeated three times, mean values, standard deviations and the coefficient of variation (CV%) were determined for each test direction. The results show a CV of 14.1% in the course direction, 11.3% in the wale direction and 13.15% in the perpendicular one. The somewhat high CV values are justified by the fact that the experimental measurements for fabrics made from Outlast yarns are 30% lower than those for fabrics made from the other three yarns.

The curves generated with LabView 8.2 software are shown in figure 2. The frequency for each material and test direction was measured in the graphs from the first highest peak, which represents the natural frequency of the material.

RESULTS AND DISCUSSIONS

This study deals with the influence of yarns type on the natural frequencies of knitted materials, with the aim of achieving a PPE with higher comfort by using high-performance yarns. The measured natural frequencies of the knitted materials were analysed and their values were displayed, correlated with the main knitting parameters in order to draw the appropriate conclusions and define further research limits.

a *b* *c*

Fig. 1. Free vibration method for measuring the natural frequencies: *a* – piezoelectric hammer; *b* – data acquisition system; *c* – LabView Software

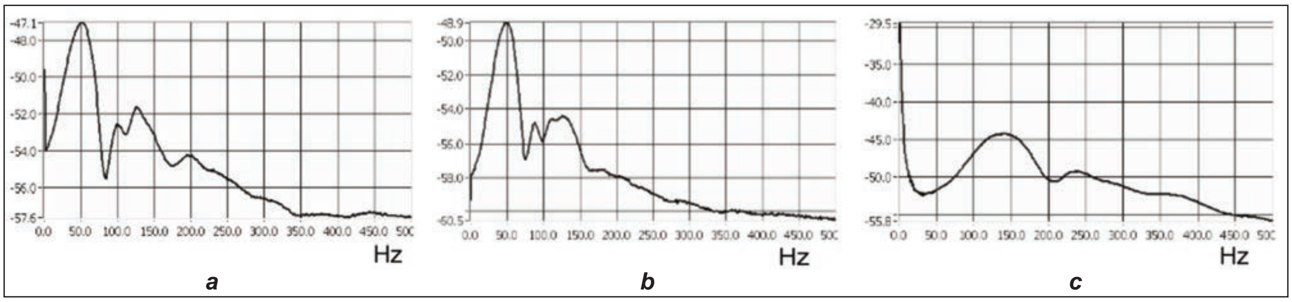

Fig. 2. Recorded values of the natural frequencies of the knitted material [40]: *a* – coursewise; *b* – walewise; *c* – perpendicular

The influence of yarn type on the natural frequencies of knitted materials

When analysing the data obtained, it was found that the Outlast fabrics, which are 100% viscose type, had the lowest values for natural frequencies in all three test directions and the Coolpass and Coolmax fabrics, which are 100% polyester, had the highest values for natural frequencies (figures 3). Dri Release fabrics, with a small percentage of 10–15% cotton, in addition to the predominantly polyester component, registered similar values with synthetic yarns, for perpendicular and coursewise directions (figure 3, *a* and *b*), even higher for the walewise (figure 3, *c*). The hypothesis regarding the influence of yarn type on the behaviour of knitted fabrics in the vibration environment is thus confirmed. It is therefore worth investigating blended yarns further to improve the comfort of products designed to protect against vibrations. The different behaviour of knitted fabrics made of different yarn types was confirmed by the analysis of weft knitted fabrics previously subjected to the same vibration tests [39, 45].

The influence of the fabric's thickness on the natural frequencies of knitted materials

The diagram in figure 4 shows that the natural frequencies of Coolpass fabrics increase with increasing thickness and do not decrease as expected. Similar values for the natural frequencies were measured for Coolmax and Dri Release knitted fabrics regardless of the thickness. With Outlast fabrics, the differences in the measured frequencies could not be correlated with the variation in their thickness.

One explanation for this behaviour could be that the knitted fabrics in the group studied have very low thicknesses 0.51–0.73 mm and the differences between them are insignificant.

The influence of fabric mass on the natural frequencies of knitted materials

The influence of fabric mass per unit area (g/m^2) on the natural frequencies was not investigated to date and no studies on the influence of this parameter were found in the literature. Although the tested

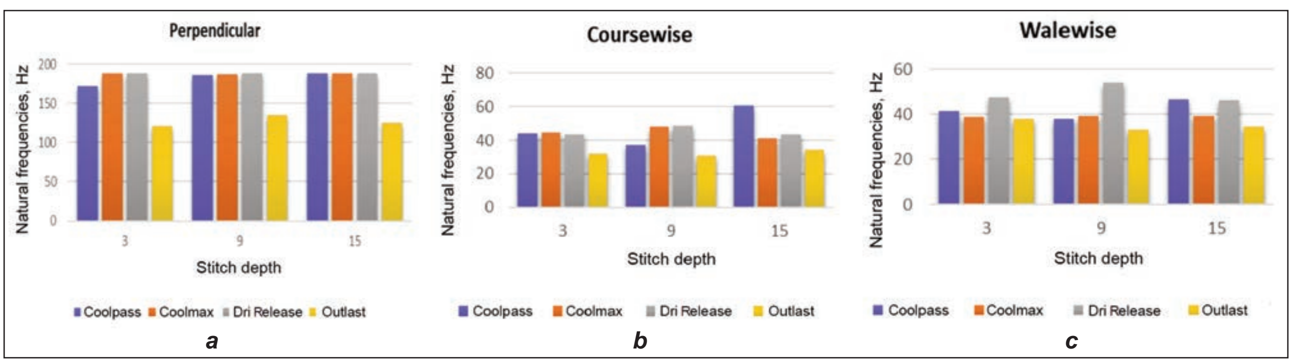

Fig. 3. Natural frequencies of knitted fabrics from different yarns: *a* – perpendicular; *b* – coursewise; *c* – walewise

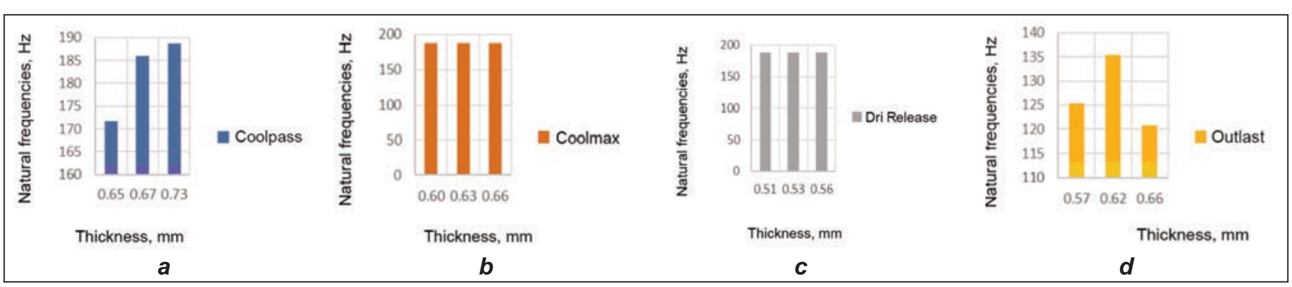

Fig. 4. Natural frequencies of knitted fabrics and the thickness:
a – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

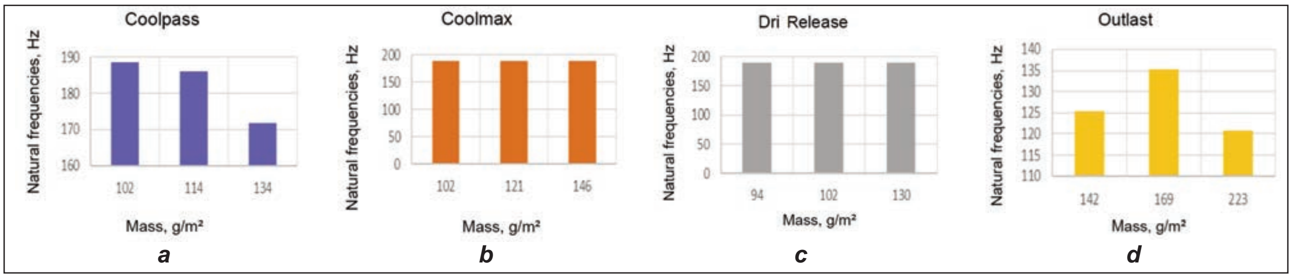

Fig. 5. Natural frequencies of the fabrics and the mass per unit area:
a – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

fabrics showed a significant increase in mass with decreasing stitch depth, the recorded frequency values could not be correlated with this parameter. The diagram in figures 5 shows that the natural frequencies of the Coolmax and Dri Release knitwear showed identical values regardless of the variation in the mass of the material. The range of values was between 94–146 g/m^2, but their behaviour is comparable, which led to the same conclusion that the most important influencing factor is the type of raw material and not the specific weight of the knitted fabric.

In the Coolpass knitwear, the increase in mass caused a decrease in the recorded natural frequencies. In the case of Outlast materials, the differences in the recorded frequencies could not be correlated with the variation in mass at all.

The influence of the test direction on the natural frequencies of knitted materials

Figure 6 shows that the frequency level for each of the four yarns fabrics, is comparable in the wale and course directions and that approximately four times higher values were measured in the perpendicular direction. The previous research demonstrated that the highest values of natural frequencies are recorded in the perpendicular direction and this indicates a higher stiffness of the materials in this direction of testing [29–30, 39, 40].

The values displayed show that the frequency levels for the three raw materials (Coolpass, Coolmax and DriRelease) are comparable in the course 40–75 Hz and wale 37–50 Hz directions, while the values in the perpendicular direction are around four times higher 186–190 Hz. Outlast knitted fabrics showed lower values in all directions, respectively 29–37 Hz in the row direction, 30–40 Hz in the wale direction and 116–140 Hz in the perpendicular direction.

The influence of stitch density on the natural frequencies of knitted materials

The tightness of the knitted fabric can be adjusted on knitting machines by the different positions of the stitch cam. The higher the division of the stitch cam, the longer the stitch length, the looser the knitted fabric and the lower the stitch density. When the recorded natural frequencies were analysed, it was found that they did not confirm the hypothesis put forward in the authors' previous studies, in the sense that the higher the NP value, the lower the recorded natural frequencies. For this group of knitted fabrics, the differences recorded as a result of the variation in stitch depth on the three levels were inconclusive in that

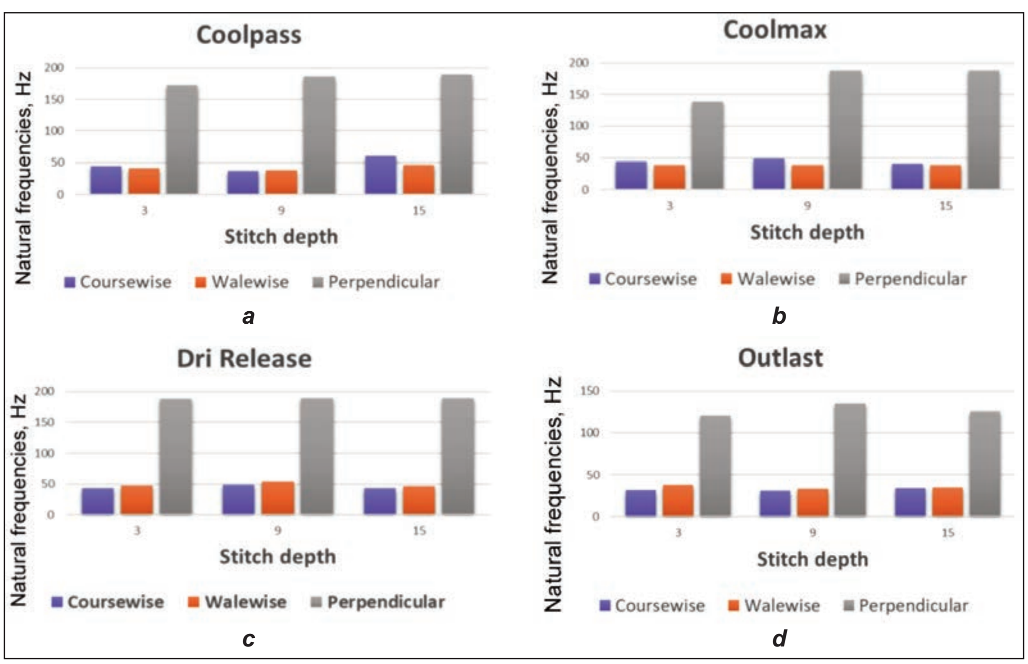

Fig. 6. Natural frequencies of the fabrics and the test direction: *a* – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

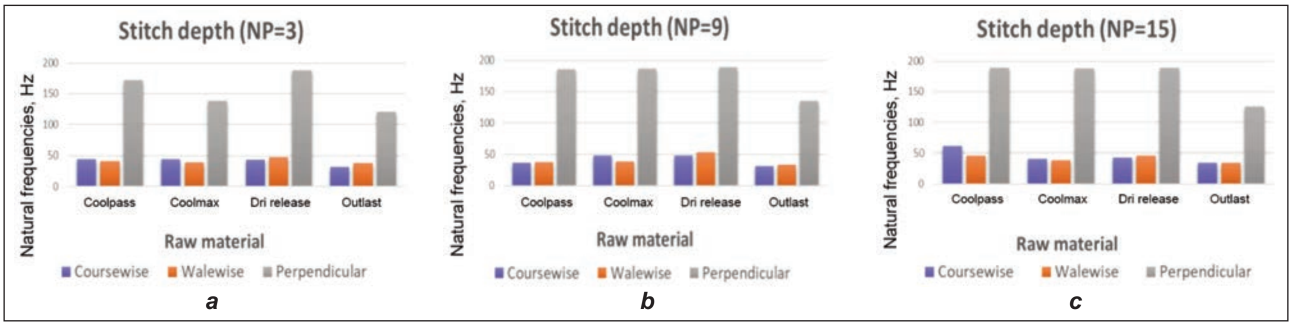

Fig. 7. Natural frequencies of the fabrics and the stitch depth values: *a* – stitch cam depth value 3; *b* – stitch cam depth value 9; *c* – stitch cam depth value 15

the values obtained for the same raw material were quite close to each other, with differences of 10–15 Hz and the increases or decreases in the recorded frequencies could not be correlated with the stitch depth value (figure 7).

CONCLUSIONS

The energy emitted in the form of vibrations from various electrical or mechanical sources and absorbed by workers can have a negative impact on their health and productivity at work and, with prolonged exposure, can lead to permanent occupational diseases.

One of the properties of materials relevant to a vibrating environment is their natural frequency, which provides information about their stiffness. The higher the measured natural frequencies, the stiffer the material.

The thickness and specific mass of the fabrics were investigated in this study and no correlation was found with the recorded natural frequencies, and this led to the conclusion that the type of yarns is the main influencing factor when it comes to knitted, very thin and stretchable linings as part of the overall construction of a PPE.

As the negative effects of vibrations increase in cold working environments, special attention must be paid to the comfort of fabrics by selecting the right yarns with excellent comfort properties. From this point of view, the use of synthetic-natural blended yarns that improve both the mechanics and comfort of protective materials is a worthwhile further research objective.

This research opens up new ideas for the development of materials that meet the dual requirements of PPE in terms of mechanical absorption of vibrations and adaptive comfort in different environmental conditions. The use of knitted fabrics for this purpose is a promising research direction, as today's knitting technology allows the development of materials with suitable physical properties such as weight, thickness, density and different raw materials.

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Flame retardant properties of fabrics designed to be used in military camouflage

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ABSTRACT – REZUMAT

Flame retardant properties of fabrics designed to be used in military camouflage

In this study, wool/aramid blended yarns, as well as viscose FR yarns, were used to produce flame-retardant woven fabrics. Many fire retardancy standards also include tear strength, abrasion resistance, tensile strength and dimensional change of the fabrics during fire hazards. Therefore, these tests were included to study the fire retardant performances of the fabrics produced with 100% wool/aramid blended fibres and viscose FR fibres in the warp and wool/aramid blended fibres in the weft direction. As a result of the study, no statistically significant differences were found in the mechanical properties of the fabrics. In contrast, the thermal protective performance of the fabrics produced with wool/aramid blended yarns was better than the ones produced with viscose FR warp yarns. On the other hand, the vertical flame-retardant performance of fabrics produced with viscose FR yarns was better than those produced with wool/aramid blended yarns in both directions. As a result of the study, it was found that the use of viscose FR fibre, which is a more accessible and comfortable alternative to the wool/aramid blend, in the warp or weft direction will minimize fabric costs while providing similar flame-retardant performance without losing fabric mechanical properties.

Keywords: *aramid, wool, viscose FR, flammability, thermal protective performance, dimensional change.*

Proprietăți ignifuge ale țesăturilor concepute pentru a fi utilizate în camuflajele militare

În acest studiu, au fost utilizate fire în amestec de lână/aramidă, precum și fire de viscoză FR, pentru a produce țesături ignifuge. Multe standarde de rezistență la foc includ, de asemenea, rezistența la rupere, rezistența la abraziune, rezistența la tracțiune și modificarea dimensională a țesăturilor în timpul riscurilor de incendiu. Prin urmare, aceste teste au fost incluse pentru a studia performanțele ignifuge ale țesăturilor produse cu fibre în amestec 100% lână/aramidă și fibre de viscoză FR pe direcția urzelii și fibre în amestec lână/aramidă pe direcția bătăturii. În urma studiului, nu s-au constatat diferențe semnificative din punct de vedere statistic în ceea ce privește proprietățile mecanice ale țesăturilor. În schimb, performanța de protecție termică a țesăturilor produse cu fire în amestec lână/aramidă a fost mai bună decât cea a țesăturilor produse cu fire de viscoză FR pe direcția urzelii. Pe de altă parte, performanța de ignifugare verticală a țesăturilor produse cu fire de viscoză FR a fost mai bună decât a celor produse cu fire în amestec de lână/aramidă în ambele direcții. Ca rezultat al studiului, s-a constatat că utilizarea fibrelor de viscoză FR, care reprezintă o alternativă mai accesibilă și mai confortabilă la amestecul de lână/aramidă, pe direcția urzelii sau a bătăturii, va minimiza costurile țesăturilor, oferind în același timp performanțe similare de ignifugare, fără a pierde proprietățile mecanice ale țesăturilor.

Cuvinte-cheie*: aramidă, lână, viscoză FR, inflamabilitate, performanță de protecție termică, modificare dimensională*

INTRODUCTION

Fire hazards are associated with a variety of properties of a material in a particular scenario. It is determined by a combination of factors, including the material ignitability, the rate at which heat is released from it when it burns, the total amount of heat that is released, the flame spread, the smoke production, and the toxicity of the smoke [1]. As it is so far known, no natural fibre – except asbestos – is meeting all the fire hazard needs. Therefore it is also essential to provide more escape time and to reduce burn injury levels during working [2] for protective clothing made of natural fibres that are sustainable, compatible with changing environmental needs, and have less carbon imprint [3]. Amongst natural fibres, wool fibre, with its superior properties of biodegradability and recyclability, warmth and coolness, breathability, high moisture absorption, resilience, low odour and high odour absorption, softness, and flame-resistance properties, make them used in apparel clothing as well as upholstery, carpeting etc. [4]. Wool is the most resistant fibre of all the commonly used textile fibres to burning, which has an ignition temperature of 750–800°C, a high limiting oxygen index (LOI 25–26%), does not melt or drip, and forms char [4]. However, the abrasion resistance and chemical resistance of wool fibres are insufficient to produce flame-retardant protective garments since rigid precautions should be taken for designing protective clothing [5]. For this reason, blending wool fibres with highly abrasive and chemical-resistant aramid fibres will ensure not only flame-retardant garments but also combine the high comfort properties of wool with high mechanical and temperature-resistant properties of aramid fibres together. These blends can be used in areas with less fire hazard odds but where fire protection is important. Flame-retardant viscose fibres with polyimide fibre, processed with dope dyeing technology, are combined in a 50/50 ratio blend. This fabric is extensively utilized as the primary material for specialized military uniforms in European nations. In Italy, firefighting suits, and in the UK and France, riot suits employ fabrics composed of polyimide blended with flame-retardant viscose fibres. Fabrics created from a 50/50 mixture of these fibres offer outstanding comfort and enduring flame retardancy [3]. For this reason, combining viscose FR fibres with high-technical fibres not only enhances the comfort properties of the fabrics but also decreases the production costs of a fabric consisting of aramid, polyimide, and other high-technical fibres.

Heat resistance and flammability of high-performance fibres were reviewed according to literature, and high-performance fibres such as Poly(p-phenylene-2,6-benzobisoxazole) (PBO), Poly p-phenylenediamine - terephtalamide fibres (PPTA), Poly(2,6-diimidazo[4,5-b:4´,5´-e]pyridinylene-1,4(2,5-dihydroxy)phenylene) (PIPD), phenolic fibres, melamine fibres, and polyimide fibres were evaluated using cone calorimeter as well as were examined in terms of heat resistance using combined TGA/DSC. PBO and PIPD fibres exhibited the best performance [6]. In another study, PBO, PPTA, and wool-spun yarns were used to produce knitted fabrics in different blend ratios to study the heat and fire resistance of fabrics. It was found that blends of wool with p-aramids improved the FR performance of the fabrics, while blends of wool with PBO did not enhance the FR properties of the fabrics [7]. FR performance of the knitted fabrics made of blends of wool with PPTA fibres was examined and it was found that even with low percentages of PPTA of at least 30% in the blends compared to the previous study in which the blend was processed yarn by yarn, better FR results were obtained [8]. The effect of yarn count (10, 20, 30 Ne) and fibre type (para-aramid, meta-aramid, and flame-retardant polyester (FR PES) staple fibres) on the mechanical and flammability properties of the woven fabrics were investigated [9]. P-aramid fibres were found to be thermally more stable than m-aramid and FR PES fibres as the 100% p-aramid fabrics produced smaller carbonized areas and no holes or cracks [9]. The burning behaviour of woven fabrics produced from flame-retardant (FR) viscose fibres with m-aramid fibres in 3 different ratios as well as nylon 6.6 fibre with FR viscose and m-aramid fibres again in 3 different ratios was studied. It was found that blending viscose fibre with m-aramid fibres improved the limiting oxygen index, contact, radiation and convective heat index properties of the fabrics compared to that of the fabrics made of 100% FR viscose or m-aramid fibres [10].

This study was performed to produce flame-resistant camouflage fabrics that can be used in protective clothing for soldiers who need extra protection due to their job definitions. However, high flame-resistant textile materials produced from highly technical fibres to be used in protective clothing are not only sufficient by themselves. Besides, the comfort properties of the textile material during a field operation are also important. Different fibres should be blended in fibre form to produce a flame-resistant fabric having good mechanical and comfort properties. Blends of aramid fibres with wool staple fibres exhibit good mechanical properties and comfort properties, resulting in high flame-resistant textile products. This study differs from the previous studies in blending wool fibres with m-aramid/p-aramid/antistatic fibres in the form of fibre, which is very difficult since it is difficult to find long staple p-aramid fibres. Using viscose FR fibres and combining them with polyimide fibres are very popular in Europe in the production of military uniforms. Therefore, blends of wools with m-aramid/p-aramid/antistatic fibres were used to produce woven fabrics, the mechanical and flame retardancy tests were measured, and the results were examined in detail. Viscose FR fibres were also used in warp direction as an alternative to wool/m-aramid/p-aramid/anti-static fibres to evaluate the performance of viscose FR fibres, which are easily accessible and low-priced.

MATERIALS AND METHOD

Blends of m-aramid, p-aramid, and anti-static fibres with wool were used to produce single and plied yarns. These yarns were then used in the production of woven fabrics.

Foremost, the manufacturer performed the blending of m-aramid/p-aramid/anti-static fibre, and the combed fibre blend in the form of tops was supplied by the manufacturer. Aramid fibres exhibit high mechanical properties, flame retardancy, and resistance to chemicals. Anti-static fibres are somehow different in structure from the other fibres. These fibres consist of a carbon core and an insulating sheath of nylon 6. These fibres and the supplied blend are presented separately in figure 1. These

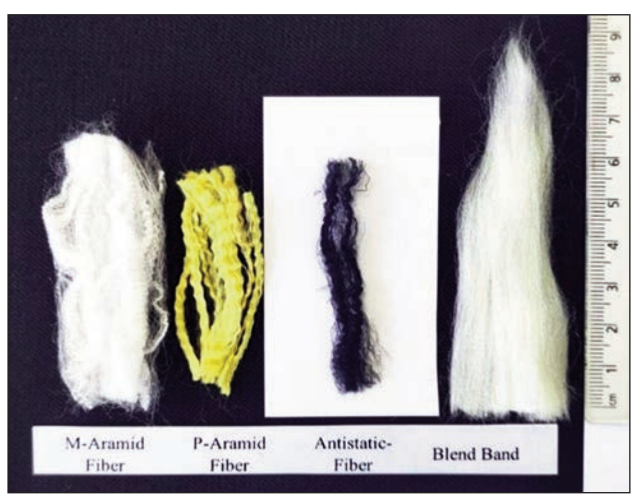

Fig. 1. M-aramid, p-aramid, antistatic fibre and the supplied blend from the right to the left

Table 1

FIBRE PROPERTIES USED WITHIN THE STUDY					
Fibre properties	**Wool**	**M-Aramid fibre**	**P-Aramid fibre**	**Antistatic fibre**	**Viscose FR**
Diameter (micron)	20	14.25	12.25	18.50	12.02
Diameter (dtex)	4.28	2.2	1.7	3.1	1.7
Variation of diameter (CV%)	19.63	-	-	-	11.76
Length (mm)	75	75	51	76	40
Variation of length (CV%)	42	-	-	-	5
Strength (g/den)	1.22–1.55	3.95	23	2.1	2.83
Elongation (%)	25–35	29.7	3.6	44.6	13

combed tops were blended in the mélange stage of wool yarn production with wool fibre in 50/50 ratios.

The properties of wool, m-aramid, p-aramid, and antistatic fibres were presented in table 1 (diameter, diameter variation, fibre length, variation of length, sliver cv). The following equation was used to convert the values between micron and dtex to compare the fineness of each fibre. For m-aramid, p-aramid, and antistatic fibres, 1.38 g/cm^3, 1.44 g/cm^3, and 1.15 g/cm^3 densities can be used, respectively. Besides, the standard deviation of diameter for synthetic fibres is very small and can be ignored. For wool fibres, 1.314 g/cm^3 for density and the standard deviation of 3.926 were used, and fineness in dtex was calculated.

$$dtex = 0.007854\,(d^2 + s^2) \times density \qquad (1)$$

Easy accessibility, low price, and high comfort properties of viscose FR fibres make them a good alternative for flame-resistant textile products. Therefore, yarns made for woven fabrics were produced with wool/aramid blended fibres, and an alternative to wool/aramid fibres was viscose FR yarns, which were also used. For yarn production, wool/m-aramid/p-aramid/anti-static fibre blend was processed on Zinser 451 ring machines with 9000 rpm spindle speed in the yarn count of Nm 50/1 with 650 turns/meter (T/m). After conventional yarn production, doubling and twisting of the yarns were performed simultaneously on Savio two-for-one machines, and yarns with Nm 50/2, 650 T/m in the S direction were produced. Viscose FR fibres were supplied from another yarn manufacturer and these yarns were doubled with the exact yarn count and twists and then dyed for camouflage fabrics.

The fabrics were produced in plain and twill 2/1 patterns on Dornier rapier weaving machines with dobby mechanisms. To produce plain fabrics, 20 warps and 19 wefts per cm were used, while 28 warps and 24 wefts per cm were used for twills. Viscose FR yarns were also used as warp yarns as an alternative to wool/aramid blended yarns. As a result, using two different patterns with two different warp yarns produced four types of woven fabrics. The properties of the woven fabrics and the blend ratios of the final fabrics are presented in table 2. All fabrics were treated with same processes such as open width washing, continuous pressing (100 °C, 15 m/min), stenter (130 °C, 40 m/min), singeing, open width washing, stenter (130 °C, 40 m/min), shearing of both sides, stenter (120 °C, 25 m/min with 20 g/l extrasoft + 10 g/l sotycel), continuous decatizing under pressure (backside, 20 m/min), decatizing and finally stenter (130 °C, 40 m/min) under the same conditions.

The properties of the woven fabrics under laboratory conditions were measured for each fabric after 24 hours of conditioning at 20±2 °C and 65±2% relative humidity. The mass per unit area and widths of the fabrics were measured according to ISO 3801:1977 and ISO 3932 standards, respectively. Tensile and tear strength of the fabrics were performed based on the ISO 13934-1 and ISO 13937-2 standards, respectively, both in warp and weft directions. Seam slippage measurements were performed according to ISO 13936-1. The fabrics' abrasion resistance

Fig. 2. Measurement of thermal protective performance on the left and vertical flammability on the right

Table 2

FABRIC PROPERTIES USED WITHIN THE STUDY				
Fabric properties	**Viscose FR_Plain**	**Viscose FR_Twill**	**Wool_Aramid_Plain**	**Wool_Aramid_Twill**
Pattern	Plain	Twill 2/1	Plain	Twill 2/1
Warp density (threads·cm^{-1})	20	28	20	28
Weft density (threads·cm^{-1})	19	24	19	24
Warp threads	Nm 50/2 Plied 650S 100% Viscose FR	Nm 50/2 Plied 650S 100% Viscose FR	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre
Weft yarns	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre
Fabric blend	52/24/24 52% Viscose FR 24% Wool 24% blend of M. Aramid P. Aramid Antistatic fibre	54/23/23 54% Viscose FR 23% Wool 23% blend of M. Aramid P. Aramid Antistatic fibre	50/50 50% Wool 50% blend of M. Aramid P. Aramid Antistatic fibre	50/50 50% Wool 50% blend of M. Aramid P. Aramid Antistatic fibre

and pilling tendency were measured based on ISO 12947-2 and ISO 12945-2, respectively. Determination of dimensional change of the fabrics with steaming on ironing machines was performed according to ISO 53984-2. Dry-rubbing, wet-rubbing, and dry-cleaning fastness of the fabrics were also measured according to ISO 105-D01, ISO 105-X12, and ISO 105-X12 standards, respectively.

Thermal protective performances and vertical flammability of the fabrics were measured according to ISO 17492:2003 and ASTM D 6413-08:2015. Fabric samples should be pretreated according to ISO 6330:2012 before vertical flammability of the fabrics. Fabric samples were washed at 60±3°C with ECE reference detergent of (20±1 g) 5 times and dried with a tumble dryer 5 times.

Analysis of variance was performed for the observed measurements. Based on the experimental design and data type, variance analysis with one factor, two factors, and Friedman non-parametric analysis was performed. Obtained p-values less than 0.05 mean that the effect of that specific factor has a statistically significant effect on that fabric property.

RESULTS AND DISCUSSION

The yarns were produced in the yarn count of Nm 50/2 as a plied yarn. To compare the flame-resistance performance of different fabrics that are inherently FR, such as wool/aramid/anti-static fibre blend and an FR viscose yarn, which are accessible and less costly, Nm 50/2 viscose FR double-plied yarns were also produced. The properties of produced single and plied yarns of wool/aramid/anti-static fibre blends and doubled viscose FR yarns before and after dyeing processes are given in table 3.

The mean values of yarn count and turns per meter were observed to be similar for viscose FR and wool/aramid blended yarns. However, yarn quality parameters such as yarn evenness (U%), coefficient variation of yarn evenness (CVm), thin, thick places, and neps values were better for raw viscose FR yarns compared to those of the wool/aramid blended yarns. This is due to the nature of wool fibre because wool is a natural fibre; it consists of a high coefficient of variation values for fibre properties of fineness, length, etc. Therefore, this property during the conversion of fibres to yarns is reflected in yarns. The effect of doubling could easily be seen when the results of the wool/aramid blended or raw viscose FR yarns were observed. Yarn doubling enhanced the yarns' properties, resulting in better U%, CVm, thin, thick places and neps. In addition to quality parameters, yarn doubling improved the tenacity and elongation properties of the yarns and decreased the hairiness of these yarns regardless of fibre type. When the results of the tenacity values of doubled wool/aramid blended and viscose FR yarns were examined, the tenacity values of wool/aramid blended yarns were 35% higher than that of the viscose FR yarns. This is due to the nature of aramid fibres, which have high tenacity properties. On the other side, the effect of package dyeing can easily be seen from the results of the yarn quality parameters of viscose FR yarns. Thick places and neps values

Table 3

MEASURED PROPERTIES OF THE YARNS USED WITHIN THE STUDY											
Fibre blend	**Nominal count**	**Count (Nm)**	**T/m**	**U%**	**CVm**	**H (S3)**	**Thin –50%/km**	**Thick +50%/km**	**Neps +200%/km**	**Tenacity (cN/tex)**	**Elongation (%)**
Wool-Aramid	Nm 50/1	50.74	656.40	17.12	23.30	2207.88	243.16	781.32	4538.58	14.00	15.12
Plied Wool-Aramid	Nm 50/2	25.61	642.80	12.88	17.61	1536.60	4.75	320.50	2843.70	17.49	24.31
Raw Viscose FR	Nm 50/1	50.67	905.00	11.40	14.45	1101.00	10.00	75.00	112.00	10.77	7.10
Plied Raw Viscose FR	Nm 50/2	26.13	649.10	8.44	10.67	572.60	0.00	1.75	10.50	12.64	11.87
Dyed Viscose FR	Nm 50/2	25.08	641.80	8.44	11.23	971.00	0.00	1.00	3.00	11.31	15.45

increased after package dyeing due to the movement of the dye solution from inside to outside and vice versa. Furthermore, the hairiness of the dyed yarns almost doubled, and the tenacity of the yarns was affected negatively, as expected.

The mass per unit area results of the fabrics are presented in figure 3. Weft and warp densities were fixed considering the weaving patterns of the fabrics on the weaving machine. The effect of the weaving pattern on the mass per unit area results can easily be seen from the results. Twill fabrics had higher mass per unit area results regardless of fibre type used in the warp direction since high warp and weft densities were used during the production of twill fabrics as well and higher fabric shrinkages occurred compared to that of plain fabrics due to the higher capacity of free moveable yarns in the twill structure. Based on the results, using viscose FR yarns in the warp direction of plain fabrics did not change mass per unit area results compared to the plain fabrics made of wool/aramid blended yarns in the warp direction. However, the situation is different for twill fabrics. Based on two-factor variance analysis without replications, there was no statistically significant difference between the mean values of each group ($p > 0.05$).

The tensile strength values of the fabrics are given in figure 4. The first bars in each group represented the tensile strength values of the fabrics in the weft direction. As mentioned in the materials and method section, wool/aramid blended yarns were used in the weft direction of all fabrics. As the values in the weft direction were observed in detail, no difference was found except due to the effect of weaving pattern differences. In twill fabrics, the tensile strength values of the fabrics were higher than that of the plain fabrics based on the higher weft densities used to produce twill fabrics. Based on the analysis of two-factor variance without replication, no significant differences between mean values of either yarn type or pattern type were found ($p > 0.05$).

The second bars in each group represented the tensile strength values in the warp direction. Using wool/aramid blended yarns in the warp direction increased the tensile strength values of the fabrics compared to that of the fabrics produced with viscose FR yarns due to lower tenacity values of viscose FR yarns compared to that of wool/aramid blended yarns (wool/aramid blended plied yarns had 54.6 % higher tenacity values). This difference in yarn tenacity values was reflected directly in the results of plain and twill fabrics produced with either viscose FR warp yarns or wool/aramid blended warp yarns. Based on the statistical analysis of two factors without replication, no significant difference was found in terms of different yarns and pattern use ($p > 0.05$ both for yarn type and pattern type).

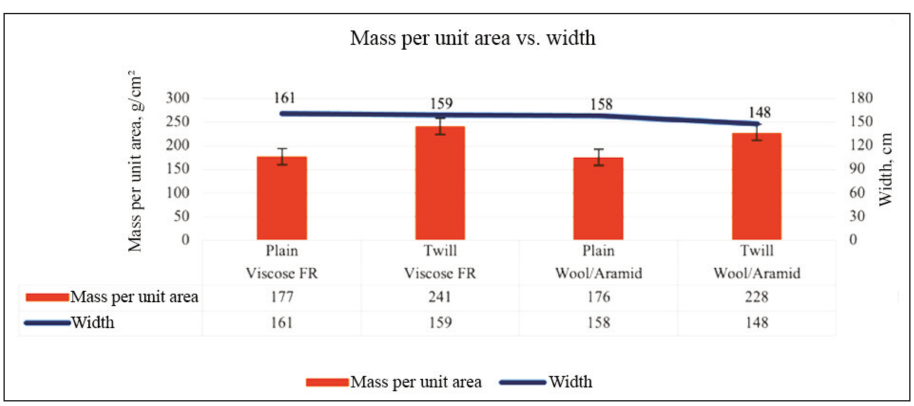

Fig. 3. Mass per unit area results of the fabrics based on the fabric width values

Tear strength is one of the essential mechanical tests that the fabrics meet the requirements of flame-retardant standards. Generally, tear strength mainly depends on free movable yarns and the capacity of yarns packing together. Thus, these two parameters are influenced by the weaving pattern and related yarn density of fabrics, which are measured in that direction. Along with these parameters, the constituent yarn tenacity of the fabric is one of the most critical factors. When the results were evaluated in this context, weaving patterns, warp/weft densities, and viscose FR instead of wool/aramid blended yarns were the factors that affected the tear strength results of the fabrics.

The first bars in each group represent the values of the tear strength in the weft direction. In the weft direction of all fabrics, the same yarns, wool/aramid blended yarns, were used. Thus, in the first pair, the difference was related to the weaving pattern and the weft density. These two parameters inversely affect the tear strength of the fabrics. As it is well known, increasing the movement ability of yarns in the fabric structure increases the tear strength of the fabrics. While the twill pattern causes yarns to be grouped and acted together and increasing the weft yarn density causes the yarns to be packed in a denser structure and makes their movement difficult, on the one hand, using twill instead of plain increased the tear strength values on the other hand, increasing the weft density decreased the tear strength values of the fabrics. As a result, a 7.25% increment in the tear strength in the weft direction occurred in the twill fabrics produced with viscose FR warp yarns. However, a 3.75% decrement had occurred in the weft tear strength values of the fabrics based on the pattern change produced with wool/aramid blended warp yarns, which was insignificant and was under the acceptable quality limits. Another significant result obtained from the weft tear strength of the fabrics produced with viscose FR warp yarns and wool/aramid blended warp yarns was that higher weft tear strength values were obtained with the fabrics produced with 100% wool/aramid blended yarns due to higher tenacity values of wool/aramid blended compared to that of viscose FR yarns. However, no statistically significant difference was found between the mean values of fabric groups based on the two-factor ANOVA without replication ($p > 0.05$).

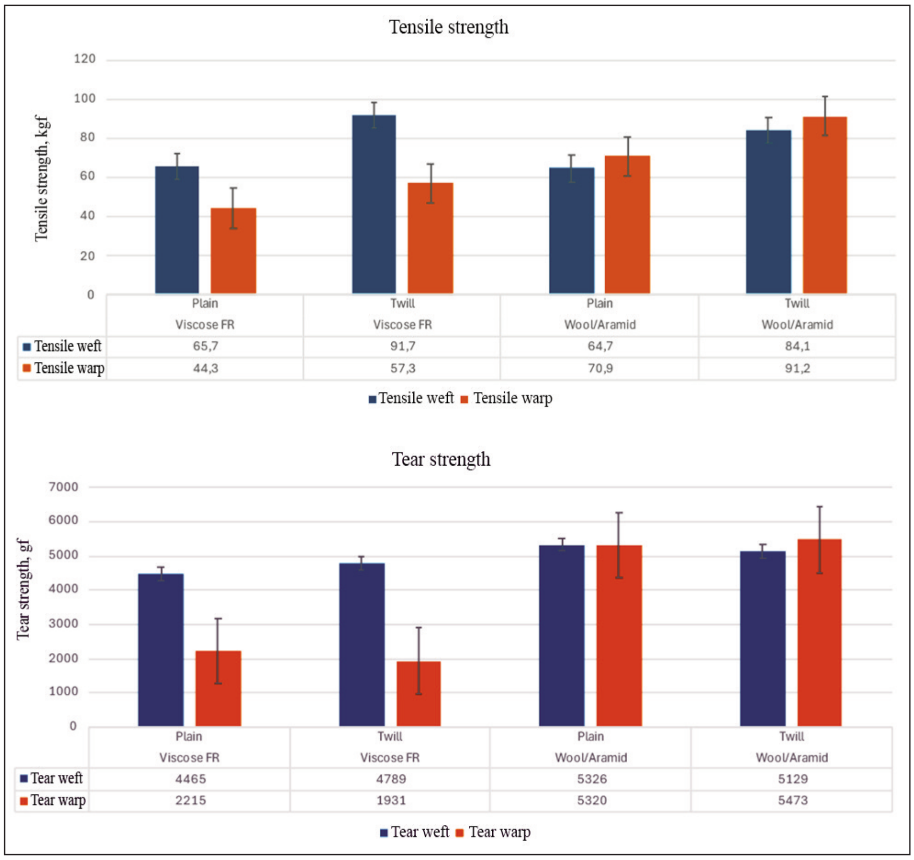

Fig. 4. Tensile and tear strength of the fabrics in both directions

The most significant difference occurred in the warp tear strength values. Using viscose FR in the warp direction led to low tear strength values due to lower tenacity values of viscose FR yarns compared to wool/aramid blended yarns. Using twill patterns and high warp densities in the fabric construction affected the warp tear strength similarly as explained in the weft tear strength. Based on the statistical analysis, except for the yarn parameter in warp direction results, no significant difference was found for mean differences ($p = 0.041$ for different warp yarn use in warp direction results).

Seam slippage is another crucial mechanical property that should be measured for most flame-retardant standard tests. The observed measurements of the fabrics in weft and warp directions are presented in figure 5. Seam slippage is defined as the slippage of weft threads on the warp or slippage of warp threads on the weft, the value of which depends on the fabric structure and the finishing applied when the stitch is subjected to a particular load. This not only results in partial or complete deterioration of the appearance of the garment but also reduces the lifespan of the garment. The fabrics' mechanical properties have a great impact on seam slippage; for example, increasing fabric thickness results in decreasing seam slippage. As skips increase in the texture structure, thread slippage becomes easier, and weft density has a greater effect on stitch slippage than warp density. When the results were evaluated within the relevant factors, the weft direction seam opening strength values were similar because the same weft yarns of wool/aramid blended yarns were used. On the other hand, seam slippage strength results in warp direction were all the same despite using viscose FR yarns in the warp direction. No statistically significant difference was found between the means based on the use of different warp yarns and patterns.

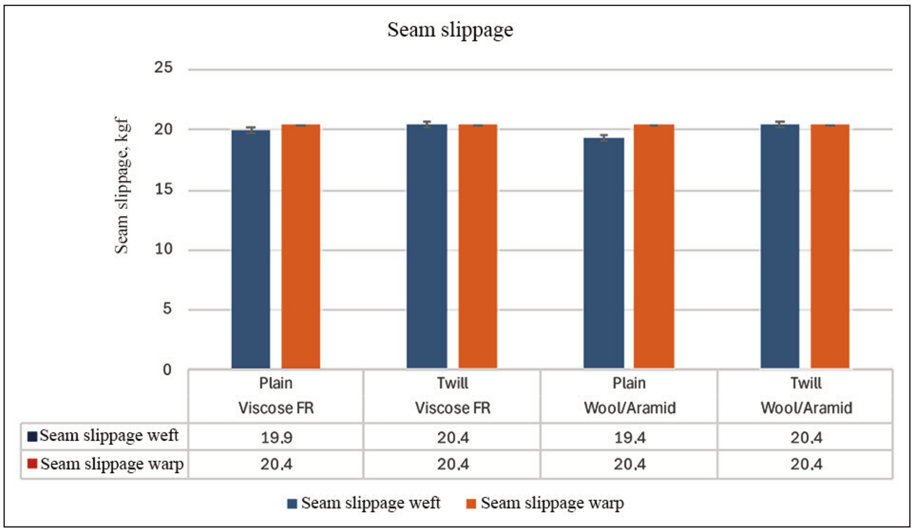

Fig. 5. Seam slippage of the fabrics in both directions

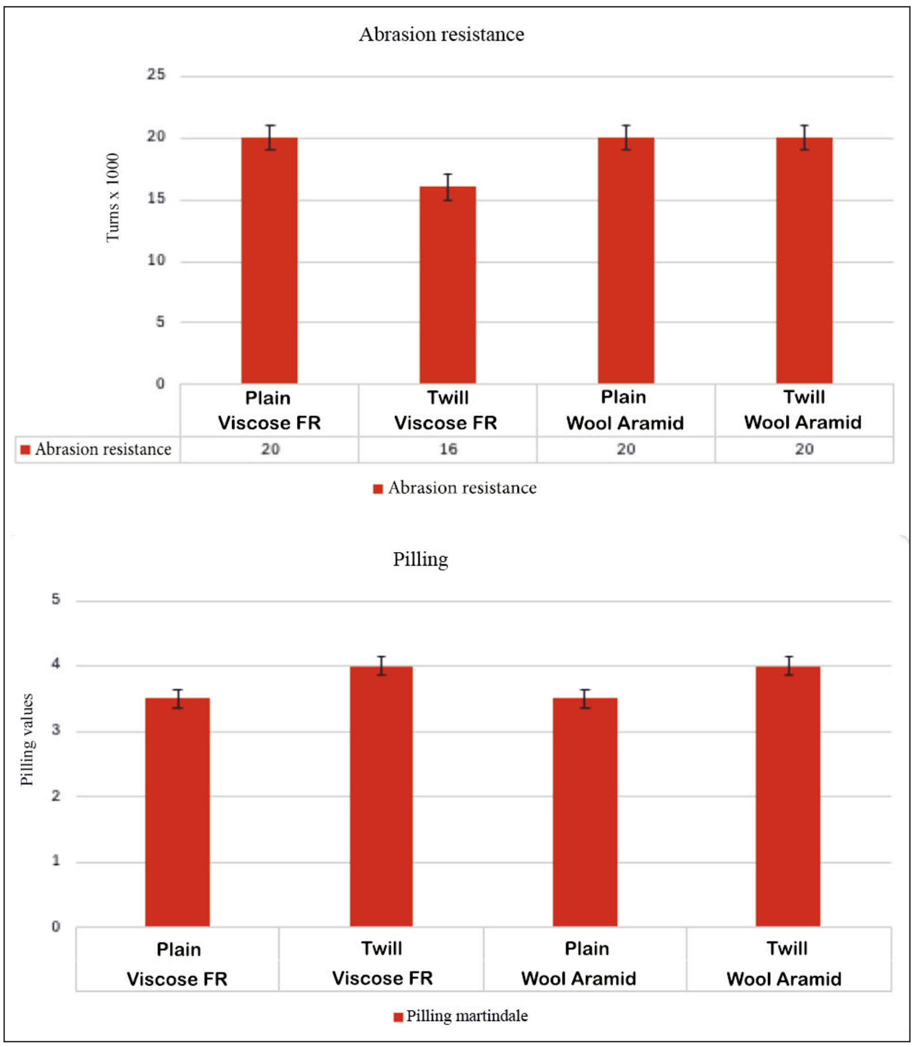

Fig. 6. Abrasion resistance and pilling properties of the fabrics

Abrasion properties of the fabrics affect the garment's appearance during usage. Abrasion of the fabric can lead to a reduction in weight and thickness, and eventually, the fabric will fail, with a hole forming, which exposes the wearer directly to an electric arc or fire threat [11]. Thus, some parts of the garments must endure abrasive forces, such as the crotch area for pants and armpits for shirts. Uniforms, especially for police forces or firemen, must meet these requirements as well as they can allow different body movements and withstand extreme conditions.

Therefore, the abrasion resistance of the fabrics was measured and presented in figure 6. All fabrics had the same abrasion values except twill fabrics produced with viscose FR warp yarns. According to statistical analysis of two factors without replication, no statistically significant difference was found between the means based on different warp yarn and pattern use ($p > 0.05$).

The pilling property is another important fabric property that affects the garment's appearance during usage. The pilling results of the fabrics were measured and presented in figure 6.

Commonly, the pilling property of a fabric is affected by fibre type, yarn property, especially hairiness, and fabric construction (warp/weft densities, weaving pattern). When results were evaluated in this context, it can easily be seen that all the fabrics had similar piling results. There was no difference observed regarding the yarn type since the expectation was that using viscose FR yarns would cause less pilling in the fabrics since viscose FR yarns had less hairiness; on the other hand, wool/aramid blended fibres are long staple fibres, which would cause less pilling. These two factors reconciled, and the fabrics had the same pilling values. On the contrary expectation, the twill pattern improved the pilling results of the fabrics compared to the plain fabrics. In twill fabrics, yarn floats are more compared to plain fabrics in which yarns would be more exposed to friction forces and cause more pilling on the fabric surface. However, this situation is valid for fabrics with the same densities. In this study, twill fabrics had higher densities of warp/weft which would result in denser structure and less exposure to friction forces per unit yarn. Pilling values are ordinal values; therefore, based on Friedman's non-parametric test results, there were no statistically significant differences between fabric groups. Dimensional changes after the Hoffman press in both directions were presented in figure 7. Fabric shrinkage is essential, especially for woollen fabrics. However, shrinkage is another important property, and a flame-retardant fabric should meet the requirements of related standards since nobody wants his/her clothing to shrink under fire conditions. Low shrinkage values mean that the dimensional change of fabrics is low and fabrics are stable or set. All dimensional changes, both in weft and warp directions, were low for all fabrics. For the weft direction, dimensional change in twill fabrics was 0.3%, while for plain, this value was 0.5%. For warp direction, no trend was observed regarding different yarn composition and weaving patterns. Based on a statistical analysis of two factors without replication, no statistically significant difference was found between the means based on different warp yarn and pattern use ($p > 0.05$).

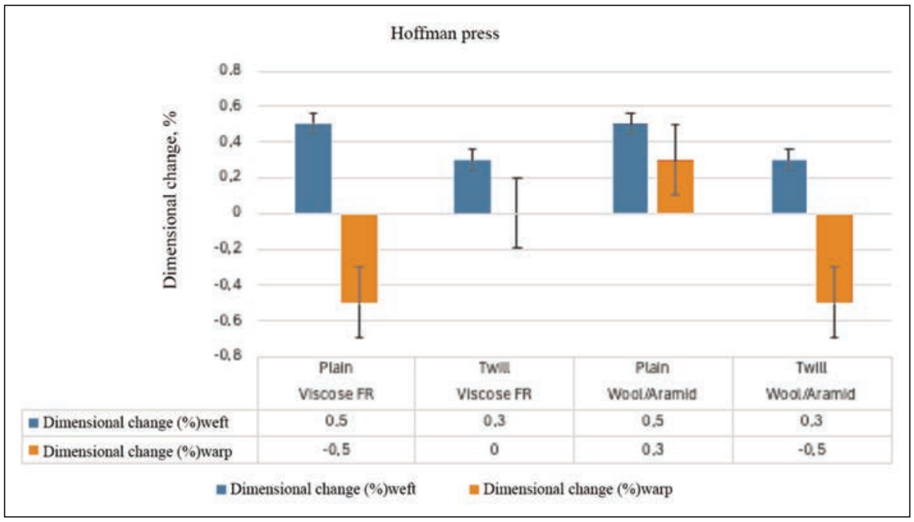

Fig. 7. Dimensional changes of the fabrics after Hoffman press in both directions

Flammability characteristics and thermal barrier performance are important for a garment to provide flame and thermal protection [12]. The thermal protection, or thermal barrier performance, of a fabric, can be evaluated by benchtop tests that expose the outside surface of the fabric to a heat source and measure the heat flux transmitted on the back side of the fabric. A standard version of a thermal protection test, commonly called the Thermal Protective Performance (TPP) test, is described by ISO 17492 [12], which simulates typical fire conditions through the combination of convective heat and radiant heat. Therefore, a specimen is exposed to typical fire conditions: The heat source consists of 50% convective heat and 50% radiant heat. The heat flow adds up to 84 kW/m^2 (approximately 2 cal/cm^2/sec.). The test determines the time and applied heat energy per unit area (TPP) on the back of the textile which would result in second-degree burns on the skin. Higher TPP values mean the product will provide more insulation to the wearer from outside exposures. In other words, higher values of TPP mean that the product will increase the amount of time available before a burn at a known exposure. TPP is calculated with the equation of $TPP = time\ to\ second - degree\ burn \times exposure$. When the results were evaluated, plain fabrics produced with 100% wool/aramid blended yarns had higher values of both TPP and time to record pain. Statistical analysis was performed, and it was found that differences between these fabrics regarding TPP variables were statistically meaningful. However, for flame-resistant fabrics, the minimum limit for TPP rating is 35 cal/cm^2, which means that all fabric samples failed to pass.

The results of the vertical flammability test are shown in table 5. Ten specimens were evaluated for vertical flame testing (five samples from each direction of the fabric). Each sample was exposed to a controlled flame for a specified amount of time before the source of the flame was removed. Measurements were taken as after flame time – the length of time for which a material continues to burn after the ignition source has been removed; after glow time – the time afterglow continues after the removal of the ignition source and the cessation of flaming, and char length-in measuring flame resistance of textiles, the distance from the fabric edge, which is directly exposed to the flame to the furthest point of visible fabric damage after a specified tearing force has been applied.

Table 4

THERMAL PROTECTION PERFORMANCES OF PLAIN FABRICS					
Warp	**Weft**	**Time to record pain (s)**	**Time to 2nd degree burn (s)**	**TTP rating (cal/cm^2)**	**Fabric Failure Factor**
Viscose FR	Wool/Aramid	3.80	5.17	10.37	5.87
Wool/Aramid	Wool/Aramid	4.83	6.50	13.00	5.63
p (sig. value)		0.00	0.00	0.00	0.00

Table 5

RESULTS OF VERTICAL FLAMMABILITY TESTS OF PLAIN FABRICS

Parameter	Weft	Wool/Aramid	Wool/Aramid	Wool/Aramid	Wool/Aramid	p (sig.value)
	Warp	**Viscose FR**	**Viscose FR**	**Wool/Aramid**	**Wool/Aramid**	
	Pre-treatment	**No**	**5w-5d**	**No**	**5w-5d**	p1/p2
After flame time (s)	warp	0.00[1]/0.00[2]	0.00[1]/0.00[2]	0.00[1]/0.00[2]	0.22[1]/1.10[2]	0.33/0.33
	weft	0.00[1]/0.00[2]	0.00[1]/0.00[2]	0.56[1]/2.80[2]	0.00[1]/0.00[2]	0.33/0.33
After glow time (s)	warp	0.00[1]/0.00[2]	0.00[1]/0.00[2]	2.92[1]/3.40[2]	3.98[1]/4.30[2]	0.00/0.00
	weft	0.00[1]/0.00[2]	0.00[1]/0.00[2]	2.96[1]/3.90[2]	5.08[1]/7.50[2]	0.00/0.01
Char length (mm)	warp	46.20[1]/51.00[2]	49.40[1]/53.00[2]	77.60[1]/101.00[2]	68.40[1]/80.00[2]	0.00/0.54
	weft	142.20[1]/182.00[2]	125.20[1]/132.00[2]	89.88[1]/101.00[2]	63.20[1]/88.00[2]	0.00/0.00
Melting/dripping	warp	No	No	No	No	-
	weft	No	No	No	No	-

Note: [1]First values are averages and [2]the second are maximum values observed during tests. p1 stands for the possibility of the mean difference between the fabrics made of viscose FR and wool/aramid blended yarns. p2 stands for the possibility of the mean difference between the non-treated and treated yarns.

Observations include any melting and/or dripping that may occur during testing [13].

It was observed that both the “after flame” and “after-glow time” of the fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns was less than the plain fabrics produced with wool/aramid blended yarns both used as warp and weft yarns. Most protective clothing standards, such as in ASTM F 1506-22, and NFPA 2112, after the flame time of the protective clothing, should be less than 2 seconds. When the results were evaluated in this context, all fabrics had less than 2 seconds on average after flame time. According to the Standard on Emergency Services Work Apparel of the National Fire Protection Association, Massachusetts, USA (NFPA 1975), it is recommended that the char length should not be more than 150 mm [14]. Based on this result, the fabrics produced with viscose FR warp yarns and wool/aramid blended yarns passed the test with average values of char length. However, the non-treated fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns failed to pass the char length in the weft direction since the maximum result of the tests was 182.00 mm. During this test, melting/dripping of the samples was also noted, and there was no observation, including any melting/dripping.

Fastness results of the fabrics are presented in table 6. All fabrics had the same dry and wet rubbing fastness results. Nevertheless, the fastness of dry-cleaning values of fabrics produced with viscose FR yarns was less than that of the fabrics produced with wool/aramid blended yarns.

Table 6

RESULTS OF DIFFERENT FASTNESS RESULTS OF THE FABRICS

Warp	Viscose FR	Viscose FR	Wool/ Aramid	Wool/ Aramid
Pattern	Plain	Twill	Plain	Twill
Dry rubbing	4.5	4.5	4.5	4.5
Wet rubbing	4.5	4.5	4.5	4.5
Dry-cleaning	3	3	4	4

CONCLUSION

In this study, flame-resistant camouflage fabrics to be used in military operations were produced by using the yarns of wool fibres blended with m-aramid, p-aramid, and antistatic fibres and the yarns of viscose FR fibres. The fabrics were produced in two different patterns, resulting in four different fabrics. Thermal protective performance and vertical flammability of the fabrics, as well as tear strength, seam slippage, shrinkage, and abrasion resistance, which are found in many flame retardancy standards, were also measured. As a result of the study, the mechanical performances of the fabrics did not show significantly different results, while results of TPP and vertical flammability tests of the fabrics led to different conclusions.

Plain fabrics produced with 100% wool/aramid blended fibres had better results than those produced with viscose FR warps and wool/aramid blended weft yarns in terms of TPP results. However, the results of vertical flammability tests of the fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns were better than those produced with 100% wool/aramid blended yarns. Blending aramid fibres with wool fibres in 50/50 ratios decreased the flammability performance of aramid fibres relatively compared to using 100% viscose FR. As a result, fabrics with viscose FR yarns may be used in which the wearer may be subjected to direct flame, not for a prolonged time; on the other hand, fabrics made of wool/aramid blended fibres may be a good alternative for the wearer subjected to severe radiant and convective heat.

As it is well known, these flammability standards and tests aim for real-life situation simulation. However, under actual conditions, fabrics can behave differently from the results obtained from the measurements. At least these tests give a comparative idea of the produced fabrics, and these designed fabrics may be used, for example, in military field operations where neither direct flame nor radiant and convective heat for prolonged periods are exposed.

The most significant limitation of this study is to blend the wool fibres with p-aramid fibres, which are very difficult to find in long staples. Therefore, the blending of m-aramid/p-aramid/and antistatic fibre was performed in another professional fibre mill.

Another limitation is the cost of the designed fabrics. For this reason, viscose FR fibres, which are less costly and more comfortable compared to aramid fibres and are very popular in the production of military uniforms, were added to the study. Thus, using 100% viscose FR fibres in one direction of the fabric improved the vertical flammability properties of the fabrics compared to wool/aramid blended yarn usage. Meanwhile, the mechanical properties of the fabrics under examination differed slightly from each other which is also another plus for viscose FR fibres. Furthermore, the production costs of fabrics using viscose FR warp yarns were 30% less than the cost of fabrics made of 100% wool/aramid blended fibres. In future works, fabrics produced with 100% viscose FR, and 100% aramid blended yarns can also be added. In addition to the mechanical and flammability properties of the fabrics, comfort properties such as thermal insulation and air and water permeability of the fabrics can also be studied.

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Development of insect repellent textiles via treating with microcapsules containing *Citrus aurantium* L. peel essential oil

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ABSTRACT – REZUMAT

Development of insect repellent textiles via treating with microcapsules containing *Citrus aurantium* L. peel essential oil

This study aimed to extract Citrus aurantium L. (bitter orange) peel essential oil (CPEO) and test its repellent effect against Culex mosquitoes by incorporating it into textiles in the form of microcapsules. CPEO was obtained from dried citrus peel using the hydrodistillation method with the Clevenger apparatus. Microcapsules containing the essential oil were formed using the complex coacervation method. The volatile compounds of the microcapsules containing CPEO were characterized by gas chromatography-mass spectrometry (GC-MS). Microcapsules with a spherical and uniform shape, as well as appropriate diameter distributions, were observed in optical microscope images and then applied to textiles. The cotton, polyester, and acrylic fabrics were treated with microcapsules using an exhausting method. Scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX) and Fourier transform infrared (FTIR) spectrophotometry analysis were conducted to characterize the fabrics. Finally, an excito chamber test unit was fabricated to evaluate the insect-repellent effects of fabrics against Culex mosquitoes. This study revealed that the fabrics functionalized with CPEO microcapsules exhibit significant repellent effects against Culex mosquitoes.

Keywords: *Citrus aurantium L., complex coacervation, Culex, insect repellent, microcapsules, textiles*

Dezvoltarea de materiale textile insectifuge prin tratarea acestora cu microcapsule care conțin ulei esențial din coaja *Citrus aurantium L.*

Scopul acestui studiu a fost de a extrage uleiul esențial din coaja Citrus aurantium L. (portocală amară) (CPEO) și de a testa efectul său insectifug împotriva țânțarilor Culex, prin încorporarea acestuia în materiale textile sub formă de microcapsule. CPEO a fost obținut din coaja uscată de citrice prin metoda hidrodistilării cu aparatul Clevenger. Microcapsulele care conțin ulei esențial au fost formate prin metoda coacervării complexe. Compușii volatili ai microcapsulelor care conțin CPEO au fost caracterizați prin cromatografie de gaze-spectrometrie de masă (GC-MS). Microcapsulele cu o formă sferică și uniformă, precum și distribuții adecvate ale diametrului, au fost observate în imagini de microscop optic și apoi aplicate pe materialele textile. Materialele textile din bumbac, poliester și cele acrilice au fost tratate cu microcapsule utilizând o metodă de epuizare. Pentru caracterizarea materialelor textile au fost efectuate analize de microscopie electronică de baleiaj cu dispersie de energie (SEM-EDX) și spectrofotometrie în infraroșu cu transformată Fourier (FTIR). În cele din urmă, a fost fabricată o unitate de testare cu cameră excito pentru a evalua efectele repelente ale materialelor textile împotriva țânțarilor Culex. Acest studiu a arătat că materialele textile funcționalizate cu microcapsule CPEO prezintă proprietăți insectifuge semnificative împotriva țânțarilor Culex.

Cuvinte-cheie*: Citrus aurantium L., coacervare complexă, Culex, insectifug, microcapsule, textile*

INTRODUCTION

Insects are among the deadliest creatures in the world because they transmit fatal diseases such as plague, malaria, cholera, fever, tularemia, typhus, and Crimean-Congo hemorrhagic fever [1]. Many tropical diseases, including malaria, dengue, yellow fever, and filariasis result from the bites of infected female mosquitoes of the genera *Aedes Meigen*, *Anopheles Meigen, Culex L.*, and *Haemagogus L.* bloodsuckers [2, 3]. Malaria is specifically caused by transmitting the *Plasmodium* parasite, a single-celled organism, to humans by *Anopheles* mosquitoes [4]. In addition, insects and pests cause fear and discomfort in humans. Many synthetic and natural substances are used to protect against insects. Synthetic substances typically include pesticides (insecticides), naphthalene, boric acid, and fumigants. However, fumigants and other pesticides can cause health problems such as headaches, nausea, and respiratory issues. Other synthetic insect repellents include N,N-diethyl-meta-toluamide (DEET), picaridin, and permethrin [5]. Since the body absorbs these synthetic substances and can remain under the skin, they may cause health problems when used over long periods [6]. Recent increases in these health problems have led people to seek natural alternatives to synthetic and hazardous substances. Citronella, neem, and lemon eucalyptus are among the most effective natural insect-repellent agents [5].

Nowadays, the importance of multidisciplinary studies is increasing. Research that combines fields such as food science, chemistry, pharmacy, and textile science is becoming more common. While chemists, food scientists, and pharmaceutical researchers study synthetic and natural compounds, textile scientists focus on methods for producing and analysing insect-repellent textile materials containing these compounds. To date, various methods have been utilized in the production of insect repellent textiles including electrospinning techniques, microcapsule applications, and cyclodextrin applications [5, 7]. Microencapsulation is the most preferred method [8] due to its advantages of ease of application, cost-effectiveness, and suitability for scale-up [9–12]. Additionally, microencapsulation ensures the long-term preservation of the encapsulated agent and maintains the effectiveness of essential oil components over time [13].

The effectiveness of insect-repellent textiles can be tested by various methods. The most commonly used techniques are cage test, cone test, and excito chamber test [5, 14]. In the cage test, which evaluates repellent efficiency against mosquitoes, the cage sizes should be between 35–40 cm according to the World Health Organization (WHO) [15]. Some studies have reported modifications to cage sizes. Bano [16] used a cage with dimensions of 18×18×18 cm^3 whereas Phasomkusolsil and Soonwera [17] used a cubic cage with a unit length of 30 cm. Anitha et al. [18] chose a 32 cm for their cubic cages. Larger cage sizes were tested by Chang et al., Ffei and Xin, and Vigneshkumar and Vijay Kumar Vediappan [19–21]. The cage test is designed to observe the landing of mosquitoes on treated and untreated fabrics. Logan et al. [22] used 50 female mosquitoes in the cage test in their study. The test chamber was 50×50×50 cm^3. In the test method, mosquito-repellent compounds were applied to the forearm from the elbow to the wrist of volunteer subjects. The control arm was placed in a cage, and landings were recorded for 3 minutes while escapes were observed.

In the cone test, parts of human parts are not used as bait for mosquitoes. Instead, artificial or animal blood is used to attract them. A cone is placed over the treated fabric, and mosquitoes are introduced into this cone and exposed to the treated fabric for 3 minutes. The behaviour of the mosquitoes is then observed for an additional 3 minutes [14].

In the excito chamber test method, there are two chambers connected by a tunnel referred to as the exposure chamber and the escape chamber. The escape behaviour of mosquitoes from one chamber to another is examined under exposure to the repellent compound [23].

To date, various studies have been conducted to prevent many mosquito-borne diseases, using both synthetic and plant-based agents. In N'Guessan et al.'s study, DEET (N, N-diethyl-meta-toluamide), a chemical repellent was microencapsulated. It was observed that the encapsulated DEET was released from the microcapsules slowly and was effective in killing the mosquitoes in the environment for at least 6 hours. Additionally, the study demonstrated the applicability of these microcapsules on clothing and bedding materials [24]. Since the chemical mosquito repellents can be harmful to human skin and health, the use of natural agents has gained importance. Although the natural agents do not have the direct killing effect as synthetic repellents, their repellent efficacy has been demonstrated by several studies in the literature [25, 26].

In the study conducted by Anitha et al., 100% polyester fabrics were treated with microcapsules containing lemon oil, and their mosquito-repellent effect was evaluated. The tests demonstrated the microencapsulated polyester fabric containing lemon oil exhibited a high level of mosquito-repellent effectiveness [18]. In 2017, Showler examined the repellency of various plant-based substances, including *Allium* (garlic), *Azadirachta* (neem), *Chrysanthemum* (pyrethrum), *Cinnamomum* (cinnamon), *Cymbopogon* (lemongrass), *Derris* (rotenone), *Eucalyptus*, *Festuca* (tall fescue), *Melaleuca* (tea tree), *Melinis* (molasses grass), *Mentha* (mint), *Nepeta* (catnip), *Nicotiana* (tobacco), *Pelargonium* (geranium), *Pogostemon* (patchouli), *Ricinus* (castor bean), *Rosa* (rose), *Syzygium* (clove), *Vitex* (monk's pepper), and *Zyloxanthum* (Japanese pepper), against horn flies and horse flies which are blood-feeding ectoparasites of wild and domesticated animals [27]. Although plant oils and bioactive compounds are known for their repellent effects, the use of chemicals remains more effective and permanent in some applications [27].

In another study, the microcapsules containing limonene and permethrin with ethyl cellulose shells were produced and applied to cotton fabrics by padding, and their mosquito-repellent effect was tested. The study reported death rates of *Culex* mosquitoes as 41% for limonene and 54% for permethrin. Additionally, it was found that the treated fabrics maintained their repellent effect even after 20 washing cycles [28]. Saeidi et al. investigated the fly-repellent effect of essential oils extracted from the peels of *Citrus reticulata Blanco* (tangerine), *Citrus limon* L. (lemon), and *Citrus aurantium* L. (bitter orange). They used an olfactometer to evaluate the repellency of these essential oils. The results indicated that all tested Citrus peel essential oils had a strong fly-killing and repellent effect [29]. Prakash et al. applied extracts of *Citrus sinensis* (sweet orange) and *Citrus aurantifolia* (lime) extracts to cotton nets to enhance their mosquito-repellent effect. They conducted the cage test, modified excito chamber test, antibacterial test, and washing resistance tests on the nets. The results showed that the extracts had an antibacterial effect against *Escherichia coli* and *Staphylococcus aureus,* and the nets exhibited a repellent effect after several washings [30].

Flies and insects in the environment are not only disturbing but also can cause allergic reactions upon contact with the skin. Most natural fly and insect repellents are available in the form of essential oils. However, the volatile nature of these oils results in a temporary effect that fades quickly. To achieve a long-term effect, it is necessary to release these compounds at regular or sustained intervals.

Unfortunately, controlled release is challenging with traditional textile finishing methods. Recently, textile researchers have increasingly focused on microencapsulation to extend the effective period and reduce the rapid release of essential oils from fabrics.

This study aimed to produce microcapsules containing *C. aurantium* peel essential oil (CPEO), a natural and aromatic agent, treat three types of fabrics with these microcapsules, and test the insect-repellent effect of treated fabrics using the excito chamber test method. Another objective of the study was to characterize the fabrics treated with these microcapsules. To the best of our knowledge, no other study has conducted repellency tests on fabrics containing CPEO microcapsules using an excito chamber test unit. Additionally, the volatile compounds of CPEO-containing microcapsules were identified for the first time by GC-MS in this study.

MATERIALS

All chemicals used in the study were obtained from Sigma-Aldrich and were used without further purification. The fruits of *Citrus aurantium* L. plant fruits were collected from the Aegean region of Türkiye. The solid phase micro-extraction (SPME) technique was employed to identify the volatile compounds in CPEO-containing microcapsules.

The filter fabric made of 100 % polyester monofilament yarn with 420 mesh, was purchased from a local supplier. The properties of the fabric onto which the microcapsules were transferred are presented in table 1.

During the exhausting process a styrene-acrylic copolymer-type binder, Pigmacolor BSA was used. Distilled water was employed throughout all experiments, and the tests were conducted in triplicate.

The excito chamber test unit consists of two chambers; the exposure chamber and the escape chamber. Both chambers were made of glass and measured 34 cm × 32 cm × 32 cm, as specified in the literature [18]. The upper part of the exposure chamber is covered with a gauze-like fabric to allow the survival of the mosquitoes placed in the chamber as larvae. A hole with a diameter of 9 cm is drilled into the front surface of this chamber to facilitate easy hand access. This hole is kept closed with a dense fabric to prevent the escape of mosquitoes during rearing. Additionally, the two chambers were connected by a tunnel made of acetate sheet, which had a lid that was easy to open and close manually.

METHODS

Citrus aurantium peel essential oil (CPEO) extraction

In this study, the conventional hydrodistillation technique was chosen for the extraction of *C. aurantium* peel essential oil. First, *C. aurantium* fruits collected from the Aegean region were washed, weighed, and manually peeled in the laboratory. The peels were cut into small pieces (approx. 2×2 cm). To determine the maximum oil yield, preliminary trials were conducted at different solid-to-liquid ratios (w/v). Specifically, 100, 120, 150, 200, and 250 g of dried peels were added to 500 ml of distilled water, and the hydrodistillation was carried out using a Clevenger-type apparatus for a minimum of 3 hours, following the method described by Azhdarzadeh and Hojjati [31]. All extracted essential oils were filtered through anhydrous sodium sulfate and stored in amber vials at 4°C for further analysis.

Preparation of microcapsules

The complex coacervation method was employed for the microencapsulation. Gelatin and gum arabic were used as shell materials, while CPEO served as the core material. Initially, a 2% (w/w) gelatin aqueous solution, the carrier polymer solution, was prepared at pH 7 and 40°C. 4 ml of CPEO were dispersed in this aqueous polymer solution. To form an emulsion, 5% Span80 was added to disperse the water-insoluble CPEO droplets in the aqueous gelatin solution. Emulsion formation was achieved using a mechanical stirrer (M Tops Co, MS-3040 model, Seoul, Korea) at a stirring speed of 1500 rpm. Subsequently, a negatively charged gum arabic aqueous polymer solution (20% w/v) at pH 7 and 40°C was added to the emulsion, stabilizing it with the two polymers. While stirring continued, the pH was adjusted to 4 to form a liquid complex coacervate. This adjustment allowed the polymers to form a polymer complex through electrostatic effects. The pH value of the complex coacervation for gelatin-gum arabic polymers was between 4.0 and 4.5, causing the system to separate into two liquid phases: the coacervate (polymer-rich phase) and the equilibrium solution (polymer-poor phase). The system temperature was

Table 1

THE PROPERTIES OF FABRICS USED

Fabric type	Raw material	Mass per unit area (g/m^2)	Structure	Yarn linear density
1	Polyester	110	Woven	8 Tex multifilament
2	Cotton	59	Woven	19.7 Tex
3	Acrylic	195	Weft knitted	66.7 Tex

then reduced to room temperature with an ice bath. A solid shell formed through the gelation of the gelatin in the coacervate at this temperature. To increase the shell's strength, the temperature was lowered further to 5–10°C. The microcapsule shells were hardened by adding a 25% glutaraldehyde solution in water, which cross-linked the gelatin via reactions with amino groups in the gelatin chain. The microcapsules were placed on the filter fabric, washed with dilute isopropyl alcohol (30% v/v) to remove the excess oil, and rinsed three times. The microcapsules were stored as is at +4°C until use. The complex coacervation process parameters, including temperature, pH, stirring speed, and polymer concentration were optimized based on optical microscope analyses.

These parameters resulted in microcapsules with uniform morphology and minimal diameter distribution. Initially, optical microscope images of the microcapsules were captured, and diameters and diameter distributions were measured using ImageJ Measurement and Visualization Software.

The SEM-EDX analysis (LEO 1430 VP Leo Electron Microscopy Ltd., Cambridge, UK) was performed to determine the morphology and elemental composition of the microcapsules.

GC-MS analyses

For GC-MS analyses, the microcapsules were dried to ensure reliable results. The volatile compounds in CPEO were determined using the solid phase microextraction (SPME) technique [33] with a GC-MS (GC 6890, MS 6890N, Agilent Technologies, Wilmington, DE, USA). The HP-5MS column, which is nonpolar (30 m × 0.250 mm id × 0.25 µm film thickness) (J&W Scientific, Folsom, CA, USA) was used for the separation of volatile compounds. One gram of CPEO was weighed into a 40 ml SPME vial (Supelco, Bellefonte, USA) and kept in a 40°C water bath (GFL, Model 1103, Burgwedel, Germany) for 20 minutes. Subsequently, the SPME fibre (2 cm to 50/30 lm DVB/Carboxen/PDMS, Supelco, Bellefonte) was inserted into the headspace of the vial and kept in 40°C water bath for an additional 20 minutes before being immediately injected into the device. The flow rate of helium selected as the carrier gas was set at 1.2 ml/min. The temperature program of the GC oven was as follows: 40°C for 5 minutes, then it raised from 40 to 230°C at a rate of 10°C/min and held for 20 min at this oven temperature. The operating conditions of the detector of MS were 280°C capillary direct interface temperature, 70 eV ionization energy, 35–350 amu mass, and 4.45 scans/s scan rate. Identification of volatiles in CPEO was based on mass spectra comparison of unknown compounds with those in the National Institute of Standards and Technology (NIST) and the Wiley Mass Spectral Data Registry, databases [34]. The amounts of volatile compounds are expressed as percentage (%) through peak normalization. The tests were repeated twice. All essential oils were injected twice.

Collection of mosquito larvae/rearing

In this study, *Culex* mosquito larvae were collected along with water from stagnant areas. The larvae were transferred to the laboratory and placed in petri dishes containing the collected water, which was then introduced into the exposure chamber. The gauze-like fabric used as a cover facilitated the air transfer necessary for larvae to undergo their transformation into pupae, a process that took approximately one week. The pupal stage lasted for 3–4 days. Eventually, the pupae matured into adult mosquitoes (teneral stage), which began to fly within the chamber. The adult mosquitoes were fed with a sugar/water solution until the tests were conducted. The stages of rearing are illustrated in figure 1.

Treatment, morphological and structural characterizations of fabrics

Microcapsules produced with optimum process parameters were applied to the fabrics specified in table 1, using the exhaustion method. Fabric samples measuring 5×5 cm^2 were fully immersed in a treatment bath containing Pigmacolor BSA binder (5% v/v) and microcapsules (7.5% w/v). The liquor ratios used were 9:1, 17:1, and 5:1, corresponding to microcapsule concentrations of 1.32, 2.52, and 5.43 g/L for cotton, polyester, and acrylic fabrics, respectively. Each mixture was stirred for 15 minutes at room temperature. Subsequently, the fabrics were removed from the bath, the excess solution was removed, and the fabrics dried at room temperature.

a *b* *c*

Fig. 1. Mosquitoes: *a* – larval; *b* – pupal; *c* – adult

Following the treatment, the fabrics underwent morphological and elemental analyses using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) (LEO 1430 VP (Leo Electron Microscopy Ltd., Cambridge, UK)), and attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectrophotometry (Spectrum Two, Perkin Elmer, USA). SEM-EDX analyses were conducted at an accelerating voltage of 20 kV, with the samples being gold-sputtered before analysis. Both microcapsules and fabrics (untreated and treated) were analysed individually. The ATR-FTIR spectrophotometry, which is suitable for thin surfaces and soft polymers, was employed to record spectra in the range of 4000–400 cm^{-1}, presented as wavenumber versus transmittance (%).

Repellency tests

In this study, the repellent effects of fabrics treated with CPEO microcapsules against mosquitoes were evaluated using the excito chamber test unit, as shown in figure 2.

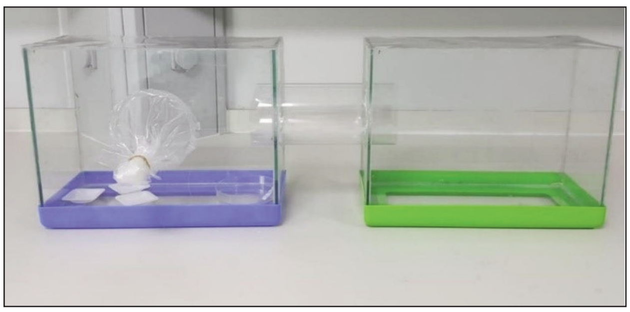


Fig. 2. Excito chamber test unit: exposure chamber (left) and escape chamber (right)

For the excito chamber test of adult *Culex* mosquitoes, initially, 10 mosquitoes were placed in the exposure chamber. Next, 5×5 cm^2 fabric samples were individually introduced into the exposure chamber, while the partition between the chambers was kept closed. Each fabric was placed separately, and light pressure was manually applied (tabbing) to simulate body contact during movement, which facilitated the release of the oil from the microcapsules into the air. The exposure duration was set between 10–12 minutes based on the recommended time in the literature [14] and the retention times of the most abundant volatile compounds in CPEO. After the exposure period, the partition between the chambers was opened manually. The escape behaviours of the mosquitoes to the escape chamber were analysed using the equation provided in reference [32]:

$$\textit{Efficiency of mosquito repellency} \ (\%) = \frac{\textit{Number of the mosquitos escaped} + \textit{Number of the mosquitos dead}}{\textit{Number of the mosquitos exposed}} \times 100 \quad (1)$$

The tests were repeated twice. Additionally, a control test was performed with the lid open, where no exposure sample was placed in the exposure chamber.

RESULTS AND DISCUSSION

CPEO hydrodistillation

The conventional hydrodistillation technique was employed for the extraction of *C. aurantium* peel essential oil. The optimum solid/liquid ratio for achieving the highest essential oil yield (%) was determined to be 200 g of dried peels in 500 ml of distilled water, among the tested ratios of 100, 120, 150, 200, and 250 g. The highest yield observed in this study was 1.7 ml/kg which is consistent with the range of 1.2–4.6 ml/kg reported by Bourgou et al. [35] for bitter orange peel essential oils.

Microencapsulation and GC-MS results

The optical microscope and SEM images of the microcapsules produced using the complex coacervation method are shown in figure 3. The microcapsules had spherical structures with an average diameter of 68.5±34.2 μm based on measurements of 50 microcapsules using ImageJ software.

After the microencapsulation of CPEO, the microcapsules were characterized by GC-MS to identify the volatile compounds. The compound names, retention times, and percentages calculated from peak areas normalization are provided in table 2. A total of 44 compounds were identified and quantified. The most abundant volatile and aromatic compound in the encapsulated CPEO was D-limonene, which constituted 39.14% of the total. This finding is consistent with reports from various researchers indicating that D-limonene is responsible for the characteristic citrus aroma in all citrus varieties, often comprising up to 90% of the volatile compounds in bitter orange [39, 40]. Other major volatile compounds identified were p-xylene, linalool, and mentha-1,4,8-triene, with percentages of 5.71%, 3.78%, and 3.74%, respectively. While the volatile profile of CPEO aligns with previous literature, it is important to note that variations in volatile compounds can arise due to climatic conditions, geographical origins, and different oil extraction techniques, even for the same plant species.

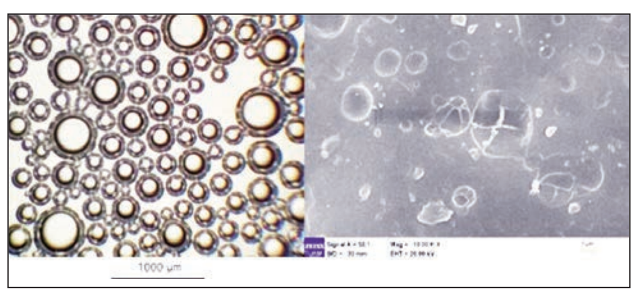


Fig. 3. Optical microscope (X40) and SEM images (X10 K) of microcapsules

D-limonene, the predominant volatile compound in the microcapsules, is known for its insect-repellent properties [41]. This finding supports the observed repellent effects of fabrics treated with D-limonene-rich microcapsules.

Table 2

VOLATILE COMPOUNDS OF CPEO-C MICROCAPSULES			
Compound	**Retention time (min)**	**Area (%)**	
		Mean	**Std. Dev.**
Methyl-d3 1-Dideuterio-2 propenyl Ether	2.963	0.12	0.08
Pyridine	4.007	2.07	1.33
Hexanal	5.286	1.99	1.11
p-Xylene	7.441	5.71	2.86
α-Pinene	7.441	0.45	0.07
Benzaldehyde	8.889	1.17	0.53
Benzoic acid	9.544	2.56	2.25
β- Pinene	9.655	0.88	0.18
m-Cymene	10.173	0.46	0.05
D-Limonene	10.804	39.14	16.50
Hexadecane, 2,6,10,14-tetramethyl-	11.368	0.31	0.17
Linalol oxide	11.732	1.86	0.17
cis-Linalol oxide	12.01	0.94	0.19
Linalool	12.194	3.78	0.05
3-Ethyl-3-methylheptane Heptane, 3-ethyl-3-methyl-	12.297	1.18	0.07
2-Cyclohexen-1-ol, 1-methyl-4-(1-methylethenyl)-, trans-	12.793	0.88	0.06
L-Camphor	12.971	0.67	0.41
Borneol (1,7,7-trimethylbicyclo[2.2.1]heptan-2-ol)	13.316	0.77	0.02
Terpinen 4-ol	13.485	0.41	0.08
m-Thymol	13.59	0.26	0.03
α-Terpineol	13.691	2.75	1.10
P-Menth-6-en-2,3-diol	13.847	1.69	0.46
cis-Carveol	14.112	1.58	0.52
Nerol	14.227	0.66	0.26
p-Cumic aldehyde	14.44	0.31	0.17
Carvone	14.503	1.73	0.02
trans-Geraniol	14.604	1.11	0.96
Decanedioic acid, didecyl ester	14.956	0.57	0.57
cis-Anethole	15.114	0.53	0.17
p-Thymol	15.283	1.05	0.82
4-carene	15.841	0.93	0.64
3-Methylene-1,5,5 trimethylcyclohexene	15.977	0.61	0.13
α-Cubebene	16.091	0.36	0.28
2,6-Octadien-1-ol, 3,7-dimethyl-, propanoate	16.381	0.22	0.16
3,7-Dimethyl-6-nonen-1-ol	16.716	0.35	0.12
2-ally furan	16.897	0.42	0.01
Caryophyllene	16.996	0.20	0.07
Mentha-1,4,8-triene	17.099	3.74	1.72
α-Caryophyllene	17.437	0.14	0.01
Phenol, 2,5-bis(1,1-dimethylethyl)	18.028	0.29	0.06
1,3-Benzodioxole, 4-methoxy-6-(2-propenyl)	18.204	0.21	0.07
Caryophyllene oxide	19.047	0.53	0.04

SEM-EDX analyses

The SEM-EDX analysis results were examined regarding the detected element average normalized weight percentages. Results are given in table 3. Initially, the microcapsules were analysed, revealing that oxygen was the most prevalent element at approximately 48%, followed by carbon at around 30%. Nitrogen was the least detected element, constituting 21.8% of the microcapsules.

For pure cotton fabrics, approximately 49% consisted of carbon, while about 43% was oxygen, and only 8% was nitrogen. In contrast, cotton fabrics treated with

Table 3

SEM-EDX RESULTS OF MICROCAPSULES AND FABRIC SAMPLES							
Detected element (normalized weight %)	**Microcapsules**	**Fabric samples**					
		Pure cotton	**Treated cotton**	**Pure polyester**	**Treated polyester**	**Pure acrylic**	**Treated acrylic**
Oxygen	47.89	43.27	51.75	51.73	47.13	18.95	16.14
Carbon	30.31	48.71	36.03	48.27	42.55	50.09	53.07
Nitrogen	21.80	8.02	12.22	0.00	10.32	30.96	30.79
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

microcapsules showed increased percentages of oxygen (~52%) and nitrogen (~12%), compared to the untreated cotton. These increases can be attributed to the presence of microcapsules on the fabrics.

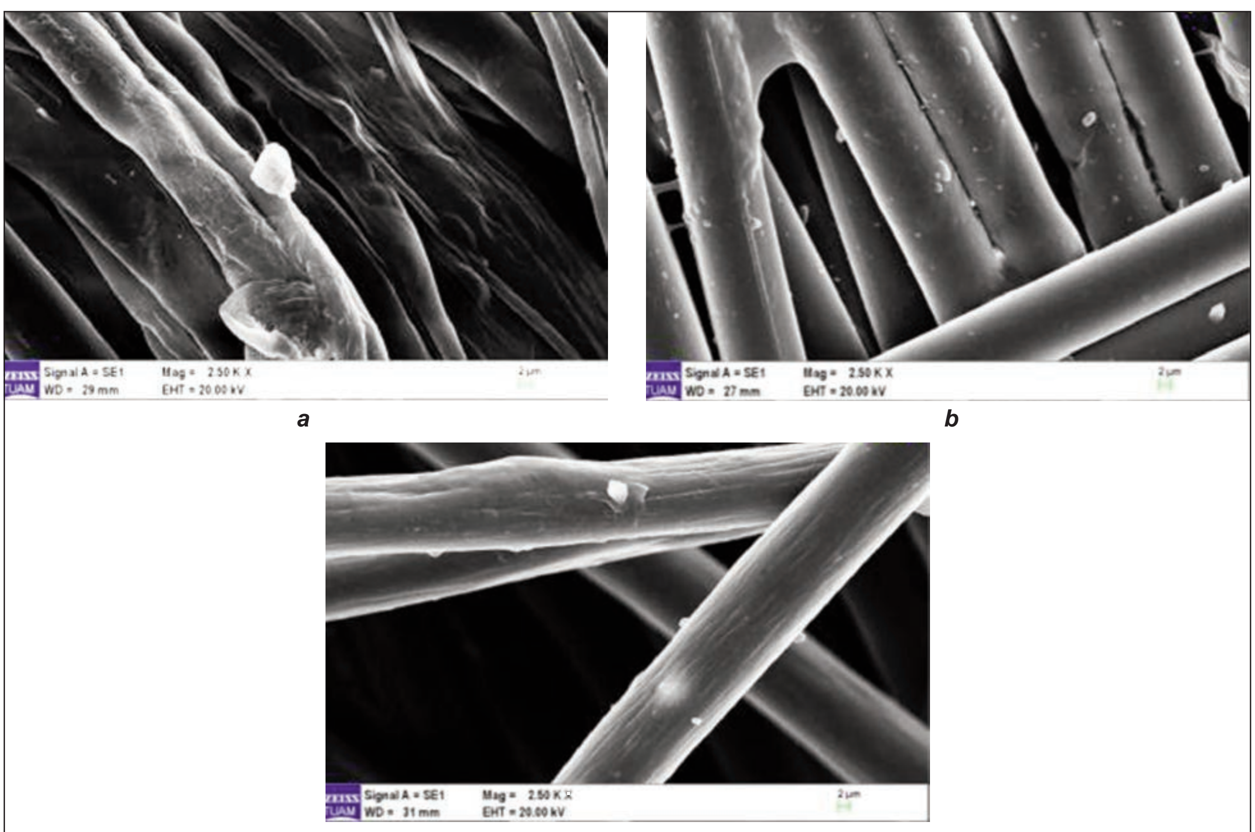
SEM-EDX analyses are less effective for detecting elements with low atomic numbers, such as hydrogen. For pure polyester fabrics, the dominant elements were oxygen (~52%) and carbon (~48%). The presence of nitrogen (~10%) in polyester fabrics treated with microcapsules indicates the successful transfer of the microcapsules to the fabric.

In acrylic fabrics, only slight changes were observed. There was approximately a 3% decrease in oxygen and a 3% increase in carbon in the treated acrylic fabrics compared to the pure ones.

Figure 4 displays the SEM images of fabrics treated with microcapsules, illustrating the presence of microcapsules on the fabrics.

FTIR results

Figure 5 presents the FTIR spectrum of the dry microcapsules. The peaks seen in the 1500–400 cm^{-1} fingerprint region correspond to those reported in the literature on pure gelatin and pure gum arabic [42, 43], which are used as shell material. Broadband between 3600–3100 cm^{-1} was formed by -OH stretching of alcohols in the structure. The peak observed at 1722 cm^{-1} is attributed to the C=O stretching [44, 45]. The peak at 1631 cm^{-1} belongs to NH stretching and the presence of amide I [42, 43]. Bending vibrations in NH and CN groups of gelatin (amide II and amide III) cause the peaks at 1537 and 1247 cm^{-1}, respectively [42]. CH bending vibrations in gum arabic cause a peak at 1453 cm^{-1} [43]. Symmetric and asymmetric bending vibrations of both gum arabic and gelatin polymers create a peak at 1380 cm^{-1} [42–44].



a *b* *c*

Fig. 4. The SEM images of: *a* – cotton; *b* – polyester; *c* – acrylic fabrics treated with microcapsules (X2.50 K)

As seen from the GC-MS characterization, the main component of the CPEO was D-limonene, whose chemical structure is given in figure 5. The methyl groups of D-limonene can be seen in the image. The peaks observed between 2941–2854 cm^{-1} and 1453–1339 cm^{-1} are attributed to methylene bond vibrations (C-H) [45]. The intense peak at 2924 cm^{-1} is particularly indicative of essential oils [45]. Moreover, peaks at 1722, 1537, and 1408 cm^{-1} are created by the C=C stretching of the aromatic ring [46]. These findings confirm the successful encapsulation of CPEO.

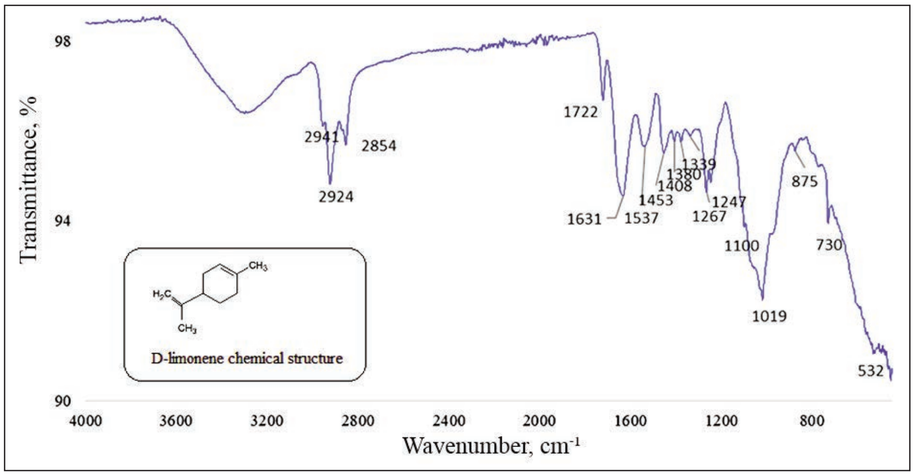


Fig. 5. FTIR spectrum of microcapsules and chemical structure of D-limonene

The FTIR spectra of pure and treated 100% cotton fabrics are given in figure 6. The FTIR spectrum of the pure cotton fabric aligns with literature values in the 1500–450 cm^{-1} wavelength region [47, 48]. A low-intensity peak was observed at 1734 cm^{-1} in the spectrum of cotton fabric treated with microcapsules. As oxidation of carbonyl groups creates peaks at around the 1650–1800 cm^{-1} range, the peak at 1734 cm^{-1} may have originated from the vibration of carbonyl groups of gelatin polymer or the C=C stretching of the D-limonene aromatic ring [42, 45]. Both FTIR spectrophotometer and SEM-EDX analyses prove the presence of microcapsules on the cotton fabric, even in small amounts.

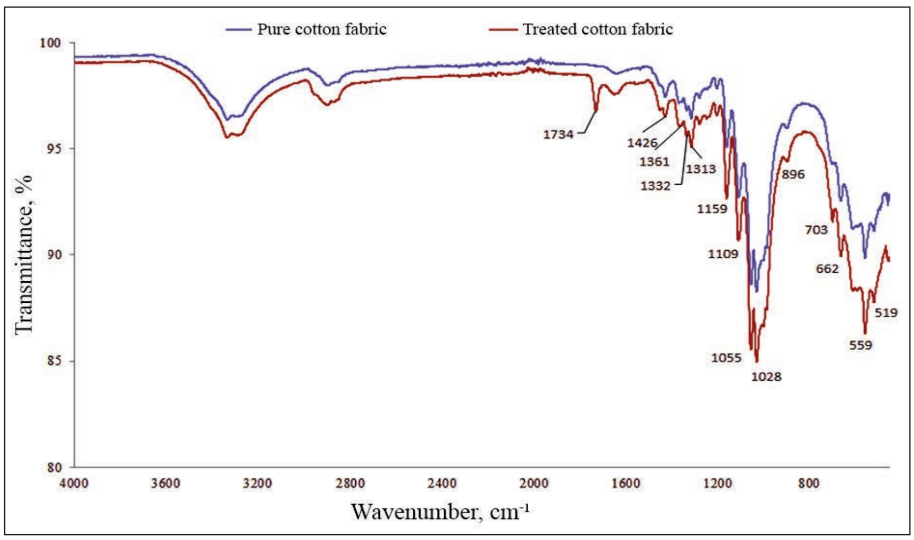


Fig. 6. FTIR spectra of pure and treated cotton fabric

Figure 7 shows the FTIR spectra of pure and microcapsule transferred 100% polyester fabrics. As given in reference [49], characteristic peaks of pure polyester fabric are observed at 1408 (aromatic ring), 1340 (carboxylic ester), 1239 (carboxylic ester), 1092 (C-O-C asymmetric stretch), 1017 (O = C-O-C or secondary alcohol groups), 970 (C = C stress), 871 (C-O-C C symmetric stress), 869, 831, 723 and 505 cm^{-1} [50, 51]. There was a strong peak at 1713 cm^{-1} and it depended on the vibration of carbonyl groups. It is known that even slight changes in the intensities of the peaks in the functional group region in the wavelength range of 4000–1500 cm^{-1} indicate the differences created on the material when the amounts and thicknesses of the tested materials are kept constant [52]. In this

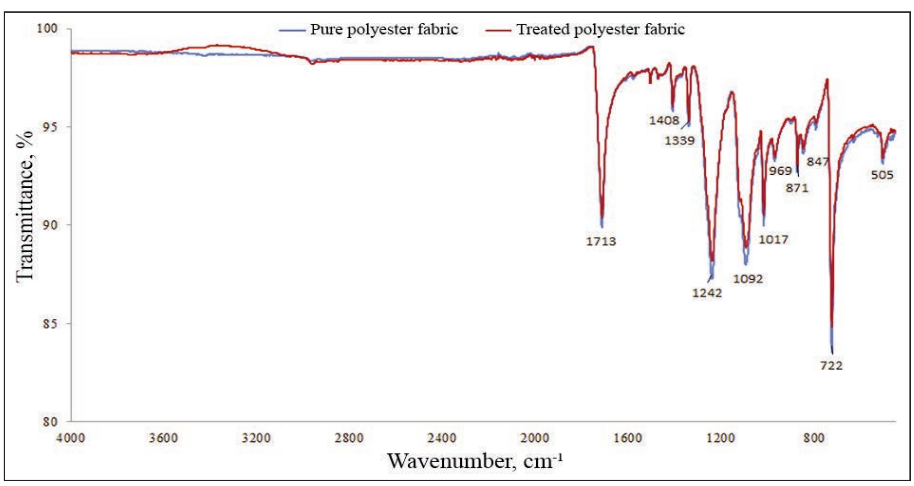


Fig. 7. FTIR spectra of pure and treated polyester fabric

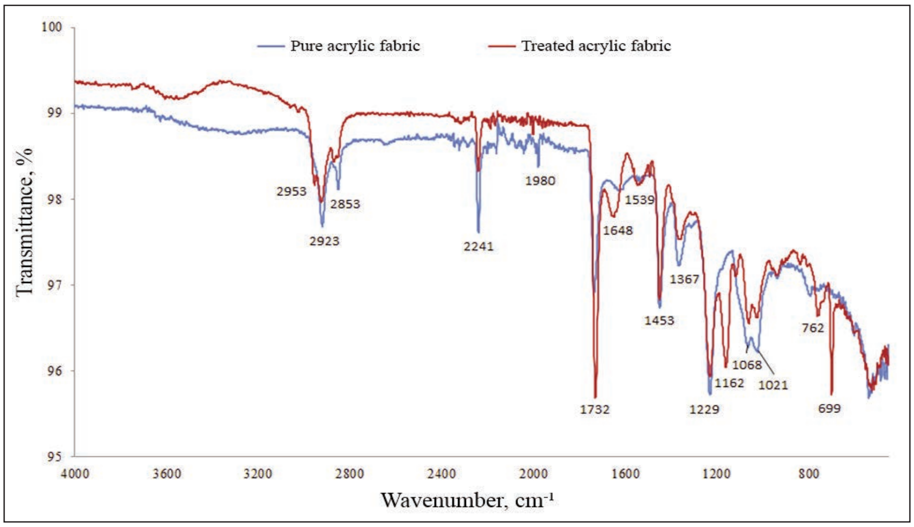


Fig. 8. FTIR spectra of pure and treated acrylic fabric

context, the decrease observed in the strength of the peak at 1713 cm^{-1} in microcapsule transferred fabrics when compared to pure fabric may be elucidated by the interactions that occurred between carbonyl (C = O) groups and microcapsules.

The FTIR spectra of pure and microcapsule transferred fabric 100% acrylic fabrics are given in figure 8. There are two characteristic peaks of acrylic at wavelengths of 1453 cm^{-1} (CH bending) and 1299 cm^{-1} (C-bending). In addition, the strong peak observed at 2241 cm^{-1} is explained by the vibration created by the nitrile groups (-CN) [53]. The presence of microcapsules and the vibration of carbonyl groups in gelatin that form the shell material of microcapsules are responsible for the intensity increase at 1732 cm^{-1}. In addition, the peak at 1539 cm^{-1}, which was not observed in pure fabric, appeared in microcapsule transferred acrylic fabric due to the amide (CONH-) groups. A decrease in the intensity of the peak at 2241 cm^{-1} created due to nitrile groups was observed. The peak at 2953 cm^{-1} created due to the methyl bond vibrations of the microcapsules (namely D-limonene) [45], was observed in the treated acrylic fabric. However, it was not seen in the pure fabric.

Repellency test results

The insect repellent effects of fabrics treated with CPEO microcapsules were evaluated using the excito chamber test unit in this study. Initially, a control test was conducted. When no fabric sample was placed in the exposure chamber and the lid between the chambers was opened, adult *Culex* mosquitoes exhibited flying behaviour only within the exposure chamber and did not move to the escape chamber.

GC-MS analysis identified the three most abundant components of CPEO as D-limonene, p-xylene, and linalool, with retention times of 10.804, 7.44, and 12.194 minutes, respectively. The insect-repellent effects of these components have been reported in the literature [41, 54, 55]. Taking into account the retention times of these components, the waiting period in the test chamber was set to 10–12 minutes. After the waiting period, the number of mosquitoes that moved to the escape chamber was counted. The average mosquito repellency effects for the cotton, polyester, and acrylic fabrics were found to be 80±0%, 80±0%, and 70±0%, respectively. During repellency tests, none of the mosquitoes died but escaped. The repellency effects observed were notably high, aligning with the findings reported in the literature, where repellency efficiencies of plant extracts such as neem, mint, and tulsi leaves ranged from 40% to 90% [36–38].

CONCLUSIONS

In this study, the *C. aurantium* peel essential oil was extracted with a Clevenger apparatus with a 1.7 ml/kg oil yield. The aromatic essential oil was microencapsulated in gelatin and gum arabic polymers via the complex coacervation method at 40 °C initial temperature and with a 1500 rpm stirring speed. The optical microscope images denoted the spherical and uniform microcapsule morphology and reasonable diameter distributions were calculated. The average diameter of the microcapsules was measured as 68.5±34.2 µm. According to the GC-MS analysis, the most abundant aromatic compound of the microcapsules was determined as D-limonene with a percentage of approximately 40% of the total. The SEM-EDX and the FTIR analyses confirmed the successful transfer of microcapsules onto cotton, polyester, and acrylic fabrics. Repellency tests demonstrated that these treated fabrics exhibited 70–80% repellent effects against *Culex* mosquitoes. Future studies may focus on exploring alternative methods for transferring microcapsules onto fabrics, such as impregnation, and developing methods to effectively release the microcapsules through controlled pressure.

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Effect of atmospheric plasma process on the water-repellent finishing performance and permanence

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ABSTRACT – REZUMAT

Effect of atmospheric plasma process on the water-repellent finishing performance and permanence

This study aims to investigate the effect of atmospheric plasma treatment on the performance and permanence of water repellency finish. Air and nitrogen plasma treatments were applied to pre-treated polyester-based fabrics prepared for dyeing. Fluorocarbon solutions, with and without cross-linkers, were applied to the fabrics using the pad-dry-cure method. Contact angle measurements, FT-IR analysis, SEM analysis, and whiteness measurements were conducted. The samples underwent repeated washing 10 times, and measurements were retaken. The contact angle values of fabrics with plasma pre-treatment and water-repellent properties, using only fluorocarbon, were better than those of fabrics with water-repellent properties using cross-linker and fluorocarbon. The contact angle values obtained 20 seconds after the drop was placed on the fabric were very close for both samples. Similar permanence properties were obtained after repeated washings when atmospheric plasma pre-treatment was used instead of the cross-linking chemical used to ensure the permanence of the water-repellent finishing.

Keywords: *atmospheric pressure plasma, water-repellent, finishing, contact angle, permanence*

Influența procesului cu plasmă atmosferică asupra performanței și durabilității finisajului hidrofug

Scopul acestui studiu este de a investiga influența tratamentului cu plasmă atmosferică asupra performanței și durabilității finisajului hidrofug. Tratamentele cu plasmă atmosferică și cu azot au fost aplicate materialelor textile pe bază de poliester pretratate pregătite pentru vopsire. Soluțiile de fluorocarburi, cu și fără agenți de reticulare, au fost aplicate pe materialele textile folosind metoda de fulardare-uscare-condensare. Au fost efectuate măsurători ale unghiului de contact, analize FT-IR, analize SEM și măsurători ale gradului de alb. Probele au fost supuse spălării repetate de 10 ori, iar măsurătorile au fost efectuate din nou. Valorile unghiului de contact ale materialelor textile cu pretratare cu plasmă și proprietăți hidrofobe, folosind doar fluorocarbură, s-au dovedit a fi mai bune decât cele ale materialelor textile cu proprietăți hidrofobe folosind agent de reticulare și fluorocarbură. Valorile unghiului de contact obținute la 20 de secunde după ce picătura a fost plasată pe materialul textil au fost foarte apropiate pentru ambele probe. Proprietăți similare de durabilitate au fost obținute după spălări repetate atunci când s-a utilizat un pretratament cu plasmă atmosferică în locul agentului de reticulare chimic utilizat pentru a asigura durabilitatea finisajului hidrofug.

Cuvinte-cheie*: plasmă la presiune atmosferică, hidrofug, finisare, unghi de contact, durabilitate*

INTRODUCTION

Textiles are subjected to chemical (wet) processes in order to provide the desired functional properties [1]. The plasma process stands out as one of the most promising technologies, offering an alternative to various wet processes in textiles while reducing energy, water, and chemical usage [2].

Expectations for fabrics are increasing day by day, and fabrics are endowed with different usage properties according to these expectations. Water repellency is one such expectation. The chemicals utilized in the water-repellency process form a film layer on the product surface capable of retaining water for a certain period, thus enabling water repellency [3]. Fluorocarbons are extensively employed in water-repellent finishing processes owing to their oil and dirt-repellent properties [4]. There are various studies in the literature regarding the addition of water repellency to fabrics. Balcı et al. compared the foam application method, which imparts water repellency to denim fabric using different chemicals, with impregnation and coating methods [5]. Akıncı et al. investigated the effects of weft density and filament fineness on the degree of water repellency in water-repellent fabrics. They observed that the filament fineness and density values did not consistently result in an increase or decrease in the water contact angles of the fabrics [6].

In order to impart water-repellent properties to fabrics, various methods are employed including the sol-gel method [7–11], nanocoating [12], chemical modification [13–16], etc. In recent years, research has been focused on surface activation of textiles using plasma and plasma graft polymerization [1, 17].

Contact angle measurement, Bundesman sprinkler test and spray test methods are used to determine the water repellency of fabrics. Contact angle measurements are the primary method used to determine the wettability of various materials, including polymer materials. The main criterion for defining a surface as hydrophobic or hydrophilic is the size of the contact angle formed by a water droplet on the surface. In other words, the tendency of the liquid to spread on the solid surface indicates the water-repellent property of the solid. If the angle measures less than 90°, it indicates a hydrophilic surface; if it exceeds 90°, it suggests a hydrophobic surface, and if it surpasses 150°, it characterizes a superhydrophobic surface. When the surface is hydrophilic, the water droplet tends to spread across the solid surface, whereas, in the case of a hydrophobic surface, the water droplet is observed to remain stationary on the surface in a spherical shape [18].

In their study, Rajar et al. achieved water repellency on polyamide 6 (PA 6) fabrics by employing sol-gel finishing after oxygen plasma treatment. The findings revealed that both plasma treatment and finishing application influenced the morphological and chemical properties of the fibres. The researchers noted that the plasma treatment enhanced the adhesion of the water-repellent finish to the fabric, leading to a significant increase in washing durability on PA 6 fabric [8]. Dasdemir and Ibili 2017 developed superhydrophobic nonwoven surfaces via electrospraying. After the successful application of fluorochemical solutions to nonwoven fabrics by filling and electrospraying, they made contact angle measurements and obtained superhydrophobic surfaces [19]. Park et al. conducted a study where they generated a super-repellent fabric employing the plasma-enhanced chemical vapour deposition (PECVD) method, incorporating oxygen plasma etching and hexamethyldisiloxane (HMDSO). They successfully attained contact angles exceeding 160 degrees [20]. In their research, Furlan et al. administered a water repellent and flame-retardant finishing solution, formulated with fluoroalkyl-functional siloxane and organophosphonate, onto polyester samples after oxygen plasma treatment. They observed that oxygen plasma notably enhanced the wettability of polyester fibres, leading to increased absorption of the finishing solution. As a result, the treated samples exhibited superhydrophobic and flame-retardant properties [21]. Liu et al. utilized a solution composed of perfluoroalkyl acrylate, epoxide-containing silane, and silica nanoparticles to achieve amphiphobic fabric, followed by argon-plasma treatment. They introduced the argon-plasma-enriched coating method as a convenient approach for producing long-lasting superophobic fabrics [22]. In their study, Kale and Palaskar employed a blend of argon and hexamethyldisiloxane to impart water-repellent properties to 100% cotton fabrics using the plasma polymerization technique. They reported that the treated fabrics exhibited notable resistance to wetting with water [17]. Zanini et al. investigated the hydrophobic and oleophobic modification of pure cashmere and wool/nylon fabrics through plasma treatment at atmospheric pressure followed by impregnation with fluorocarbon resin. They determined that the fabric surface treated with plasma before the finishing process exhibited a greater amount of fluorocarbon resin, resulting in a more uniform coating of the textile fibres [23]. In their study, Leroux et al. achieved hydrophobic fabric by directly injecting a fluoropolymer into the plasma dielectric barrier discharge. They concluded that air plasma treatment significantly improved the adhesion of the fluoropolymer to the polyester fabric [24].

Based on this information, the current study aimed to examine the impact of atmospheric pressure plasma treatment on the water-repellency performance and durability of fabrics. For this purpose, atmospheric plasma pretreatment was applied to polyester-based fabrics. The water-repellent finishing solution was applied to the fabrics using the pad-dry-cure pad-dry-cure method. Water repellent properties of the fabrics were evaluated by contact angle measurements, FT-IR and SEM analysis. Following 10 repeated wash cycles, contact angle measurements, FT-IR, and SEM analysis were conducted again to assess the permanence of the finish.

MATERIALS AND METHODS

Materials

The fabric utilized in this study is 100% polyester-based with a weight of 160 g/m^2. It has a weft density of 25 threads/cm and a warp density of 56 threads/cm. The weft linear density is 300 denier, while the warp linear density is 100 denier.

Methods

Atmospheric pressure plasma pretreatment was first applied to polyester-based fabrics using air and nitrogen gases. The water-repellent finishing process involved the application of liquors containing fluorocarbon + crosslinker, as well as liquors containing only fluorocarbon. After finishing the process, contact angle measurements, FT-IR analysis, SEM analysis and Berger whiteness measurements of the samples were performed. To investigate the permanence of the finish, the fabrics were subjected to a repeated home washing process 10 times and contact angle measurements, FT-IR analysis, SEM analysis and Berger whiteness measurements were made again (figure 1).

Atmospheric pressure plasma

Atmospheric pressure plasma pretreatment was applied to polyester-based fabrics, using two types of gases: air and nitrogen. The parameters of the atmospheric pressure plasma process are outlined in table 1.

Water repellent finishing

Water-repellent finishing was applied to polyester-based fabrics using a laboratory-type vertical padding machine, following the pad-dry-cure method. The uptake ratio was set at 50%. The water-repellent finishing recipe used for the samples is detailed in the provided table 2. The pH of the solution prepared as per the formulation was adjusted to 5. Following impregnation, the fabrics were dried at 120°C for

3 minutes. Subsequently, they were cured at 160°C for 2 minutes.

Contact angle measurements were performed before and after repeated washings according to the dynamic drop sessile method using an optical goniometer (Attension, Theta Lite 100, Sweden). FT-IR analysis of the fabrics was made using Perkin Elmer UATR Two before and after repeated washing, and whiteness measurements were made using the Datacolor device.

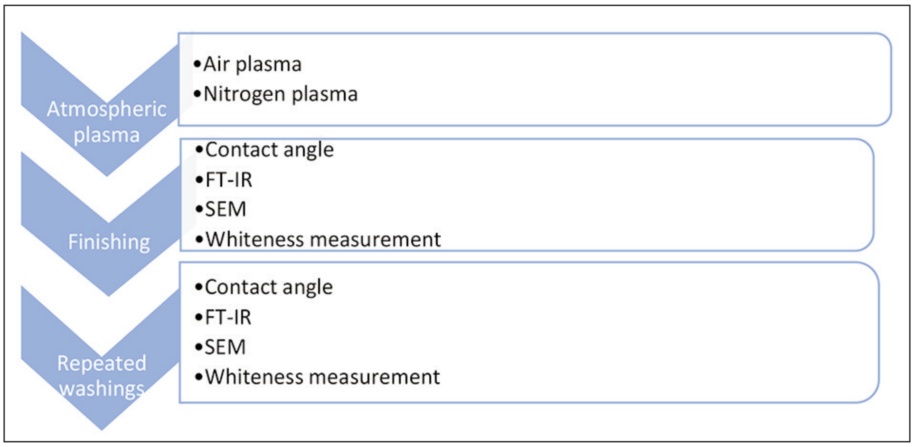


Fig. 1. Flow Chart

Table 1

PARAMETERS OF THE ATMOSPHERIC PRESSURE PLASMA							
Jet	**Voltage (V)**	**Frequency (kHz)**	**Power (Watt)**	**Distance (mm)**	**Pressure (bar)**	**Ionisation gas**	**Speed (m/min)**
RD1010	280	21	600	10	3	Air	5
PFW70	280	21	600	3	3	Nitrogen	5

Table 2

WATER REPELLENCY TEST PLAN					
Sample number	**Sample code**	**The raw material of the fabric**	**Plasma gas**	**Fluorocarbon (Mithril SFC) (g/l)**	**Cross-linking (Mithril EXT) (g/l)**
1	PES-R-F+C	100% polyester	Reference	50	10
2	PES-A-F+C	100% polyester	Air	50	10
3	PES-N-F+C	100% polyester	Nitrogen	50	10
4	PES-R-F	100% polyester	Reference	50	-
5	PES-A-F	100% polyester	Air	50	-
6	PES-N-F	100% polyester	Nitrogen	50	-

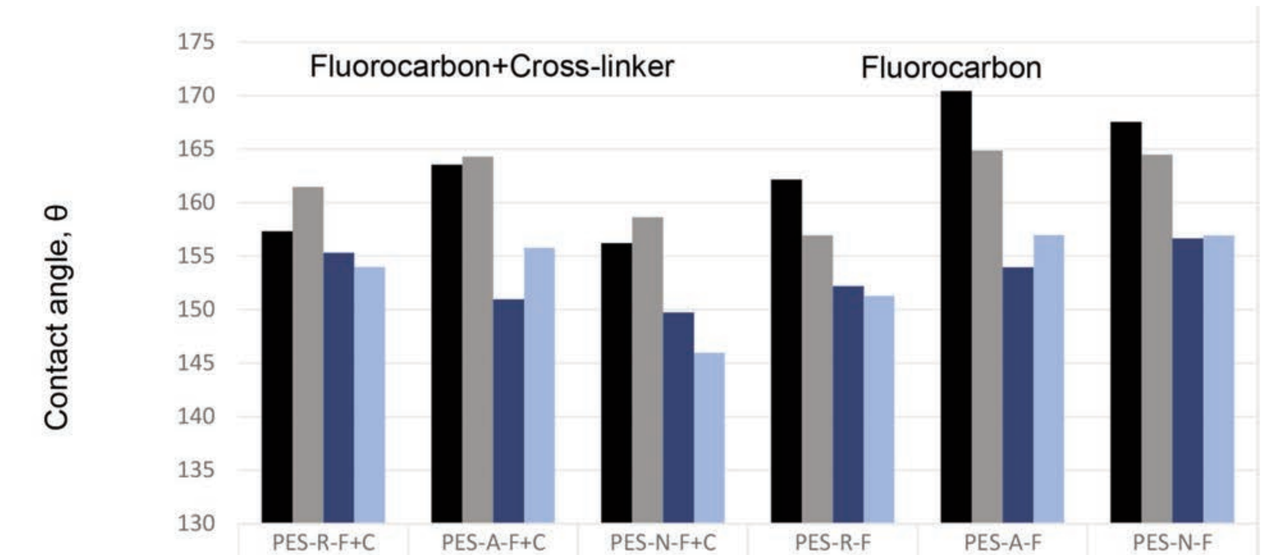
Repeated washings

Fabric samples were subjected to a household washing procedure in a washing machine at 30°C for 30 minutes, with a total of 10 repetitions. The recommended amount of detergent, adjusted according to the weight of the fabric, was used for each wash cycle. Following the repeated washings, contact angle measurements, FT-IR analysis, SEM analysis, and whiteness measurements were conducted once more.

RESULTS AND DISCUSSION

Contact angle

Initially, contact angle measurements were conducted immediately after the droplet was applied to the finished fabric (Finished-0 sec) and then after 20 seconds. Subsequently, contact angle values were measured when the droplet was first applied to the fabric after undergoing 10 wash cycles, and again after 20 seconds. All the results obtained are presented in the figure 2. When the test results were examined, as expected, the contact angle values of the fabrics decreased after repeated washings. When examining the contact angle values measured immediately after the droplet was first applied to the fabric (0 sec), in the case of utilizing fluorocarbon and crosslinker in the water-repellency solution, it was observed that the contact angle of the sample treated with nitrogen plasma was very close to that of the reference sample. However, the contact angle value of the sample treated with air plasma increased by approximately 4% compared to the reference sample. Upon examining the values measured at the end of 20 seconds, it was found that the value of the sample treated with nitrogen plasma was lower than that of the reference sample. Conversely, the value of the sample treated with air plasma increased by 1.7% compared to the reference sample. It can be concluded that air plasma application improves the contact angle values of



	PES-R-F+C	PES-A-F+C	PES-N-F+C	PES-R-F	PES-A-F	PES-N-F
Finished 0 sec	157.33	163.56	156.25	162.19	170.46	167.54
Finished 20 sec	161.48	164.32	158.65	156.95	164.89	164.52
10 Washed-0 sec	155.33	150.99	149.77	152.21	153.96	156.69
10 washed-20 sec	153.99	155.79	145.99	151.31	156.98	156.95

Fig. 2. Contact angles

fabrics after finishing. After repeated washings, the contact angle values of the air and nitrogen plasma applied samples were lower than the reference sample. The plasma treatment appears to have had an adverse impact on the contact angle values in the samples subjected to repeated washing (10 times) following the water-repellency finishing process.

In the finishing process using only fluorocarbon after the plasma treatment, when the drop was first dropped on the fabric, the contact angle value of the air plasma applied sample improved by 5% compared to the reference sample, and the nitrogen plasma applied sample improved by 3.2%. As a result, plasma pretreatment improved the initial contact angle values of the fabrics. 20 seconds after the drop was dropped on the fabric, the contact angle values of the samples showed similar behaviour and improved compared to the reference sample. When the contact angle values measured after 10 repeated washings were examined, the contact angle values of the plasma-treated samples were higher than the reference sample.

Contact angle values were found to be better in fabrics with plasma pre-treatment and water-repellent properties with only fluorocarbon than in fabrics with water-repellent properties using crosslinkers. The contact angle values obtained 20 seconds after the droplet was applied to the fabric were nearly identical to those of the reference sample when fluorocarbon and cross-linker were applied. Plasma treatment also provides the permanence value after repeated washings provided by the cross-linking chemical. As a result, plasma pretreatment of polyester fabrics eliminates the necessity of employing cross-linkers and yields superior water-repellency values.

The impact of plasma type and washing method on the contact angle values of fabrics was analyzed using analysis of variance, and the findings are outlined in table 3.

In the test results of between-subject effects, it can be concluded that plasma type and washing type factors have an effect on the general linear model in the case of using fluorocarbon and cross-linker in polyester fabrics, as well as in the case of using only fluorocarbon.

Table 3

TESTS OF BETWEEN-SUBJECTS EFFECTS						
	Dependent variable: contact_angle					
Substance	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
F+C	Plasma type	317.664	2	158.832	5.193	0.049
	Wash type	1390.855	3	463.618	15.159	0.003
F	Plasma type	90.797	2	45.399	16.961	0.030
	Wash type	317.522	3	105.841	39.541	0.000

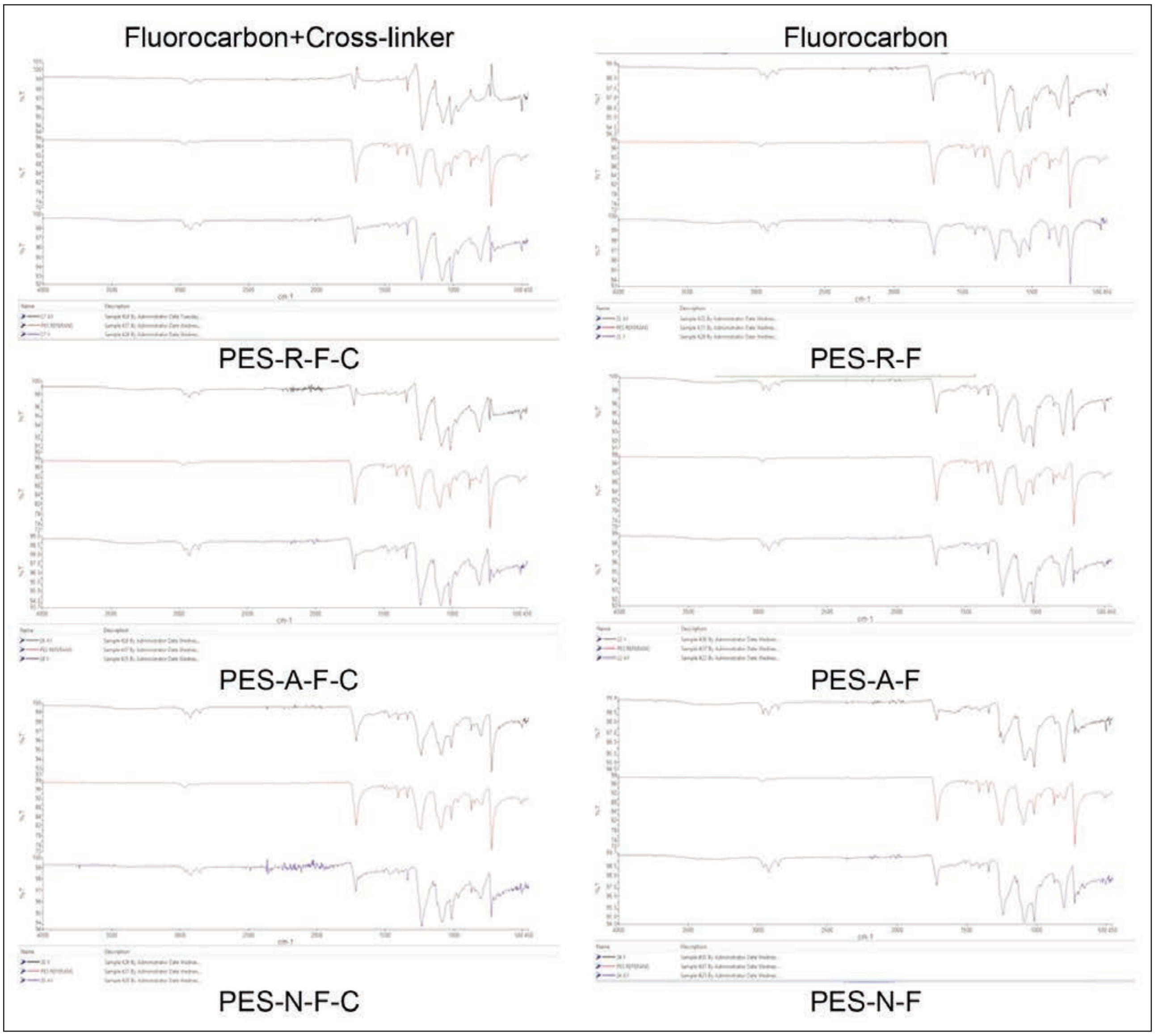


Fig. 3. FT-IR analysis

FT-IR Analysis

Measurements of the finished and washed fabrics were conducted, with the untreated fabric serving as the baseline in the FT-IR spectrum. When the infrared spectrum is examined; -NH stretching vibration was observed at 3000 cm^{-1}, the presence of C=O groups in the structure of urethane was observed in the 1700–1740 cm^{-1} band, and C-F stretching vibrations were observed at 1000–1400 cm^{-1}. Additionally, it has been observed that finished fabrics and washed fabric peaks appear the same way. It has been noted that the washing process applied to the fabric does not effectively remove the finishing chemicals (figure 3).

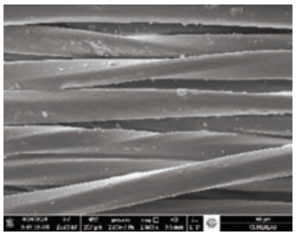
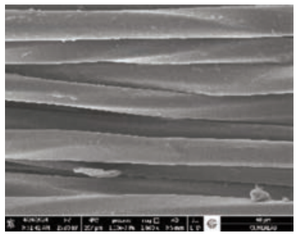
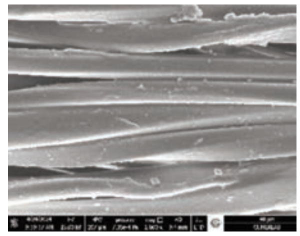
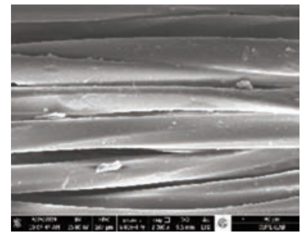
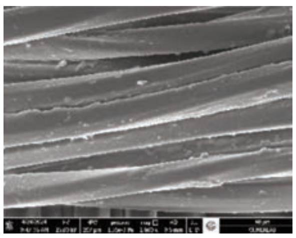
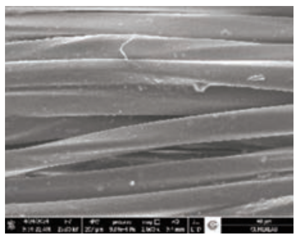
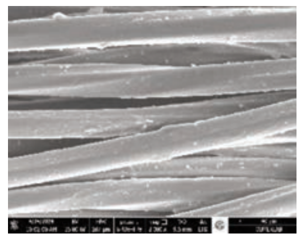
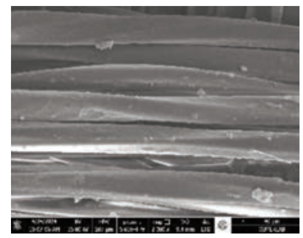
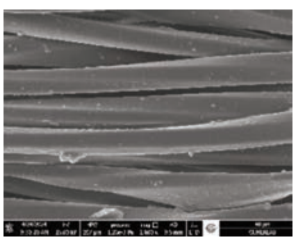
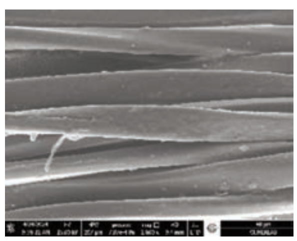
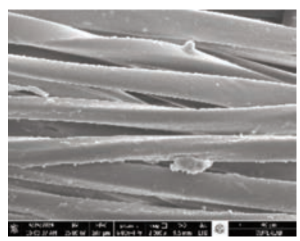
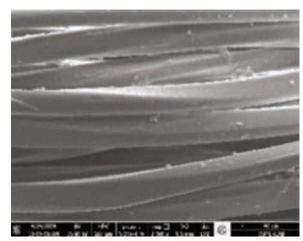
SEM Analysis

SEM analysis of the fabrics was conducted after finished and after 10 times repeated washings (table 4). According to the contact angle measurement results, the highest values were observed in PES-A-F and PES-N-F samples after finishing. When all sample surface morphologies were examined after repeated washings, the contact angle of the PES-N-F sample was higher than the other samples after repeated washings, although no cross-linker was used.

Whiteness measurement

The water repellency finishing of polyester-based fabrics and the whiteness degrees after repeated washings were measured and the results are shown in figure 4. When the whiteness measurement results taken immediately after the water-repellent finishing process was examined, it was found that air plasma pretreatment applied to fabrics treated with both fluorocarbon-containing and fluorocarbon-crosslinker-containing finishing liquors reduced the whiteness values of the fabrics. It is thought that air plasma causes oxidation on the fabric surface [25] and the decrease in whiteness values is due to this reason. Nitrogen plasma pretreatment applied after the water-repellent finishing increased the whiteness values of the fabrics only slightly. The whiteness values

Table 4

SEM ANALYSIS			
Fluorocarbon+Cross-linker		**Fluorocarbon**	
After finish	After 10 washings	After finish	After 10 washings
			
PES-R-F-C	PES-R-F-C	PES-R-F	PES-R-F
			
PES-A-F-C	PES-A-F-C	PES-A-F	PES-A-F
			
PES-N-F-C	PES-N-F-C	PES-N-F	PES-N-F

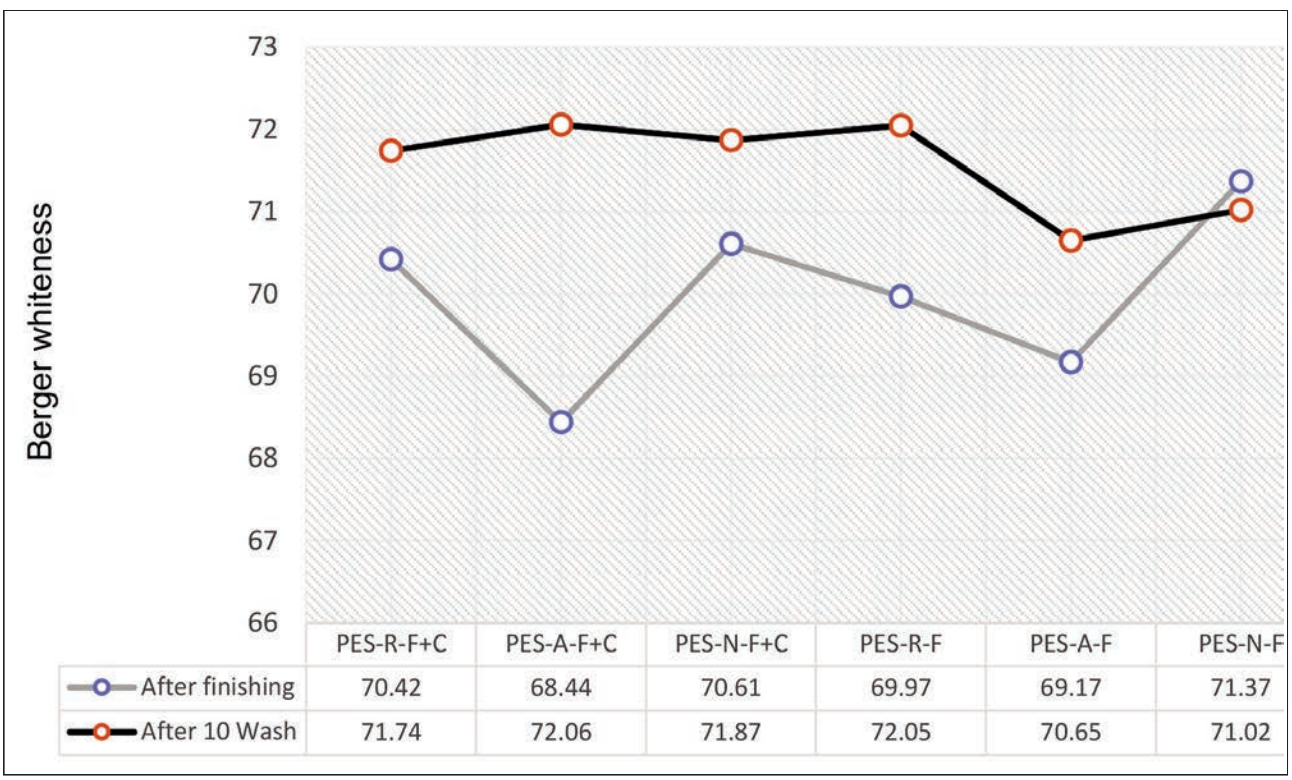


Fig. 4. Berger whiteness values

of the samples treated with nitrogen plasma were very close to the reference sample.

The whiteness values of the samples washed 10 times after the water-repellent finishing process were higher than the whiteness values immediately after finishing, except for the PES-N-F coded sample. The whiteness values of the PES-N-F coded sample were close to each other after finishing and after 10 washings. To examine the permanence of the finish, repeated home washing was performed. Due to the bleach in the detergent used, the whiteness values after repeated washings were higher than the whiteness values immediately after finishing.

CONCLUSION

This study aims to investigate the use of plasma pretreatment before finishing instead of cross-linking chemicals to ensure the permanence of the water-repellency finish. Pre-treated polyester-based fabrics, prepared for dyeing, underwent air and nitrogen plasma treatment. Fluorocarbon solutions with and without cross-linkers were applied to fabrics according to the pad-dry-cure method. Contact angle measurements, FT-IR analysis, SEM analysis, and whiteness measurements were conducted. The samples were subjected to repeated washing 10 times and measurements were made again.

It was found that applying air plasma, along with cross-linker and fluorocarbon, after the water-repellent finishing process led to an increase in the contact angle values of the fabrics. However, it was observed that both air and nitrogen plasma treatments had a detrimental effect on the contact angle values in samples subjected to 10 repeated wash cycles for this finishing type.

Plasma pretreatment enhanced the initial contact angle values of the fabrics. After 20 seconds of the droplet being applied to the fabric, the contact angle values of the samples exhibited similar behaviour and improvement compared to the reference sample. Upon examining the contact angle values measured after 10 repeated wash cycles, it was observed that the contact angle values of the plasma-treated samples were higher than those of the reference sample. The level of permanence achieved in the fabric after repeated wash cycles with cross-linker chemicals and the level of permanence in the fabric pre-treated with plasma (without the use of cross-linker) were very similar. Plasma pre-treatment eliminates the necessity of employing cross-linkers and yields superior water-repellency values.

SEM analysis results show that after multiple washings, the contact angle of the PES-N-F sample was found to be higher than that of the other samples, despite not using any cross-linker. According to FT-IR analysis, it has been noted that the washing process applied to the fabric does not effectively remove the finishing chemicals.

While nitrogen plasma has no effect on the whiteness after finishing, air plasma reduces the whiteness of the sample. In the water repellency finishing process using only fluorocarbon, air plasma decreased the whiteness value of the sample after finishing, while nitrogen plasma increased the whiteness value of the sample.

After repeated wash cycles, although the whiteness values of the samples treated with fluorocarbon and crosslinker were similar, the application of air and nitrogen plasma reduced the whiteness level of the samples treated with fluorocarbon.

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Utilising finite element analysis to evaluate gore design in bras

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ABSTRACT – REZUMAT

Utilising finite element analysis to evaluate gore design in bras

In the early stage of bra pattern making, the gore size is an important design feature to provide different effects such as enhancing the shape of the breasts and the depth of the cleavage, as well as affecting the fitting issue. However, the shaping effects in controlling the breast shape of the gore size have not been investigated in previous studies. This study proposes a finite element method (FEM) to simulate the effect of gore dimensions on breast shape in a wired-bra. A biomechanical model based on accurate geometries and mechanical properties of humans is first built. Then, the sub-model of a bra with different gore design scenarios interacts with the sub-model of the human body. A factorial analysis has been conducted that the effects of lengths of the upper gore and lower gore on the breast geometry are systematically investigated based on the numerical contact models. The length of the upper gore positively contributes to the gathering of the breasts and a deeper cleavage. While the length of the lower gore has a negative relationship with the lifting effect of the breasts and the position of the bra underwire. Reduced lower gore length would lead to a poor fit of the underwire against the breast roots. The method proposed in this paper can be used by bra designers to predict the breast deformation, and thus reducing the time required for the designing of pattern making at the early stages.

Keywords: *gore, finite element, bra design, shaping effects, factorial analysis*

Utilizarea analizei cu elemente finite pentru evaluarea designului benzii dintre cupe la confecționarea sutienului

În faza incipientă a modelului de sutien, dimensiunea benzii dintre cupe este o caracteristică importantă de design pentru a oferi diferite efecte, cum ar fi îmbunătățirea formei sânilor și adâncimii decolteului, precum și soluționarea problemei de potrivire. Cu toate acestea, efectele modelării în controlul formei sânilor în raport cu dimensiunea benzii dintre cupe nu au fost investigate în studiile anterioare. Acest studiu propune o metodă a elementelor finite (FEM) pentru a simula efectul dimensiunilor benzii dintre cupe asupra formei sânilor în cazul unui sutien cu armătură. Mai întâi este construit un model biomecanic bazat pe geometrii precise și pe proprietățile mecanice ale corpului uman. Apoi, submodelul de sutien cu diferite scenarii de design al benzii dintre cupe interacționează cu submodelul corpului uman. S-a efectuat o analiză factorială conform căreia lungimile benzii superioare și a celei inferioare dintre cupe în raport cu geometria sânilor sunt investigate sistematic pe baza modelelor numerice de contact. Lungimea benzii superioare dintre cupe contribuie pozitiv la strângerea sânilor și la un decolteu mai profund, în timp ce lungimea benzii inferioare dintre cupe are impact negativ asupra efectului de ridicare al sânilor și poziției armăturii sutienului. Reducerea lungimii benzii inferioare dintre cupe ar duce la o potrivire slabă a armăturii la baza sânilor. Metoda propusă în această lucrare poate fi folosită de designerii de sutiene pentru a anticipa deformarea sânilor și, astfel, pentru a reduce timpul necesar pentru proiectarea modelelor în stadiile incipiente.

Cuvinte-cheie: *bandă dintre cupe, element finit, design al sutienului, efecte de modelare, analiza factorială*

INTRODUCTION

A good-fitting bra is expected to support the breasts against the effects of gravity and provide an aesthetically pleasing profile. The tension between the breasts and bra fabric is caused by the fabric's stress-strain properties and the pattern design is an important element for achieving the desired shape and amount of support for the breasts [1]. To make each bra cup located in the right position along the under-breast contour, the gore which is a rigid centre panel is used to connect two bra cups in the centre front [2]. A proper gore design can effectively hold a bra in place and even contribute to pushing up the breasts. The best-fitting gore should sit against the sternum, allowing the wearer to breathe normally [3]. The gore size, including the gore width and height, is an important bra design feature in the early stages of pattern making. Changing the gore width could provide different effects, such as enhancing the shape of the breasts and the depth of the cleavage. Increasing the gore height may also be associated with wear discomfort and make the bra style old-fashioned [4]. In traditional bra manufacturing, pattern development involves iterative processes, also called 'trial and error', to first make a prototype and then fit it to a model to check each feature. It will take a lot of repetitive work and be burdensome to do the fitting evaluation and pattern adjustment [5]. Computational technology can aid garment development, thus reducing the time and expense of the fit trial. On the other hand, the strain of the garment, the deformation of the human body and the contact pressure between the garment and the body can be systematically quantified [6]. The computational technique of Finite Element Method (FEM) has been used in the design and development processes of the fashion industry. FE simulation allows for a customer-specific model that incorporates real detailed information about the customer and analyses individual responses in terms of body reshaping and comfort pressure while fitting different garments [7–9]. About the bra design by the FE method, Bruno [10] numerically modelled bras and investigated the effects on breasts during exercise. Sun and her team [11, 12] developed an FE contact model to simulate the process of bra wearing and evaluate the breast shaping effects and pressure value of different bra features, such as cup fabrics and types of bras (with or without underwire). Zhang [13] proposed a numerical model to simulate the interaction of the bra strap and the movement of the upper body. The bra straps with different design features were evaluated based on the FE model. However, the effects of bra components such as gore size on controlling the breast shape and providing adequate support have not been fully investigated. Table 1 provides a summary of the researches on FEM used in garment design.

This paper proposed a numerical method to simulate the effect of gore dimensions on breast shape when a wired-bra is worn, thus providing useful information to bra designers to advance the design and shaping performance of wired-bras.

METHODS

Experiments

A 3D body scanning experiment by a 3D laser body scanner (Vitus, Human Solutions, Germany) was conducted to record the breast shape of a healthy 45-year-old woman after wearing a soft bra with a single-layer structure. The purpose of the soft bra was to find breast roots easily in the 3D digital image so that the breast volume was accurate in the modelling. The height of the subject was 166 cm and the weight was 61.2 kg. In the metric sizing system, her bra size was 36C. The experiment was approved by the University Human Subjects Ethics Committee.

Materials

In the current study, the bra sub-model was simplified as strapless to reduce the simulation time. The nodes at the top of the bra cups were fixed to apply the same effect as having the straps during the simulation instead of incorporating them. The bra structure built in this study is shown in figure 1.

The bra sample constructed for the FE simulation in this study was non-woven fabric for the cup and elastic fabric for the band. The gores were considered as

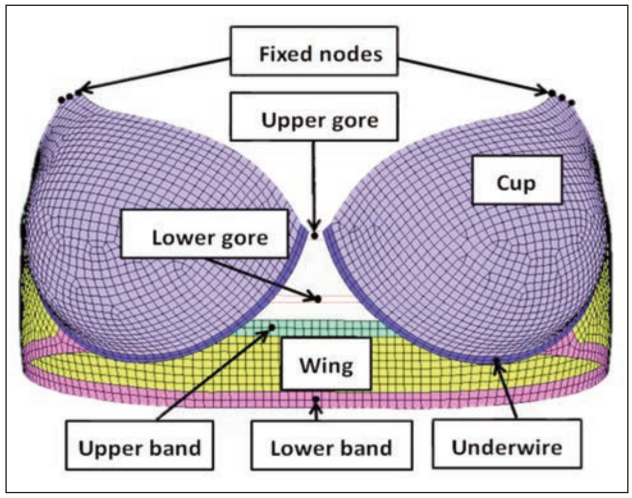

Fig. 1. Sub-model of bra without straps

Table 1

SUMMARY OF THE STATE-OF-THE-ART RESEARCH ON FEM USED IN GARMENT DESIGN					
Sr No	**Reference**	**Kind of garment**	**Design feature**	**Body modelling**	**Garment modelling**
1	[7]	Pantyhose and T-shirts	Fabric material model	Rigid	Rebar layer model & isotropic hyperelastic matrix
2	[8]	Gilet and one-piece dress	Fabric material	Shell element; linear elastic, isotropic	Shell element, linear elastic; orthotropic
3	[9]	Shoe	Sole thickness and material	Solid element; linear, elastic and isotropic (bone, ligament and cartilaginous structures), hyper-elastic (foot soft tissue)	Solid element; non-linear incompressible hyper-elastic
4	[10]	Bra	-	Solid element; hyper-elastic	Shell element
5	[11]	Bra	-	Solid element; hyper-elastic	Shell element; linear elastic; orthotropic
6	[12]	Bra	Bra cup material	Solid element; hyper-elastic	Shell element; linear elastic; orthotropic
7	[13]	Bra	Bra strap width, spacing, elongation, friction and Young’s modulus	Rigid	Shell element; linear elastic; isotropic

Table 2

MECHANICAL PROPERTIES FOR EACH BRA COMPONENT						
Bra components	**Young's modulus (MPa)**		**Shear modulus (MPa)**		**Poisson ratio**	
Cup	Course direction	Wale direction	Course direction	Wale direction	Course direction	Wale direction
	3.68	4.68	0.24	0.29	0.31	0.25
Gore	210000		78900		0.33	
Underwire	210000		78900		0.33	
Band	0.90		0.35		0.28	
Wing	0.10		0.04		0.25	

rigid lines with high stiffness. The mechanical properties for each bra component are given in table 2.

As mentioned in our previous work on the human body modelling, the material properties of soft breasts tissues [11, 12] were assumed to be isotropic and homogeneous with uniform structure inside the breast. The breast tissue was regarded as a non-compressive material with non-linear property. The hyper elastic material model was utilised to describe the behaviour of the breast tissues. The non-linear property of this material type can be defined as the strain energy density function by equation 1.

$$W(I_1,I_2) = \sum_{i,j=0}^{n} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \quad (1)$$

where C_{ij} are the hyper-elastic material coefficients to characterise the nonlinear behaviour of breast deformation. I_1 and I_2 are the first and the second invariants of the components of the left Cauchy-Green deformation tensor B, as given in equation 2.

$$I_1 = \mathrm{tr}(B)$$

$$I_2 = \frac{1}{2}\left[(\mathrm{tr}(B))^2 - \mathrm{tr}(B^2)\right] \quad (2)$$

where $B = F \cdot F^T$, F is a deformation gradient.

When n is equal to 2, the material property can be described as the Mooney-Rivlin model with five coefficients (C_{10}, C_{01}, C_{11}, C_{20}, and C_{02}). The specific details of each coefficient are given in table 3 below.

Table 3

MATERIAL COEFFICIENTS FOR BREAST TISSUES	
Parameter	**Value**
Density (kg/m^3)	1000
C_{10}	0.05
C_{01}	0.052
C_{11}	0.375
C_{20}	0.78
C_{02}	0.63

Construction of gore designs with different scenarios

Construction of the sub-model of bra started from the stress-free state process which can be obtained by the method proposed in our previous study [11]. The initial 3D bra model (figure 1) was subtracted from the three-dimensional image of the subject and the wearing tension of the bra was then released by the steps of cutting 20% length of the band, relaxing the opening force of underwires and flattening the 3D structure of band and underwires. The shape of the gore normally resembles a trapezoid shape. To simulate the effects of different gore designs, two individual design parameters (length of the upper and lower parts of the gore) were used to determine the gore shape. To obtain the initial geometric model of the bra with a specific length of the upper or lower part of the gore, a base model (GM0) with the length of the upper 10 mm and lower parts of the gore 35 mm was first constructed. Another scenario with the shorter (GM1) upper part of the gore can be obtained based on GM0 by rotating the right part of the bra against P_1 with a negative angle and the left part of the bra against P_2 with a positive angle in the *xoy* plane (figure 2). After this step, the length of the upper part of the gore can be modified with the rotation angle until the desired value is reached, while the length of the lower gore remains the same as its initial length.

Similarly, a model of the lower part of the gore which is shorter (GM2) can be obtained by rotating the right

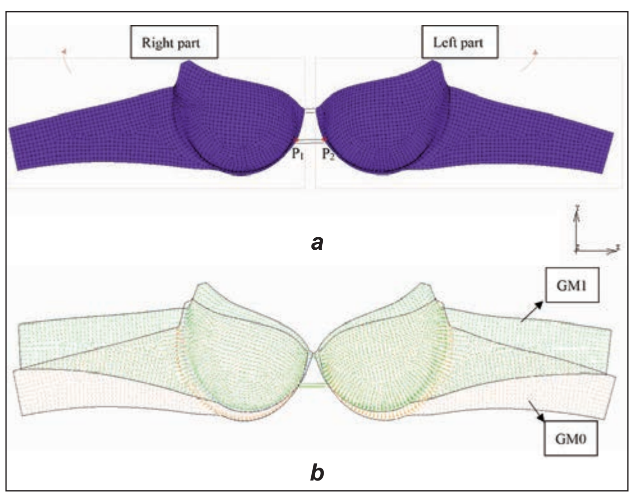

Fig. 2. Process of converting initial sub-model of bra to shorter gore (upper part): *a* – process of obtaining bra model with shorter gore (upper part); *b* – obtained sub-model of bra with shorter gore (upper part)

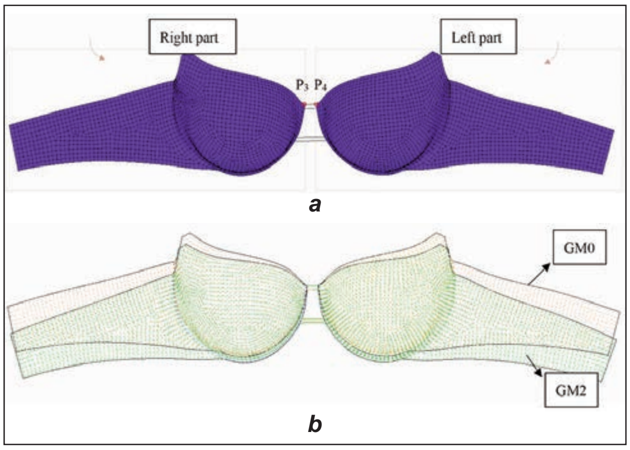

Fig. 3. Process of converting initial sub-model of a bra to shorter gore (lower part): *a* – process of obtaining a model of a bra with shorter gore (lower part); *b* – obtained sub-model of a bra with shorter gore (lower part)

part of the bra against P_3 with a positive angle and the left part of the bra against P_4 with a negative angle in the *xoy* plane. The process is presented in figure 3.

The geometric sub-model of a longer gore (upper and lower parts) was obtained by following the steps in figures 2 and 3 in the opposite rotated directions, respectively.

FEM simulation

Yu [3] reported that the gore size can lead to a change in breast shape, such as the gathering of the breasts and depth of the cleavage. However, studies in the current literature have not examined how the design parameters of the gore affect the shaping effects of a bra. To address this research gap, numerical simulation is considered to be more advantageous over wear trials, not only because it is an efficient tool to plan and visualise the design problem,

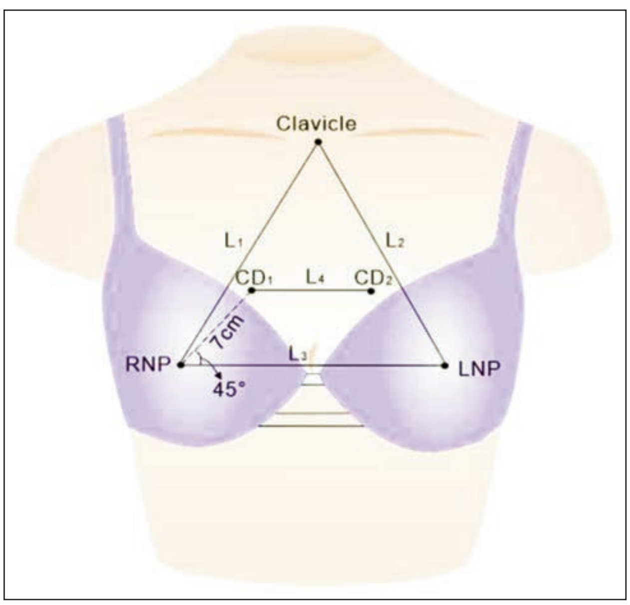

Fig. 4. Body measurements to determine the breast shaping

but also reduces time-consuming tasks such as preparing multiple design features and carrying out repetitive measurements in experiments. The simulation process of wearing a bra in a commercial FE modelling software (MSC. Marc 2014.2.0, US) has been reported in our previous study and the method has been proved to be accurate within an acceptable range in simulating the shaping effects of breasts after wearing different types of bras [11, 12]. The indicators related to the shape of the breasts applied the body measurements of L_1, L_2, L_3 and L_4 to evaluate the lifting and gathering effects. The items RNP, LNP and CD_i (i = 1 or 2) represent the right nipple point, left nipple point and cleavage dots, respectively.

Factorial design and analysis

The length of the upper and lower parts of the gore is considered to be the two fixed factors in a factorial analysis. According to the bra fitting criterion, the length of the upper part of the gore cannot exceed the width of the sternum (which is 20 mm in the model in this study). Thus, the maximum length of the upper part of the gore in the simulation is 20 mm. The factorial design in this study includes two factors each at four levels or a 4×4 simulated factorial experiments. The relationship between the real values of the gore length and the coded levels of the input variables in the factorial analysis is determined by using the following equation:

$$A_i = \frac{a_i - a_c}{\Delta a} \quad (i = 1, 2, 3, 4) \qquad (3)$$

where A_i is the coded level of the input variable (length of upper and lower parts of gore); a_i is the real value of the variables; a_c is the real value of the length of the centre of the gore and Δa is the interval between the adjacent real values. The four coded levels are: low (–1), centred (0), moderately high (1) and high (2), respectively. The interval of each level for the upper part of the gore is 5 mm, while that of the lower part of the gore is 10 mm. The difference in the height between the upper and lower parts of the gore is a fixed value of 4 mm. The parameters and their factor levels are listed in table 4.

Table 4

FACTOR LEVELS OF GORE

Parameter	Symbol	Level (code)			
		–1	0	1	2
The upper part of the gore	U	5 mm	10 mm	15 mm	20 mm
The lower part of the gore	B	25 mm	35 mm	45 mm	55 mm

Table 5 shows the response results of the 16 runs of the simulation with both variables. The results of each run do not vary and with no random errors because the numerical simulation has no repeatability errors under the same parameter input.

Table 5

DESIGN MATRIX AND RESULTS OF 16 RUNS OF SIMULATION						
No.	**U**	**B**	**L_1 (mm)**	**L_2 (mm)**	**L_3 (mm)**	**L_4 (mm)**
1	–1	–1	242.605	242.393	199.58	98.3863
2	–1	0	243.021	242.355	203.076	100.066
3	–1	1	240.456	239.925	198.998	97.0353
4	–1	2	241.374	241.167	201.471	102.367
5	0	–1	247.204	247.419	202.044	99.3466
6	0	0	242.287	241.724	204.625	102.018
7	0	1	242.253	242.802	207.403	103.51
8	0	2	237.751	237.689	208.184	101.965
9	1	–1	249.231	249.458	204.278	103.738
10	1	0	247.64	247.088	207.201	104.322
11	1	1	243.33	243.149	207.745	103.018
12	1	2	236.502	235.509	206.286	98.3262
13	2	–1	250.31	250.697	206.836	105.527
14	2	0	248.514	248.824	209.583	105.946
15	2	1	248.427	248.253	210.211	106.513
16	2	2	244.485	244.149	210.309	104.796

RESULTS AND DISCUSSION

Correlation analysis

A correlation analysis was conducted to determine the statistical relationships between the gore size and the shaping effects on the breasts (output). Pearson's correlation coefficients were calculated to verify the correlations. Table 6 provides the correlation coefficient values and significance. It can be observed that there is a statistically significant correlation between U and L_3 and L_4 (Pearson correlation coefficient r = 0.836 and P value $p < 0.01$) and a considerably significant negative correlation between B and L_1 and L_2 ($r = -0.663$; $p < 0.01$).

In table 6, it can be observed that there is a statistically positive relationship between the length of the upper part of the gore and L_3 and L_4 (r = 0.836, $p < 0.01$), which means that a shorter gore (upper part) results in a decrease in L_3 and L_4. When the upper part of the gore is considered to be a single variable in the design parameters, shortening its length has a more significant influence on the gathering than the lifting of the breasts. Two simulated cases of the upper part of the gore (i.e., $U = 1$, $B = 1$ in figure 5, *a*; $U = 0$, $B = 1$ in figure 5, *b*) are shown in figure 5 to visually show the relationship.

Figure 5 shows the displacement in the x direction and the deformation maps have the same contour scale. The former shows that when the length of the upper part of the gore is equal to the width of the sternum (which is 20 mm here), the amount of deformation at the bottom of the breasts in the horizontal direction is almost the same as that in the gravity-free state. By shortening the upper part of the gore, there is a gathering at the bottom of the breasts (see yellow and blue colours in the deformation map of figure 5, *b*).

The inverse correlation between B and L_1 and L_2 ($r = -0.663$; $p < 0.01$) shows that increasing the length of the lower part of the gore improves the lifting of the breasts. This is probably because a shorter length of

Table 6

CORRELATION ANALYSIS					
Variable	**Item**	**Output**			
		L_1	L_2	L_3	L_4
U	Pearson's correlation	0.561*	0.554*	0.836**	0.763**
	Sig. (2-tail)	0.024	0.026	0.000	0.001
	N	16	16	16	16
B	Pearson's correlation	–0.663**	–0.662**	0.313	–0.062
	Sig. (2-tail)	0.005	0.005	0.238	0.821
	N	16	16	16	16

Note: * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

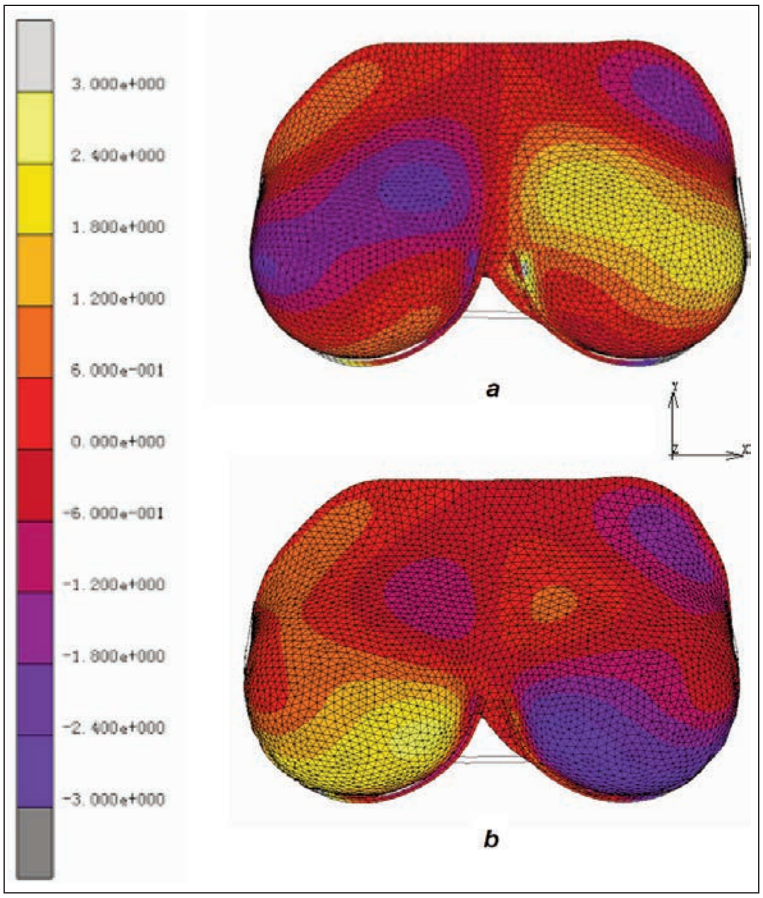

Fig. 5. Two simulated cases with different lengths of upper part of gore (unit of contour bar: mm): *a* – $U = 1$, $B = 1$; *b* – $U = 0$, $B = 1$

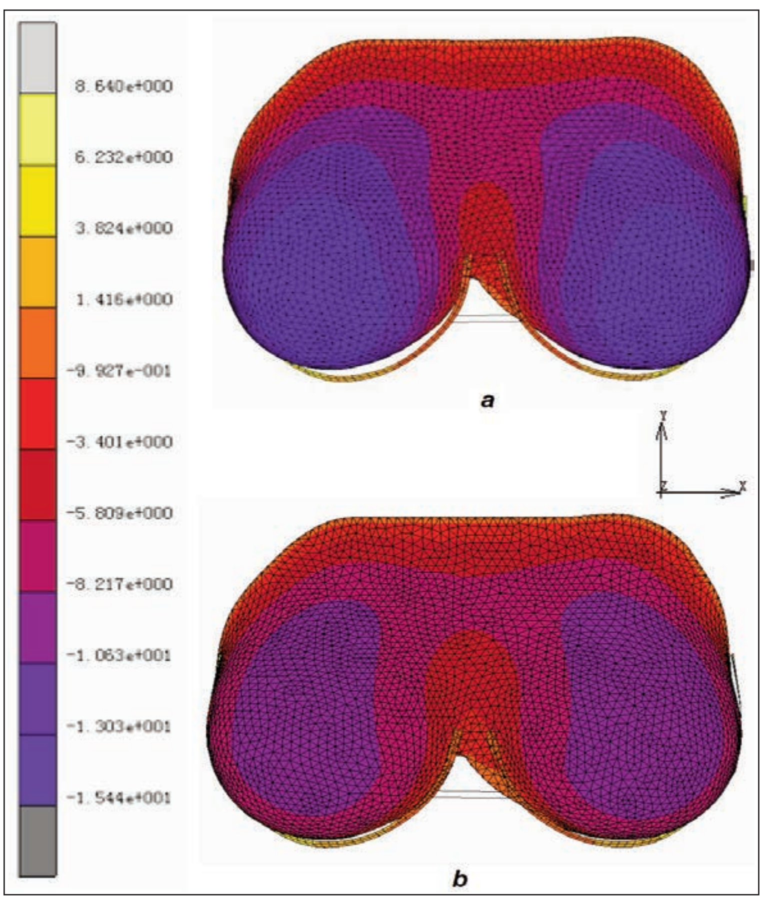

Fig. 6. Two simulated situations with different lengths of the lower part of gore (unit of contour bar: mm): *a* – $U = 1$, $B = 0$; *b* – $U = 1$, $B = 1$

the gore (lower part) causes a fitting problem in which the underwire does not align with the breast roots. Figure 6 provides examples of two lengths of the lower part of the gore. The deformation map shows displacement in the *y* direction. A darker colour indicates a greater degree of sagging phenomenon. It can be observed that when the length of the lower part of the gore is 45 mm, there is a better fit against the breast roots as opposed to a shorter gore of 35 mm. This better-fit results in raising the lift of the breasts.

Regression model

To establish a response model to approximately predict the shaping of the breasts with different combinations of the length of the upper and lower parts of the gore, a mathematical equation was established with two linear terms – one interaction term and one intercept term as follows:

$$f = \alpha_0 + \alpha_1 U + \alpha_2 B + \alpha_3 UB \qquad (4)$$

where *f* is the measured area of the body (L_1, L_2, L_3 and L_4) which represents the shape of the breasts after wearing a bra. Table 7 shows the significance level of each item by listing the coefficients (α_0, α_1, α_2 and α_3 in equation 2), standard errors (S.E.), T-value (T-test value) and P-value (probability of obtaining a certain confidence level). The R^2 and R^2_{adj} are also given to evaluate the fit of the regression model.
Based on the coefficients in table 5, the approximate models for the four measurements are described by Eq. (5a) – (5d), and the resultant models can predict the response to the two parameters of the upper and lower parts of the gore with an accuracy of 77.7%, 77.7%, 80.2% and 64.8% respectively.

$$L_1 = 244.150 + 2.241U - 2.128B - 0.48UB \qquad (5a)$$

$$L_2 = 243.968 + 2.395U - 2.206B - 0.60UB \qquad (5b)$$

$$L_3 = 203.710 + 2.549U - 0.942B - 0.137UB \qquad (5c)$$

$$L_4 = 101.203 + 2.226U - 0.270B - 0.585UB \qquad (5d)$$

CONCLUSION

In this study, based on FEM, the changes in breast shape about the upper and lower widths of the gore panel are systematically reviewed. The results of a correlation analysis show that the length of the upper part of the gore positively contributes to

Table 7

SIGNIFICANCE LEVEL OF EACH FACTOR						
Term	Coefficient	S.E.	T-value	P-value	R^2	R^2_{adj}
(L_1)					0.777	0.721
Constant	244.150	.653	373.857	0.000		
U	2.241	.533	4.203	0.001		
B	–2.128	0.533	–3.990	0.002		
*U*B*	–0.480	0.435	–1.103	0.292		
(L_2)					0.777	0.721
Constant	243.968	0.692	352.310	0.000		
U	2.395	0.565	4.237	0.001		
B	–2.206	0.565	–3.901	0.002		
*U*B*	–0.600	0.462	–1.300	0.218		
(L_3)					0.802	0.753
Constant	203.710	0.540	377.204	0.000		
U	2.549	0.411	5.780	0.000		
B	0.942	0.441	2.135	0.054		
*U*B*	0.137	0.360	0.381	0.710		
(L_4)					0.648	0.560
Constant	101.203	0.582	173.800	0.000		
U	2.226	0.475	4.682	0.001		
B	0.270	0.475	0.568	0.581		
*U*B*	–0.585	0.388	–1.507	0.158		

the gathering of the breasts, thus resulting in a deeper cleavage. The length of the lower part of the gore has a negative influence on the lifting of the breasts and the position of the bra underwire. A shorter length would lead to a poor fit of the underwire against the breast roots. Regression models of four measurements of different parts of the body are established to approximately estimate the output response (breasts) to the different combinations of design parameters of the bra gore. This study has confirmed that FEM is a useful tool that can be used by bra designers to predict the amount of breast deformation, and thus reduce the time required for the designing at the early stages of pattern making in manufacturing. However, a more realistic model of the human body and sub-model of bras with various design parameters (such as underwire shape, material property of the underwire and orientation of bra straps) should be constructed in future studies to enhance the understanding of the interaction process between the breasts and bra.

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Properties of the fabrics knitted from yarns with different slub parameters

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ABSTRACT – REZUMAT

Properties of the fabrics knitted from yarns with different slub parameters

Slub yarns, whose characteristic feature is planned thick regions in the yarn diameter, have an important place among the fancy yarns that have an increasing usage in clothing and home textile products. These yarns, used in woven and knitted fabrics, create unique visual and textural effects compared to conventional yarns, giving yarn manufacturers a competitive advantage. In this study, the performance properties of knitted fabrics produced from slub yarns were examined depending on slub parameters such as slub thickness, slub frequency, slub length, yarn twist coefficient and slub population. The results showed that slub frequency, slub thickness, and twist coefficient significantly affect the air permeability of the fabrics Additionally, the study found that slub frequency and slub thickness are important parameters for abrasion resistance, while yarn twist coefficient is crucial for bursting strength. In terms of fabric pilling property, increasing slub thickness, length, and frequency were found to increase fabric pilling tendency.

Keywords: *slub thickness, slub length, slub frequency, slub population, knitted fabric*

Proprietățile tricoturilor din fire cu diferiți parametri ai nopeului

Firele de efect cu nopeuri, a căror trăsătură caracteristică sunt regiunile groase planificate în diametrul firului, ocupă un loc important printre firele fantezie care sunt din ce în ce mai utilizate în artiocle textile pentru casă. Aceste fire, utilizate în țesături și tricoturi, creează efecte vizuale și texturale unice în comparație cu firele convenționale, oferind producătorilor de fire un avantaj competitiv. În cadrul acestui studiu, au fost examinate proprietățile de performanță ale tricoturilor din fire de efect cu nopeuri, în funcție de parametrii nopeului, cum ar fi grosimea nopeului, frecvența nopeurilor, lungimea nopeului, coeficientul de torsiune a firului și populația de nopeuri. Rezultatele au arătat că frecvența nopeurilor, grosimea nopeului și coeficientul de torsiune influențează semnificativ permeabilitatea la aer a tricoturilor. În plus, studiul a constatat că frecvența nopeurilor și grosimea nopeului sunt parametri importanți pentru rezistența la abraziune, în timp ce coeficientul de torsiune a firului este crucial pentru rezistența la rupere. În ceea ce privește proprietatea de piling a tricotului, s-a constatat că creșterea grosimii, a lungimii și a frecvenței nopeurilor duce la creșterea tendinței de piling a tricotului.

Cuvinte-cheie*: grosimea nopeului, lungimea nopeului, frecvența nopeurilor, populația de nopeuri, tricot*

INTRODUCTION

The main aim of technical research and innovation in the field of textiles has been to obtain yarns with perfect uniformity in terms of colour and structure for centuries. However, after it was seen that yarn faults could create a pleasant effect, yarn production methods that included planned faults emerged. Fancy yarns, which are produced in this way, express decorative unevenness in terms of colour form or both [1–3]. Fancy yarns are yarns that have a very diverse and complex structure are not uniform in structure and have at least one different material, colour and twist variations.

Today, fancy yarns have an important position in yarn and fabric technology in terms of their different appearance and usage properties. Fancy yarn production technologies enable the production of textile products with high added value. Slub yarns are one of the most common fancy yarns.

Slub yarns are a type of fancy yarn that achieves a slub appearance by changing the linear density of the yarn during the spinning process and is widely used in various garments due to its special appearance. Producing slub yarn instead of standard products provides a competitive advantage and economic benefit to yarn manufacturers, and also offers a better decorative effect for customers. The defining feature of slub yarns is the planned formation of irregularities of varying sizes in the yarn structure at certain intervals along their length. The different effects caused by changing length, thickness and slub spacing are used in woven and knitted fabrics, especially denim, for clothing purposes, as well as in home textiles such as curtains and upholstery [4].

Simple slub yarns; are achieved by changing the draft while producing a single-ply yarn in spinning systems. In the yarn obtained by this method, the slub and the basic yarn are integrated and the slub material is the same as the basic yarn [1]. While the

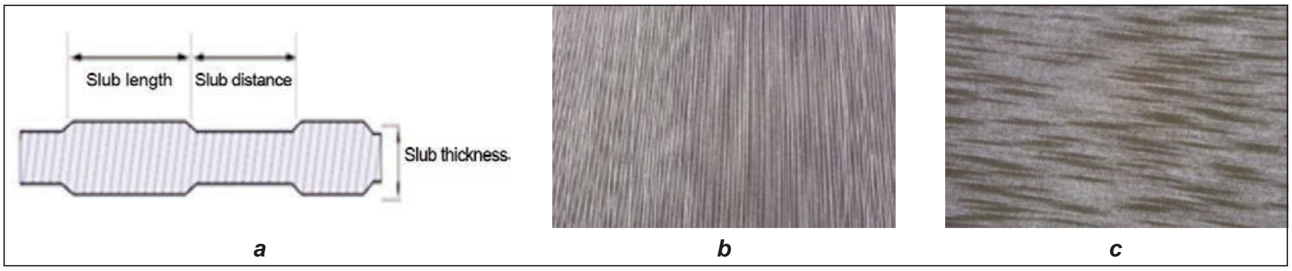

Fig. 1. Structure of: *a* – slub yarn; *b* – slub yarns; *c* – knitted fabric made from slub yarns

soft, more voluminous and thicker part of the yarn in the slub yarn structure, which has less twist, forms the slub, the other parts, which have more twist and appear thin, form the basic yarn [5]. To define simple slub yarns; the number of slubs per unit length (number/m), slub thickness ratio, slub length (cm), slub distance (cm) and slub effect structure are specified (figure 1).

Most of the previous studies on slub yarns were focused on the production technologies of slub yarns, characterisation of slub yarns, measurement of quality properties (especially evenness, hairiness and size measurements), geometric parameters and analysis methods [6–12].

There are also some studies in the literature on the properties of fabrics produced from slub yarns. Fouda 's study showed that, when the slub yarn ratio increased, the fabric weight, thickness and thermal resistance of single jersey knitted fabrics increased, the air permeability decreased, and in addition, the fabric spirality, shrinkage and abrasion resistance improved [13]. Ray et al. examined the effect of slub parameters on abrasion damage in woven fabrics using fabric mass loss and appearance change. As a result of the research, it was seen that the fabric could have less damage to its surface appearance despite higher mass loss due to abrasion [14]. Altaş and Özgen showed that the effect of slub length and slub thickness on the abrasion resistance properties of the fabric is not linear, the slub distance has a small effect on abrasion, and they found that the linear density of the yarn is the most important factor affecting the abrasion properties [15]. In another study, researchers showed that slub thickness is the most important parameter for air permeability [16]. Mukhopadhyay et al. concluded that with the increase in slub length and slub thickness, the mass loss due to abrasion in the fabric initially decreased and then increased [17]. As a result of another study, researchers suggested that the abrasion resistance of knitted fabrics produced from slub yarn is improved by lesser slub thickness whereas in the case of woven fabric, the abrasion resistance is improved by higher slub thickness [18]. Atef et al. stated that with increasing slub frequency, fabric friction, and bursting performance increased, but fabric flexibility, pilling performance, air flow rate and water vapour transmission decreased [19]. Thanabal et al. stated that as the slub thickness and slub length increase, fabric weight and bursting strength increase, while air permeability decreases. However, as the club length increased further, there was a sudden decrease in bursting strength. Researchers suggested that the reason for this is the decrease in yarn elongation due to the decrease in twists in the slub yarn section [20]. Ertekin et al. examined fabric thermal properties from elastane core slub yarns and found that the parameters of slub thickness and slub length have a significant effect on fabric spirality, relative water vapour permeability, thermal conductivity and thermal absorptivity however slub length has not significant effect on friction coefficient and air permeability characteristics [21].

Unlike other studies, this paper aimed to investigate the effects of yarn twist coefficient and different population usage on fabric properties, in addition to basic parameters such as slub length, slub thickness, and slub frequency. Moreover, while most of the previous studies focused on abrasion resistance and air permeability properties of fabrics, this study also studied bursting strength and pilling properties which have been studied in a limited number of research. A systematic and comprehensive test plan was prepared for this purpose, and all slub yarns were produced under mill conditions.

MATERIAL AND METHODS

In the study, slub yarns with different parameters were produced on the Merlin Spa spinning machine using polyester and cotton fibres, and ring-spun yarns were also produced for comparison purposes [5]. All the yarn linear density was tex 29.5 (Ne 20). The fibre length was 28.87 mm for cotton and 40 mm for polyester fibre. Slub thickness ratio (1.2, 1.4, 1.6 and 1.8), slub length (1–3, 5–7 and 10–12 cm), slub frequency (0.5, 3 and 6 number/m.) and slub population (2 different populations) were selected as slub parameters. To determine the population effect, yarns with a single type of slub length, that is, single population (basic slub – 1–3 and 10–12 cm slub length), and yarns with two different lengths of slub, that is, two populations (1–3, 10–12 (P2P3)) were produced. To examine the effect of twist, α_e=3.8, α_e = 4.2 and α_e = 4.6 were used as twist coefficients (table 1). All types of yarns were knitted in single jersey structures with the same tightness using a laboratory-type LAB KNITTER 294E MESDAN knitting machine.

Before measurements, all samples were conditioned under standard atmospheric conditions (temperature 20±2°C, 65±4% Rh) and all the measurements were performed under standard atmospheric conditions. The abrasion properties of fabrics were measured with the Martindale Pilling and Abrasion Tester according to the TS EN ISO 12947-2 standard using fine sandpaper. Bursting strength values of the fabrics were tested according to TS EN ISO 13938-1 standard using with hydraulic type TMI EC 37 testing device. TS EN 12127 and TS 7128 ISO 5084 standards were used for fabric weight and thickness respectively. Air permeability tests were done according to TS 391 EN ISO 9237 standard. The pilling test was performed on the Nu-Martindale test device according to TS EN ISO 12945-2 standard.

Evaluation of test results was carried out using SPSS statistical software. ANOVA test was conducted to decide whether the effects of slub thickness, slub length, slub frequency, yarn twist, and population were statistically significant at the 95% confidence level ($p < 0.05$) for bursting strength and air permeability. Also, Post-Hoc and multiple comparison tests were done.

Since the result of the abrasion resistance test is a discrete variable, the Kruskal Wallis one-way variance test, one of the non-parametric analysis methods, was performed to evaluate the data. The Kruskal-Wallis test is the most commonly used in testing the null hypothesis that "more than two independent samples were drawn from the same population". The alternative hypothesis is "The median of at least one main population is different from that of other populations". If $p < 0.0.5$, it is concluded that the median of at least one main population among the independent groups examined is important compared to the other populations with 95% confidence.

RESULTS AND DISCUSSION

Effect of slub thickness

In terms of the strength properties of the fabrics, as the slub thickness ratio increases, both abrasion resistance and bursting strength increase, but beyond a certain point, both values decrease (figure 2). These results are consistent with the results of Mukhopadhyay et al.'s study. As the slub yarn ratio increases, the probability of the existence of apparent thick areas resulting in higher strength in fabric increases. However, as the slub thickness ratio increases further, the twist slips into the thinner areas of the yarn, causing the fibres to move away more easily during the abrasion resistance test and slide

Table 1

YARN AND FABRIC PARAMETERS USED IN THE STUDY

Parameter	Material	Twist coefficient (α_e)	Slub type	Slub frequency (number/m)	Slub thickness (ratio)	Slub length (cm)	Fabric weight (g/m^2)	Fabric thickness (mm)	Fabric density (wales/cm)
Slub thickness	PES	3.8	Without Slub	-	-	-	164	0.687	12.5
	PES	3.8	Basic Slub	3	1.2	5–7	176	0.726	12
	PES	3.8	Basic Slub	3	1.4	5–7	163	0.741	11.5
	PES	3.8	Basic Slub	3	1.6	5–7	160	0.742	11.3
	PES	3.8	Basic Slub	3	1.8	5–7	155	0.771	11
Slub length	PES	3.8	Without Slub	-	-	-	164	0.687	12.5
	PES	3.8	Basic Slub	3	1.6	1–3	156	0.760	11.5
	PES	3.8	Basic Slub	3	1.6	5–7	160	0.742	11.3
	PES	3.8	Basic Slub	3	1.6	10–12	163	0.780	11
Slub frequency	PES	3.8	Without Slub	-	-	-	164	0.687	12.5
	PES	3.8	Basic Slub	0.5	1.6	5–7	166	0.741	11.5
	PES	3.8	Basic Slub	*3*	1.6	5–7	160	0.742	11.3
	PES	3.8	Basic Slub	*6*	1.6	5–7	155	0.705	10.5
Twist coefficient	Cotton	3.8	Without Slub	-	-	-	187	0.696	11.5
	Cotton	3.8	Basic Slub	3	1.6	5–7	189	0.717	11.5
	Cotton	4.2	Basic Slub	3	1.6	5–7	196	0.788	10.5
	Cotton	4.6	Basic Slub	3	1.6	5–7	198	0.750	11
Slub population	PES	3.8	P2, P3	3	1,6	1–3, 10–12	158	0.734	11
	PES	3.8	Basic Slub	3	1.6	1–3	155	0.760	11.3
	PES	3.8	Basic Slub	3	1.6	10–12	165	0.780	11

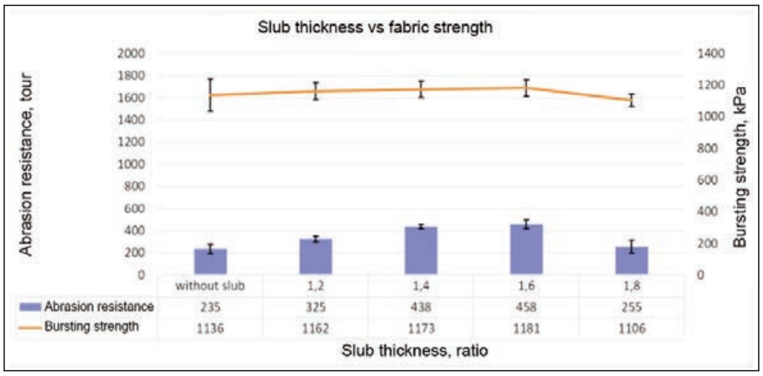

Fig. 2. Effect of slub thickness on fabric strength

over each other more easily during the bursting strength test. Moreover, at the highest slub thickness ratio, the fabrics become looser structures resulting in lower fabric strength.

At low slub thickness due to the higher fabric weight and thickness, the fabrics' air permeability values are lower than the fabrics produced yarns without slub (table 2). When the air permeability values of fabrics with slub yarns are compared it was revealed that as the slub thickness ratio increases, the air permeability value increases. Lower fabric density values, resulting from the increased thickness due to higher slub thickness ratios cause an increase in air permeability values._Here, it can be mentioned that the reduction in yarn twist caused by the thicker areas of the higher thickness ratios, enables more air to pass between the yarns.

The effect of slub thickness on the pilling properties of fabrics is also given in table 2. It is observed that fabrics produced from yarns without slub exhibit the lowest pilling tendency. As the slub thickness increases, the degree of pilling decreases, that is, the tendency to pilling increases. It is attributed to the decrease in fabric density value at high slub thickness which makes the fibre migration to the fabric surface easier causing a reduction in the pilling resistance and a decrease in twist in increased slub thickness regions causes more pilling as well.

Variance analysis test results showed that air permeability values were significant statistically (table 3). Multiple comparison test results of air permeability for slub thickness are given in table 4. According to the Kruskal Walllis test about slub thickness, the difference in mean values of abrasion resistance was significant (p = 0.017).

Table 2

EFFECT OF SLUB THICKNESS ON THE AIR PERMEABILITY AND PILLING OF THE FABRIC

Parameter	Slub thickness				
	Without slub	1.2	1.4	1.6	1.8
Air permeability (l/dm^2/min)	1783	1592	1633	1927	1998
Pilling (grade)	3	2.5	2.5	2	2

Table 3

P VALUE OF ANALYSIS OF VARIANCE REGARDING SLUB THICKNESS

Parameter	p-value
Bursting strength	0.301
Air permeability	0.000*

Note: *Statistically significant according to α = 0.05.

Effect of slub length

The fabric strength values are given in figure 3. As the test results were examined, similar to the results for slub thickness ratio, an increase in slub length caused an increase in abrasion resistance and bursting strength values of the fabrics. The abrasion resistance of the fabric increases as the slub length increases in case of longer slub length causing a higher number of fibers in the slub parts of the yarn. Furthermore, the decrease in a twist due to the longer slub regions of the yarn increases the bursting strength values by increasing the yarn elasticity. However, beyond the optimum point (5–7 cm slub length) caused the fibres to slide over each other more easily, causing a decrease in strength, as discussed in Thanabal's study in 2021 [26].

Table 4

95% CONFIDENCE INTERVAL BOUNDS ACCORDING TO TUKEY MULTIPLE COMPARISONS OF THE AIR PERMEABILITY RESULTS BASED ON THE SLUB THICKNESS

Slub thickness	Without slub	1.2	1.4	1.6	1.8
	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound
Without slub	-	–304.12/–77.22*	–262.78/–35.88*	31.21/258.12*	101.88/328.78*
1.2	77.22/304.12*	-	–72.12/154.78	221.88/448.78*	292.55/519.45*
1.4	35.88/262.78*	–154.78/72.11	-	180.55/407.45*	251.22/478.12*
1.6	–258.12/–31.22*	–448.78/–221.88*	–407.45/–180.55*	-	–42.78/184.12*
1.8	–328.78/–101.88*	–519.45/–292.55*	–478.12/–251.22*	–184.12/42.78*	-

Note: *Statistically significant according to α = 0.05.

In this study, a constant slub thickness ratio of 1.6 was used for different slub lengths, it can be said that the increase in air permeability depending on the slub length is a result of the increase in fabric porosity, similar to the effect of slub thickness. It is possible to explain the decrease in the porosity value beyond the limit value. Since the slub frequency is consistent for all yarns in different slub lengths, it is expected that the increase in slub length after a certain limit value will reduce the fabric porosity. Higher slub length results in a more uniform, thicker and heavier fabric structure in a unit area. Consequently, a decrease in fabric air permeability occurs for slub lengths of 10–12.

When the effect of slub length on the pilling properties of the fabrics was examined, it was found that fabrics produced from unslub yarns had a lower tendency to pilling than fabrics with slub yarns (table 5). As the slub length increases, the tendency to pilling increases. This can be attributed that at higher slub lengths, the decreasing twist value causes the fibres to surface more easily, thereby, reducing the fabric's pilling resistance.

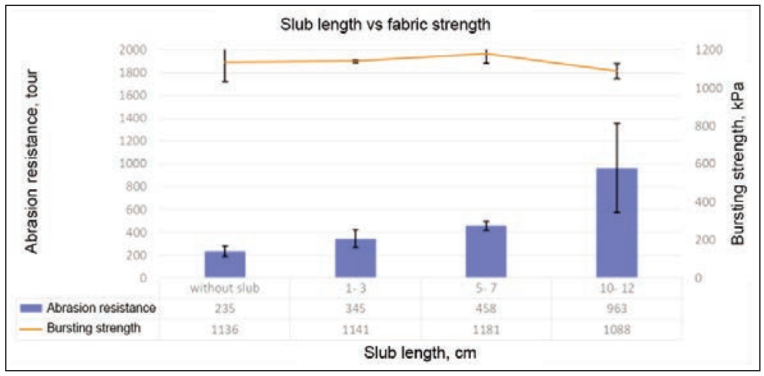

Fig. 3. Effect of slub length on fabric strength

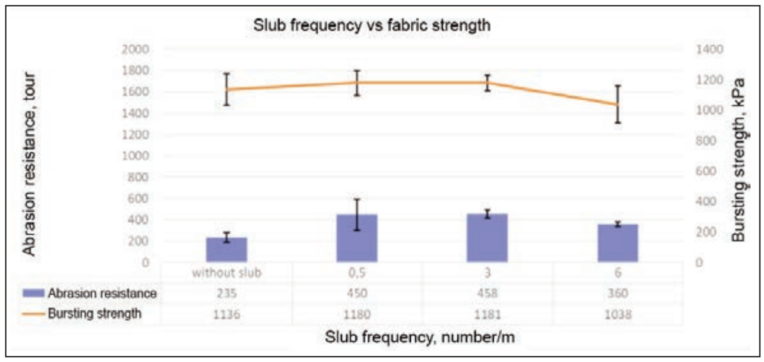

Fig. 4. Effect of slub frequency on fabric strength

According to the variance analysis, the differences were insignificant for bursting strength and air permeability (table 6). However, the Kruskal Walllis test results show that there was a significant difference between the abrasion resistance values regarding slub length ($p = 0.041$).

Table 5

EFFECT OF SLUB LENGTH ON THE AIR PERMEABILITY AND PILLING OF THE FABRIC				
Parameter	**Slub length (cm)**			
	Without slub	**1–4**	**5–7**	**10–12**
Air permeability (l/dm^2/min)	1783	1818	1927	1753
Pilling (grade)	3	2.5	2.5	2

Table 6

P VALUE OF ANALYSIS OF VARIANCE REGARDING SLUB LENGTH	
Parameter	**p-value***
Bursting strength	0.075
Air permeability	0.157

Note: *Statistically significant according to α = 0.05.

Effect of slub frequency

The abrasion resistance and bursting strength of the fabric increase as the slub frequency increases, as shown in figure 4. However, beyond a certain slub frequency limit, these values decrease. It can be interpreted that when slubs are closer with increasing frequency they behave similarly to an increase in slub length. As the higher than the optimum frequency value (3 number/m), significant decreases were detected in the abrasion resistance and bursting strength values due to the decreasing fabric density and weight, especially at a slub frequency of 6.

An increase in air permeability values is an expected result as the number of pores per unit area increases as the slub frequency increases. In terms of pilling property, more pilling was observed in slub fabrics (table 7). Especially beyond the optimum frequency value, the pilling tendency is higher for fabrics with high slub frequency (6 number/m).

Table 7

EFFECT OF SLUB FREQUENCY ON THE AIR PERMEABILITY AND PILLING OF THE FABRIC				
Parameter	**Slub frequency (number/m)**			
	Without slub	**0.5**	**3**	**6**
Air permeability (l/dm^2/min)	1783	1788	1927	1938
Pilling (grade)	3	2.5	2.5	2

Variance analysis shows that the difference between air permeability values is significant (table 8) and according to the Kruskal Wallis test results, there was a significant difference between the abrasion resistance values ($p = 0.041$). Table 9 shows the 95% confidence interval bounds of the air permeability

Table 8

P VALUE OF ANALYSIS OF VARIANCE REGARDING SLUB FREQUENCY	
Parameter	**p-value**
Bursting strength	0.088
Air permeability	0.000*

Note: *Statistically significant according to α = 0.05.

results. In cases where the slub frequency is 3 and 6, the air permeability values of the fabrics are higher than the fabrics without slub and with a slub frequency of 0.5

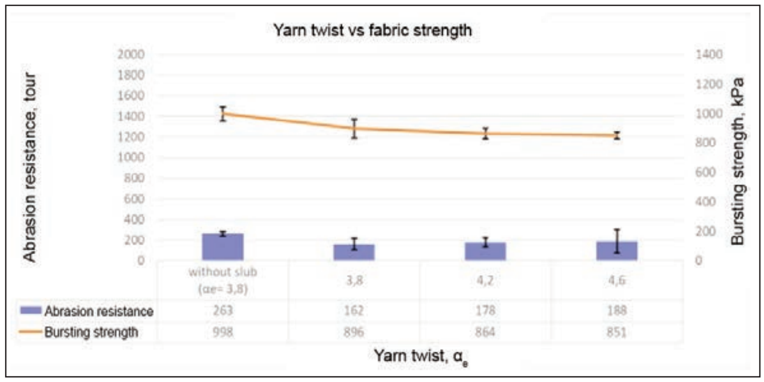

Fig. 5. Effect of twist coefficient on fabric strength

Table 9

95% CONFIDENCE INTERVAL BOUNDS ACCORDING TO TUKEY MULTIPLE COMPARISONS OF THE AIR PERMEABILITY RESULTS BASED ON THE SLUB FREQUENCY				
Slub frequency	**Without slub**	**0.5**	**3**	**6**
	Lower bound/ Upper bound	**Lower bound/ Upper bound**	**Lower bound/ Upper bound**	**Lower bound/ Upper bound**
Without slub	-	–230.43/21.10	18.90/270.43*	29.57/281.10*
0.5	–21.10/230.43	-	123.57/375.10*	134.23/385.76*
3	–270.43/–18.90*	–375.10/–123.57*	-	–115.10/136.43
6	–281.10/–29.57*	–385.76/–134.24*	–136.43/115.10	

Note: *Statistically significant according to α = 0.05.

Effect of yarn twist coefficient

The fabrics produced from cotton fibre were used to determine the effect of the twist coefficient. Because of the shorter fibre length unlike the polyester fabrics results, the strength of the fabrics in slub yarns was found to be lower than those produced with unslub yarn. The presence of slub areas leads to lower strength due to these fibre characteristics. When the effect of yarn twist coefficient on slub fabric properties is examined, as the yarn twist increases, the fibres are packed more tightly, making it difficult to separate the fibre from the yarn due to friction, thus an increase in the abrasion resistance was determined. However, the increase in twist also causes a decrease in yarn elasticity and fabric bursting strength values.

With the increase in yarn twist coefficient, a decrease in yarn diameter and an increase in air permeability were observed. When the relationship between yarn twist coefficient and fabric pilling is examined, it is seen that increasing the twist coefficient reduces the pilling tendency. The increase in the twist coefficient ensures that the fibres are wrapped more tightly into the yarn structure, which reduces the tendency to pilling (table 10).

Table 10

EFFECT OF TWIST COEFFICIENT ON THE AIR PERMEABILITY AND PILLING OF THE FABRIC				
Parameter	**Twist coefficient (α_e)**			
	Without slub (α_e = 3.8)	**3.8**	**4.2**	**4.6**
Air permeability (l/dm^2/min)	1021	1034	1176	1189
Pilling (grade)	2.5	2.5	2.8	3

The effect of yarn twist on bursting strength and air permeability values is statistically significant (table 11). While the twist increase in slub yarns did not make a significant difference for fabrics in slub yarn, it was observed that their bursting strength was significantly lower than that of yarns without slub (table 12). In cases where α_e values are 4.2 and 4.6, the air permeability value of fabrics is higher than other fabrics (table 13) The difference in mean values of abrasion resistance was insignificant according to the Kruskal Wallis test ($p = 0.270$).

Table 11

P VALUE OF ANALYSIS OF VARIANCE REGARDING TWIST COEFFICIENT	
Parameter	**p-value**
Bursting strength	0.000*
Air permeability	0.000*

Note: *Statistically significant according to α = 0.05.

Effect of slub population

The yarn which has two different slub lengths (1–3 and 10–12) was used to determine the effect of slub population. The comparison was made between fabrics produced from single slub yarn in 1–3 slub length and 10–12 slub length. Statistical analysis indicated

Table 12

95% CONFIDENCE INTERVAL BOUNDS ACCORDING TO TUKEY MULTIPLE COMPARISONS OF THE BURSTING STRENGTH RESULTS BASED ON THE TWIST COEFFICIENT				
Twist coefficient	Without slub (α_e = 3.8)	3.8	4.2	4.6
	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound
Without slub (α_e = 3.8)	-	–181.75/–20.85*	–214.19/–53.29*	–227.37/–66.47*
3.8	20.85/181.75*	-	–112.89/48.01	–126.07/34.83
4.2	53.29/214.20*	–48.01/112.89	-	–93.63/67.27
4.6	66.47/227.37*	–34.83/126.07	–67.27/93.63	-

Note: *Statistically significant according to α = 0.05.

Table 13

95% CONFIDENCE INTERVAL BOUNDS ACCORDING TO TUKEY MULTIPLE COMPARISONS OF THE AIR PERMEABILITY RESULTS BASED ON THE TWIST COEFFICIENT				
Twist coefficient	Without slub (α_e = 3.8)	3.8	4.2	4.6
	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound	Lower bound/ Upper bound
Without slub (α_e = 3.8)	-	–63.90/90.24	78.32/232.47*	91.66/245.81*
3.8	–90.24/63.90	-	65.16/219.30*	78.50/232.64*
4.2	–232.47/–78.33*	–219.30/–65.16*	-	–63.74/90.41
4.6	–245.80/–91.66*	–232.64/–78.50*	–90.41/63.74	-

Note: *Statistically significant according to α = 0.05.

that the slub population had no significant effect on the strength and air permeability of the fabric (table 14). Bursting and abrasion resistance values of two-population fabrics were between the results of single-population fabrics. Since there are slubs in two different lengths along the yarn, it was an expected result (figure 6).

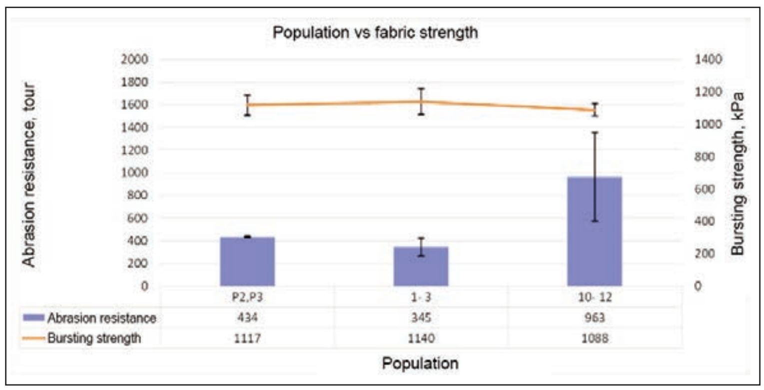

Fig. 6. Effect of slub population on fabric strength

In terms of air permeability values, the fabrics in two populations showed the highest result. This could be stated that the reason for the higher air permeability values is due to the presence of different populations in the yarn, more porous structure of the fabric.

When evaluating the pilling properties of fabrics with different populations, it was seen that fabrics produced from yarns with two different populations had a lower tendency to pilling than fabrics with a single population. It is thought that this situation is due to the lowest thickness of the P2, P3 fabric. The thickness of slub fabrics is determined by the regional slub thickness, and therefore, the slub areas are damaged first when performing the pilling test. For this reason, it can be said that the slubs are distributed homogeneously in the P2, P3 fabric and are less pilled (table 15).

Table 14

P VALUE OF ANALYSIS OF VARIANCE REGARDING SLUB POPULATION	
Parameter	p-value*
Bursting strength	0.194
Air permeability	0.120

Note: *Statistically significant according to α = 0.05.

Table 15

EFFECT OF SLUB POPULATION ON THE AIR PERMEABILITY AND PILLING OF THE FABRIC			
Parameter	Slub population		
	P2, P3	1–3	10–12
Air permeability (l/dm^2/min)	1911	1818	1753
Pilling (grade)	3	2.5	2

CONCLUSION

The increasing use of slub yarns in recent years has required examining of the properties of fabrics produced from these yarns. In this study, the effects of slub thickness, slub length, slub frequency, yarn twist and population parameters on the bursting strength, permeability and pilling properties of knitted fabrics produced from slub yarns were examined.

According to the study results it was observed that slub length and population characteristics did not have a significant effect on bursting strength and air permeability values. However, slub thickness ratio, slub frequency, and twist coefficient value are the parameters affecting air permeability significantly, and it can be said that the effect of slub parameters on fabric density and porosity is quite important.

In terms of strength properties of the fabrics, increasing the slub thickness and frequency provides increments in the fabric abrasion and bursting resistance due to the thick areas there, but using 1.6 slub thickness and slub frequency higher than 3 number/m causes these values to decrease due to easier removal of fibres in the slub areas and decreasing fabric density. Additionally, the twist value of the yarn has been found to have a significant impact on fabric bursting strength.

When the effect of slub parameters on fabric pilling properties is examined, increasing slub thickness, length, frequency and population number give rise to tendency of the fabric pilling-formation.

Considering the strength behaviours of fabrics produced from slub yarns, it was observed that the values increased up to a certain limit value and after reaching this value, the tendencies changed and began to decrease. Therefore, it is important to determine these values to obtain the optimum physical properties expected from fabrics.

In researching slub yarns and the resulting fabrics, it is advisable to carry out studies that examine the effects of slub properties on different types of fabric and fabric parameters.

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Impact of repetitive washing on recycled cotton knitted fabrics: a comprehensive physical property analysis

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ABSTRACT – REZUMAT

Impact of repetitive washing on recycled cotton knitted fabrics: a comprehensive physical property analysis

The textile industry's rapid growth has significantly increased cotton textile production, escalating the volume of textile waste. Recycling cotton waste emerges as a solution, providing an opportunity to repurpose waste into valuable products. In this regard, the durability of recycled cotton fabrics under domestic laundering conditions becomes critical to ensuring sustainable textile practices. This research explored the effects of repetitive washing on the physical characteristics of knitted fabrics containing recycled cotton. The study focused on evaluating changes in key fabric properties, such as mass per unit area, thickness, density, air permeability, and fabric stretchability, including both elongation and unrecovered elongation, after subjecting the specimens to numerous washing cycles. Initial findings highlighted a significant increase in the mass per unit area during the first 10 washes, leading to a decrease in weight beyond the 10th washing cycle. This study further identified that changes in the dimensions of the fabric play a more critical role than the loss of fibres, contributing to the increased mass per unit area values. Results showed considerable variances in fabric attributes post-laundering, with notable adjustments in thickness, density, and air permeability. The study underscored a complex interaction between the washing conditions and fabric properties, where certain characteristics, specifically air permeability and the unrecovered elongation, were significantly affected.

Keywords: *recycled cotton, knitted fabrics, repetitive washing, domestic laundering, sustainability*

Impactul spălării repetitive asupra tricoturilor din bumbac reciclat: o analiză completă a proprietăților fizice

Dezvoltarea rapidă a industriei textile a dus la creșterea semnificativă a producției de textile din bumbac și, prin urmare, la creșterea volumului de deșeuri textile. Reciclarea deșeurilor din bumbac apare ca o soluție, oferind posibilitatea de a transforma deșeurile în produse valoroase. În acest sens, durabilitatea materialelor textile din bumbac reciclat în condiții de spălare internă devine esențială pentru asigurarea unor practici textile durabile. Această cercetare a explorat efectele spălării repetitive asupra caracteristicilor fizice ale tricoturilor care conțin bumbac reciclat. Studiul s-a concentrat pe evaluarea modificărilor proprietăților cheie ale materialului textil, cum ar fi masa pe unitatea de suprafață, grosimea, densitatea, permeabilitatea la aer și elasticitatea tricotului, inclusiv alungirea și alungirea nerecuperată, după supunerea probelor la numeroase cicluri de spălare. Constatările inițiale au evidențiat o creștere semnificativă a masei pe unitatea de suprafață în timpul primelor 10 spălări, care a condus ulterior la o scădere a greutății după cel de-al 10-lea ciclu de spălare. Acest studiu a identificat în continuare faptul că modificările dimensiunilor tricotului joacă un rol mai important decât pierderea fibrelor, contribuind la creșterea valorilor masei pe unitatea de suprafață. Rezultatele au arătat variații considerabile ale atributelor tricotului după spălare, cu ajustări notabile ale grosimii, densității și permeabilității la aer. Studiul a evidențiat o interacțiune complexă între condițiile de spălare și proprietățile tricotului, în care anumite caracteristici, în special permeabilitatea la aer și alungirea nerecuperată, au fost afectate semnificativ.

Cuvinte-cheie*: bumbac reciclat, tricoturi, spălare repetitivă, spălare domestică, sustenabilitate*

INTRODUCTION

Clothing, a fundamental human necessity, has been transformed into a disposable product due to today's consumer perception, increased diversity, easy access to more affordable products, business models, etc. Consequently, the rising demand generates millions of tons of textile waste annually. This waste predominantly ends up in landfills, is burned, or is shipped abroad, with only a minimal amount undergoing recycling [1]. Cotton is a vital material in the textile industry and accounts for a significant amount of textile waste because of its comfort qualities [2]. According to projections, by 2030, there will be 148 million tons of textile waste worldwide, of which 35–40% will come from cotton waste [3].

Recycled cotton, with its potential as a prime material for a sustainable industry, can yield a variety of valuable products despite its limitations arising from its natural origins and post-processing challenges like dyeing and blending [3]. Achieving efficient recycling methods for post-consumer waste cotton is crucial to producing consistently high-quality items, reducing waste generation, and mitigating the environmental impact of landfilling and incineration [4]. Additionally, examining the fabric's structure after prolonged use is essential to understand its enduring characteristics.

Textiles, made from diverse fibres and yarns, provide various end-use applications but are significantly influenced by environmental and mechanical factors, including use conditions and maintenance practices like ironing, laundering, and exposure to sunlight [5, 6]. Laundering, critical for maintaining a garment's performance and appearance over time, subjects textiles to tough conditions such as wetting, agitation, heat, chemicals, and pressing. This repeated process alters the physical properties of textiles, leading to deformations, with knitted fabrics particularly susceptible to stretching and mechanical damage that often doesn't fully reverse, highlighting the challenges of everyday use and laundering [5].

Customers expect textiles to retain their shape, size, and performance close to new products after multiple washing cycles, with a growing demand for high-quality fabrics that maintain superior performance through numerous laundering sessions [6, 7]. This expectation is particularly challenging for knitted fabrics, which exhibit more dimensional changes and physical deformations after repeated washes compared to woven materials [8]. Therefore, it is crucial to investigate the performance changes in the tactile, mechanical, comfort, and surface properties of textiles made from recycled fibres due to the effects of repeated washing. This area attracts the attention of researchers aiming to evaluate the long-term performance of garments subjected to repetitive washing.

Studies systematically investigate the impact of principal washing and drying variables on dimensional stability and distortion of knitted fabrics [5]. The determination of the number of laundering cycles needed for knit fabrics to achieve stability, along with the effect of wash water temperature, is thoroughly examined [9], as well as the contribution of fabric characteristics and laundering to the shrinkage of weft knitted fabrics [10]. Research also explores how repetitive washing affects the air permeability of cotton woven fabrics [11] and the comfort characteristics post-laundering [12]. Novotná et al. examined how washing and moisture affect the air-permeability of 100% cotton plain weave fabrics and the impact of different seam types and found that repeated washing significantly impacts air-permeability in both dry and wet states [11]. Midha et al. evaluated air permeability, moisture vapour permeability, moisture management, and drying rate of denim fabrics with cotton, polyester, and lycra cotton weft yarns and the effects of enzyme washing and repeated laundering on these properties [12]. Optimal laundering conditions for minimising shrinkage in cellulose-based fabrics have been explored by Chung and Kim [13]. Studies on the effects of laundering on the dynamic elastic behaviour of fabrics conclude that laundering cycles do not influence the dynamic work recovery (DWR) and stress values of these fabrics [14]. Another research investigated how repeated laundering and dry-cleaning affect the comfort properties of meta-aramid fabrics, finding increased thickness, areal density, thermal resistance, and water vapour resistance but decreased air permeability due to fabric shrinkage and swelling [15]. The impact of washing cycles on the cyclic deformation of elastane-knitted fabrics was investigated. The effect of repeated washing cycles on the residual extension of the fabrics is gradual. It is seen that the fabrics of higher settings show lower residual extension for all washing cycles. The critical washing cycles in this research seem to be 5 and 15 for all test fabrics in the two different test directions [8]. The influence of recycled fibre content and selected variables on fabric performance pre and post-laundering [16] and the impact of laundering variables on microfiber release [17] have been comprehensively analysed. Another study assessed the effects of washing temperature and time on garment colour loss, colour transfer, and microfiber release using retail consumer clothing. Findings suggest that reducing laundry time and temperature could significantly extend garment longevity and reduce dye and microfiber release into the environment while also saving energy [18].

Considering the literature review, there is a research gap in assessing the physical performance of fabrics containing recycled cotton after multiple washing cycles. This study aimed to fill the gap by examining the impact of repetitive washing on the physical characteristics of knitted fabrics containing recycled cotton. The properties examined within the scope of this research were chosen due to their critical impact on the performance and longevity of textiles in daily use. The changes in critical fabric properties, including mass per unit area, fabric thickness, fabric density, air permeability, and stretchability, which include both elongation and unrecovered elongation, were evaluated following specified washing cycles. This study distinguishes itself by specifically examining the impact of repetitive washing on the physical properties of recycled cotton knitted fabrics, an area less explored in existing literature.

METHODOLOGY

Material

In the context of this study, four different single jersey fabrics with varying ratios of recycled cotton content have been selected. Different yarn counts were chosen to examine the impact of yarn variety on fabric properties post-laundering. The fabric compositions, yarn counts and mass per unit area values of the fabrics that constitute the material of the study are given in table 1. The fabrics were subjected to the same

Table 1

THE CHARACTERISTICS OF FABRICS EVALUATED

Fabric code	Fabric composition	Yarn count	Mass per unit area (g/m^2)
F1	100% R-Co	20/1 Ne	188.30
F2	60% Co, 40% R-Co	48/1 Ne	196.30
F3	75% Co, 25% R-Co	30/1 Ne	187.25
F4	80% Co, 20% R-Co	24/1 Ne	201.80

finishing processes: silicone finishing, thermofixing, and sanforisation.

Repetitive washing process

In the study, washing cycles were conducted in sets of 10 repetitions. After every 10 washing cycles, a sample piece was taken out of the wascator, and the washing process continued for the remaining samples until reaching 30 washes. As a result, fabric samples subjected to 10, 20, and 30 repeated washings were obtained. The "ISO 6330:2022 – Textile tests – Washing and drying procedures with a household washing machine" standard was used for the washing processes. The repeated washing processes conducted in the James Hill Wascator FOM71MP washing machine opted for the 4N program simulating daily use (water temperature 40 °C, spin speed 1200 rpm, and washing time of 28 minutes). Reference 3 detergent, as specified in the standard, was added to the washing process in 20 g measurements. After the washing cycles, the samples were laid out on a flat surface (Procedure C) to dry. As stated in the standard for the washing process, Type 1–100% cotton supplementary fabrics were washed together with the test samples to achieve a weight of 2000 g.
As a result of the repetitive washing procedure, in total, 16 samples were obtained, unwashed, and after 10, 20, and 30 washing cycles.

Physical evaluation

The weights of the fabrics (g/m^2) were obtained according to the "TS 251:2019 – Determination of Mass Per Unit Length and Mass Per Unit Area of Woven Fabrics" standard. Afterwards, the weight change was calculated using equation 1 [16] to demonstrate the difference that occurred during washing cycles:

$$\textit{Weight change}\ (\%) = \frac{W_0 - W_x}{W_0} \times 100 \qquad (1)$$

Where W_0 is the initial weight; W_x – weight value after related washing cycle.
In the fabric thickness analysis, the SDL ATLAS M034A model fabric thickness device was used, and tests were performed according to the "ISO 5084: 1996 – Textiles. Determination of thickness of textiles and textile products" standard. The measurements, of course, and wale numbers for fabrics were determined in accordance with the "EN 14971:2006 – Textiles. Knitted fabrics. Determination of the number of stitches per unit of length and unit area". Moreover, the air permeability test was conducted according to the "ISO 9237:1995 – Textiles. Determination of the permeability of fabrics to air" standard on an FX 3300 Air Permeability Tester device, with samples having a measurement area of 5 cm^2 and under a pressure of 100 Pascal. To measure the elasticity of fabrics, the tests were conducted according to the "ISO 20932-1: 2018 – Textiles – Determination of the elasticity of fabrics – Part 1: Strip tests" standard and the elongation values were obtained as percentages in both course and wale direction. The unrecovered elongation tests were performed using the samples of fabric elongation tests. A 50 mm distance was marked on the samples as the initial reference distance before performing the measurement. After the tests, the samples were left for 30 minutes to recover. The distance between the reference marks was then measured, taking the previously determined 50 mm length marks. The unrecovered elongation values were calculated using equation 2 [19]:

$$\textit{Unrecovered elongation}\ (\%) = \frac{Q - P}{P} \times 100 \qquad (2)$$

where C is the unrecovered elongation; P – initial 5 mm reference distance; Q – the subsequent distance between reference marks.
Statistical evaluations were conducted utilising IBM SPSS 20 software. To determine the effects of the washing cycles and fabric types on the examined parameters, namely air permeability, fabric elongation, and unrecovered elongation, independent t-tests were used, while a one-way ANOVA test was utilised to observe the effects of the number of repetitions in repeated washing processes. This independent t-test is used to determine if there is statistical evidence that the means of two independent groups are significantly different, whereas the one-way ANOVA test allows one to determine whether there are any statistically significant differences between the means of three or more independent groups. To investigate both the interaction and individual impacts of each parameter, Univariate tests were utilised. Additionally, to ascertain the significant differences between group means, post-hoc analyses were carried out employing the Duncan test. The Duncan test was utilised in this study to identify statistically significant differences between group means after conducting an ANOVA. All test outcomes were considered at a significance level of 0.05.

RESULTS AND DISCUSSION

In table 2, the mass per unit area and thickness values obtained for the sample fabrics based on the washing procedure were provided.
The change in the weights of fabrics due to washing cycles was calculated in two different ways using equation 1. Figure 1 is a graphical representation of the obtained data. The data given in the graph on the left calculates the change in weight values obtained after every 10 washing cycles based on the unwashed weight value of the fabric. The graph on the right, on the other hand, is derived by calculating the percentage change between the values obtained after every 10 washes to more easily observe the sequential change resulting from the washing cycles. The observation of negative weight loss values in figure 1 indicates an increase in the fabric weights compared to their initial values. Research in the literature showed that varying results were obtained regarding

Table 2

THE WEIGHT AND THICKNESS VALUES OF THE SAMPLES OBTAINED AFTER WASHING CYCLES					
Fabrics	Washing cycles	Mass per unit area (g/m^2)		Fabric thickness (mm)	
		Mean	Std. deviation	Mean	Std. deviation
F1	Unwashed	188.30	6.263	0.204	0.002
	10 cycles	225.30	3.564	0.201	0.006
	20 cycles	217.95	1.095	0.171	0.002
	30 cycles	217.65	2.759	0.226	0.004
F2	Unwashed	196.30	4.052	0.230	0.003
	10 cycles	212.90	8.253	0.231	0.002
	20 cycles	223.80	3.990	0.191	0.003
	30 cycles	206.05	10.872	0.244	0.006
F3	Unwashed	187.25	2.733	0.231	0.002
	10 cycles	201.90	5.064	0.232	0.003
	20 cycles	195.95	4.648	0.196	0.004
	30 cycles	192.65	4.343	0.258	0.003
F4	Unwashed	201.80	3.488	0.236	0.001
	10 cycles	218.45	7.214	0.239	0.005
	20 cycles	218.15	2.993	0.189	0.002
	30 cycles	208.85	8.077	0.253	0.004

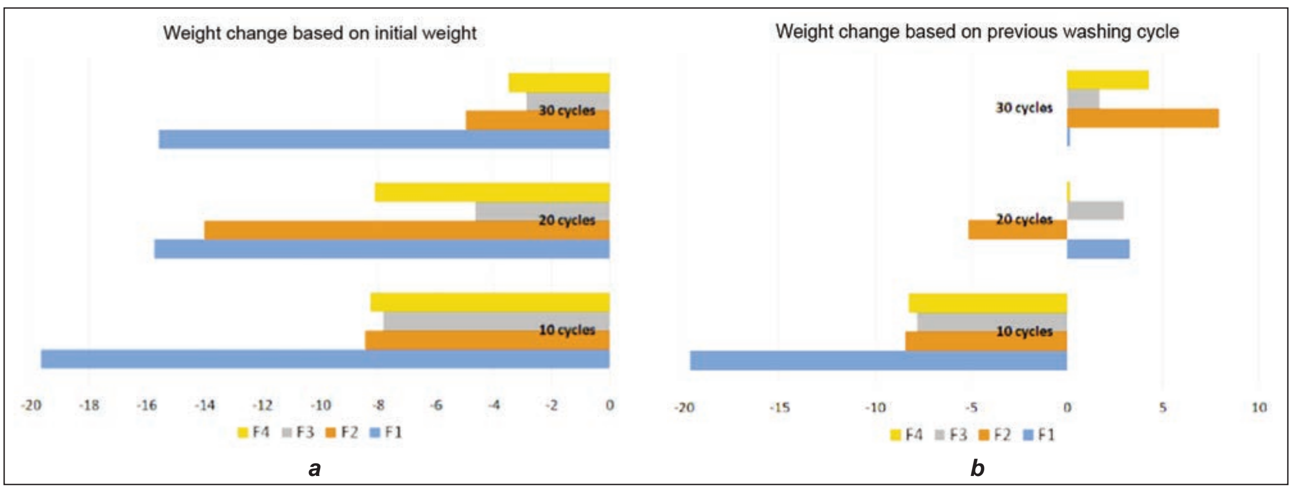

Fig. 1. The change in weight based on: *a* – the initial fabric weight; *b* – weight obtained in the previous washing cycle

this topic. Yılmaz and Keleş observed a decrease in weight change after repetitive washing in single jersey fabrics containing 50% recycled cotton and 50% PES [16]. On the contrary, Rauf et al. found a negative weight change in 100% cotton Single Jersey T-shirts, supporting the results obtained in the presented study [20]. In their 2017 study, Hernandez et al. examined microplastic waste resulting from domestic washing cycles and found that the fibre lengths in the wastewater ranged from 100 to 800 μm [21]. Although microplastics were the focus of their study, it is also evident in our study that the proportion of short fibres increases due to the recycling process of recycled cotton fibres. This increase in short fibres contributes to weight loss during the washing cycle. Statistical evaluation results also support this fact. Both the type of fabric ($p = 0.00$) and the number of washing cycles ($p = 0.00$) had statistically significant impacts on the weight of the fabric. Similarly, both fabric type ($p = 0.00$) and washing cycles ($p = 0.00$) significantly affected the fabric thickness.

In figure 1, *b*, a significant weight increase is observed in the first 10 washing cycles, with the general trend after the 10th wash being a decrease in weight. Particularly in fabrics containing recycled cotton, due to the short lengths of these fibres, a loss of weight due to fibre loss from mechanical effects during washing is expected. However, factors such as the knit type, density, yarn number, etc., especially in single jersey fabrics, significantly affect the dimensional stability. In this study, it was observed that dimensional change had a more significant effect than fibre loss, increasing the mass per unit area values.

Table 3

THE DENSITY VALUES OF SAMPLE FABRICS AS A RESULT OF WASHING CYCLES								
Fabrics / Washing cycles	F1		F2		F3		F4	
	Wale	Course	Wale	Course	Wale	Course	Wale	Course
Unwashed	12	16	16	20	16	21	14	18
10 cycles	13	17	17	21	17	21	15	19
20 cycles	12	16	15	20	16	20	14	19
30 cycles	12	16	15	20	15	20	14	18

Fabric density

The changes in the density values of the fabrics due to the washing procedure are presented in table 3. The densities of fabrics with a single jersey knit structure tend to increase up to an average of 20 washes and then decrease. Supporting these findings, Sülar and Oner indicated in their study that the critical washing cycles were determined to be 5 and 15 across all test directions [8]. It was observed that the density values of the sample fabrics used in the study also show a similar trend. The F1 fabric, which is produced from thicker yarns and contains 100% R-Co, did not show a significant change in density values due to the washing procedure compared to other samples. In line with the given literature, an increase in the row value was only observed after the 10th wash.

In addition, Anand et al. conducted cyclic washing tests using plain weaved fabric and reported that the maximum shrinkage occurred after the first washing cycle, with no significant changes observed in dimensional stability in subsequent washes [5]. The results of the present research showed a similar trend with literature, as fabric density values showed an increase after the 10th washing cycle. Regarding statistical evaluations, both fabric type (p = 0.00) and washing cycles (p = 0.00) had statistically significant effects on fabric density in both the wale and course directions.

Air permeability

Figure 2 presents a graphical representation of the air permeability values of sample fabrics after washing cycles. Upon examining the changes in fabrics due to washing cycles, it has been observed that up to the 20th wash, the fabrics' density values (table 3) increased, resulting in a decrease in air permeability values compared to the initial condition.

To determine the effect of the washing process on the air permeability values of fabrics containing recycled cotton, the air permeability values of unwashed and washed fabrics were compared, and according to the results of the independent t-test conducted, it has been determined that the washing process affects air permeability (t-value = 2.698; p = 0.05). The literature supports these findings as well. Chen-Yu et al. found that repetitive washing significantly reduces the air permeability of cotton specimens [22].

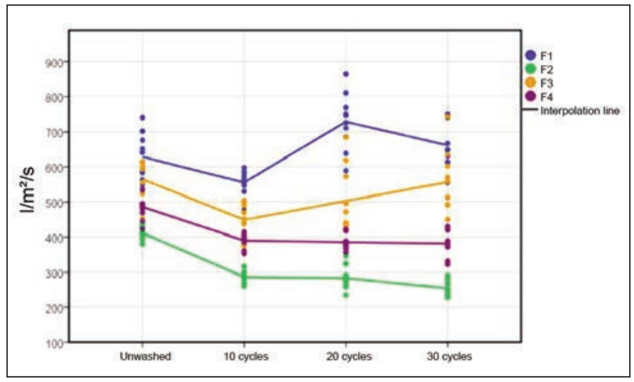

Fig. 2. Scatter diagram related to the air permeability values of fabrics considering washing cycles

Afterwards, the univariate analysis was performed to determine the impact of fabric type and washing cycles, as well as their interaction, on air permeability values. As indicated in table 4, both fabric type (p = 0.00) and washing cycles (p = 0.00) demonstrated statistically significant effects. Moreover, the interaction of these factors also exhibited a significant influence, which could potentially be due to the dominant characteristics of each parameter.

Table 4

THE UNIVARIATE ANALYSIS RESULTS FOR AIR PERMEABILITY			
Source	F	Sig.	Observed power
Fabric type	312.919	0.00	1
Washing cycle	26.956	0.00	1
Fabric type * Washing cycle	10.617	0.00	1

The results obtained by the Duncan tests are presented in table 5. Considering the effect of washing cycles on air permeability values, three subsets occurred. As stated above, during the washing cycles, shrinkage of the fabric structure was observed up to 20 washes, and as a result, the lowest air permeability values were obtained after the 10th wash, forming subset 1. The air permeability values for 20 and 30 washes, forming subset 2, showed less permeability compared to the unwashed fabrics' air permeability values. This situation is thought to be

Table 5

DUNCAN TEST RESULTS FOR AIR PERMEABILITY				
Washing cycles	N	Subsets ($\alpha = 0.05$)		
		1	2	3
10 cycles	40	420.08		
30 cycles	40		463.43	
20 cycles	40		475.08	
Unwashed	40			522.75
Sig.		1.000	0.313	1.000

not only due to the observed effect on the fabric structure but also possibly due to the use of recycled cotton, which increases the proportion of short fibres in the yarn and the ends of these fibres that block air passage.

Fabric elongation and unrecovered elongation

In figure 3, the dual axis graphs show the values of fabric elongation and unrecovered elongation values of each fabric for both course and wale directions.

Upon examining the fabric elasticity values obtained after repetitive washing tests, a significant increase in the fabric elongation values of the fabric samples was observed after the first 10 washes. This situation, as indicated by Sülar and Oner, suggests that the increase in fabric shrinkage values during the first 10 washing cycles leads to an increase in fabric elasticity [8]. However, after the 20^{th} washing cycle, a decrease in fabric elasticity values was observed due to the release observed in the fabrics. Regarding unrecovered elongation values, the fabrics coded F1 and F4, having higher fabric thickness, displayed a different trend in permanent elongation values compared to the fabrics coded F2 and F3. Senthilkumar and Anbumani found that the laundering effect does not influence the recovery of cotton/spandex knitted fabrics [14]. In our study, however, the fabrics did not contain elastane, leading to unrecovered elongation due to repetitive washing. This indicates that the presence of elastane reduces the effect of permanent elongation.

The difference in elasticity and unrecovered elongation values between fabrics subjected to repetitive washings and unwashed fabrics was evaluated using the Independent samples t-test. According to the results obtained, it was determined that washing affected the elasticity properties in both directions (course: $p = 0.00$; wale: $p = 0.00$). It was found that the effect of the washing process on unrecovered elongation values was only in the wale direction of the fabric ($p = 0.00$), while it had no effect in the course direction ($p = 0.270$).

The results of the univariate analysis are presented in table 6. Upon examining the results, it was determined that the washing cycles had no statistically significant effect on the unrecovered elongation values measured along the course of the fabrics ($p = 0.38$). Similarly, it was observed that the interaction between fabric type and washing cycle also had an insignificant impact.

Table 7 represents the values obtained from the Duncan tests applied to the fabric elongation data. It was observed that three subsets have formed in the direction of the courses and four subsets in the direction of the wales. The repetitive washing's effect of increasing density on single jersey fabrics has resulted in higher fabric elasticity in both the course and wale directions compared to unwashed samples. Upon examining table 7, it is noted that the unwashed samples form subset 1 in both directions.

In table 8, the results of the Duncan test applied to the unrecovered elongation data are presented. It was observed that in the course direction, two subsets were formed, while in the wale direction, three subsets were formed. This situation was also observed in the results of the post-hoc tests conducted to determine the effect of each washing cycle on

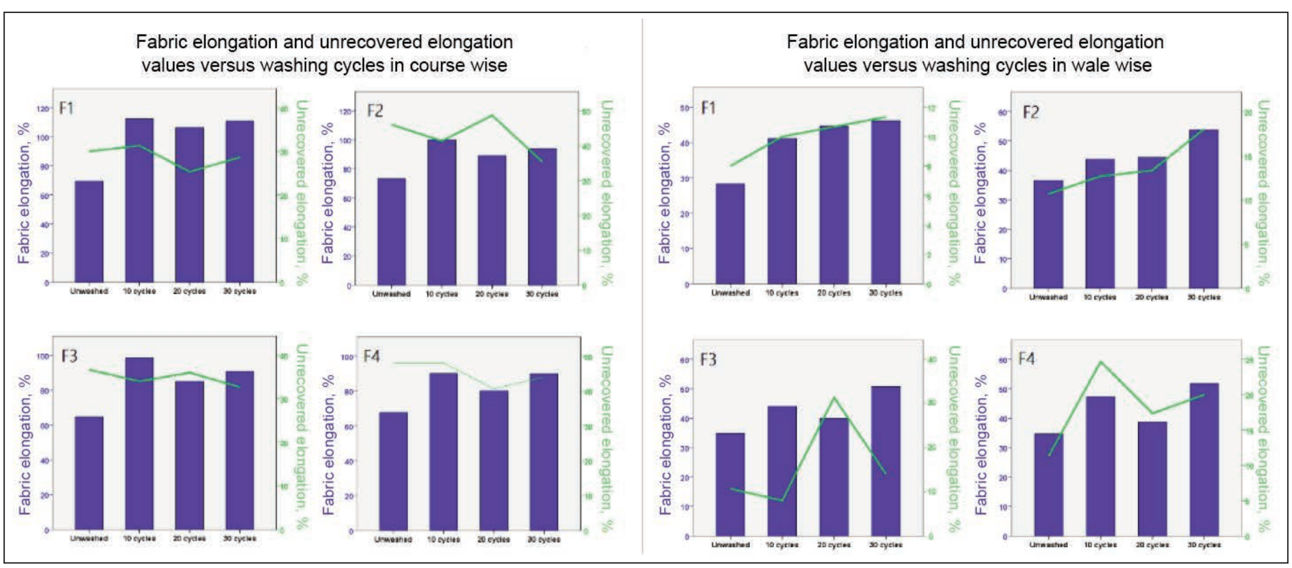

Fig. 3. Fabric and unrecovered elongation values versus washing cycles in course and wale-wise

Table 6

THE UNIVARIATE ANALYSIS RESULTS FOR FABRIC ELONGATION AND UNRECOVERED ELONGATION					
Elongation		**Source**	**F**	**Sig.**	**Observed power**
Fabric elongation	Course wise	Fabric type	55.547	0.00	1
		Washing cycle	178.788	0.00	1
		Fabric type * Washing cycle	5.903	0.00	0.999
	Wale wise	Fabric type	9.376	0.00	0.993
		Washing cycle	125.420	0.00	1
		Fabric type * Washing cycle	5.329	0.00	0.997
Unrecovered elongation	Course wise	Fabric type	40.299	0.00	1
		Washing cycle	3.164	0.38	0.678
		Fabric type * Washing cycle	2.333	0.38	0.822
	Wale wise	Fabric type	17.157	0.00	1
		Washing cycle	15.597	0.00	1
		Fabric type * Washing cycle	12.143	0.00	1

Table 7

DUNCAN TEST RESULTS FOR FABRIC ELONGATION											
Course wise						**Wale wise**					
Washing cycles	**N**	**Subsets (α = 0.05)**				**Washing cycles**	**N**	**Subsets (α = 0.05)**			
		1	**2**	**3**	**4**			**1**	**2**	**3**	**4**
30 cycles	12	68.766			-	30 cycles	12	33.623			
20 cycles	12		90.144		-	20 cycles	12		41.942		
10 cycles	12			96.436	-	10 cycles	12			44.105	
Unwashed	12			100.233	-	Unwashed	12				50.630
	Sig.	1.000	1.000	0.070	-		Sig.	1.000	1.000	1.000	1.000

the elasticity values of the fabrics in the course and wale directions. The differences in elasticity values in the course direction among the fabrics were generally found to be insignificant, with the only significant difference found between the unwashed samples and those subjected to 30 cycles ($p = 0.026$). In the wale direction, however, the differences between washing cycles were significant, with the difference between 10 cycles and 30 cycles ($p = 0.367$) and between 20 cycles and 30 cycles ($p = 0.239$) found to be insignificant.

CONCLUSIONS

The study was performed to evaluate the impact of repetitive washing on recycled cotton fabrics, highlighting the durability of these materials. The study highlights the significant impact of repetitive washing on various physical properties of recycled cotton knitted fabrics. Key findings include changes in mass per unit area, thickness, fabric density, and air permeability. The study underscores the complex interaction between washing conditions and fabric properties, emphasising the importance of understanding

Table 8

DUNCAN TEST RESULTS FOR UNRECOVERED ELONGATION									
Course wise					**Wale wise**				
Washing cycles	**N**	**Subsets (α = 0.05)**			**Washing cycles**	**N**	**Subsets (α = 0.05)**		
		1	**2**	**3**			**1**	**2**	**3**
30 cycles	12	35.167		-	30 cycles	12	10.167		
20 cycles	12	37.667	37.667	-	20 cycles	12		13.833	
10 cycles	12	38.667	38.667	-	10 cycles	12		15.833	15.833
Unwashed	12		40.1667	-	Unwashed	12			18.167
	Sig.	0.055	0.167	-		Sig.	1.000	0.109	0.063

these dynamics for the development of sustainable textile products.

Despite challenges from varied washing cycles and the origin of recycled cotton, the investigated fabrics demonstrated certain alterations observed in air permeability and unrecovered elongation. Considering the repetitive washing post-laundering, the fabrics display significant variations in key attributes, including thickness, density, and air permeability. The mass per unit area values during the initial 10 wash cycles were increased, which then transitioned to a reduction in weight after the 10th cycle. The research points out that dimensional changes in the fabric are more influential than fibre loss in contributing to the initial increase in mass per unit area. The study also utilised different yarn counts to examine the impact of yarn variety on fabric properties post-laundering. The findings indicate that yarn composition significantly affects the durability and performance of recycled cotton knitted fabrics under repetitive washing conditions.

Factors such as the type of fabric softener, the detergent used, the type and technology of the washing machine, the ratio of load capacity utilised, and the composition of the water significantly influence the characteristics of fabrics after laundering. The characteristics examined in this study were selected due to their critical impact on the performance and longevity of textiles in daily use. Other properties, such as tactile comfort, were not included due to the scope and limitations of the available data. Future research should focus on determining the more comprehensive comfort and mechanical performance characteristics of fabrics containing recycled cotton. Ultimately, this research contributes valuable insights into the sustainable development of the textile industry, promoting the efficient use of recycled materials and encouraging practices that extend the lifespan of textile products.

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Advances in diabetic footwear and plantar pressure distribution devices: literature review on design, efficacy, and patient outcomes

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ABSTRACT – REZUMAT

Advances in diabetic footwear and plantar pressure distribution devices: literature review on design, efficacy, and patient outcomes

This literature review aims to explore the significance of diabetic footwear in managing foot-related complications associated with diabetes, especially related to diabetic neuropathy, peripheral arterial disease, and ulcerations. The goal is to synthesise key research on the design, efficacy, and impact of diabetic footwear in preventing foot ulcers, reducing pressure, and promoting healing. The review highlights recent advancements in diabetic footwear technology, including innovations such as smart sensors and other industry 4.0 advancements, while also addressing the barriers to patient compliance and the challenges in evaluating long-term outcomes. Special considerations are addressed to publications and authors in the field of diabetic research as their continuous impact drives knowledge forward and provides relevant data in improving patients' quality of life. Findings show that diabetic footwear plays a critical role in preventing foot complications, but further research is needed to standardise footwear designs and assess long-term benefits.

Keywords: *diabetic footwear, neuropathy, diabetic foot, ulcers, plantar pressure offloading, footwear design*

Progrese aduse încălțămintei pentru diabetici și a dispozitivelor de distribuție a presiunilor plantare: analiza literaturii privind designul, eficiența și impactul asupra pacientului

Această trecere în revistă a studiilor recente în domeniul încălțămintei terapeutice pentru pacientul diabetic își propune să exploreze importanța încălțămintei pentru diabetici în gestionarea complicațiilor asociate diabetului la nivelul picioarelor, în special cele legate de neuropatia diabetică, boala arterială periferică și ulcerațiile. Scopul este de a sintetiza cercetările cheie privind designul, eficiența și impactul încălțămintei pentru diabetici în prevenirea ulcerației piciorului, reducerea presiunii plantare și promovarea vindecării. Analiza evidențiază progresele recente în dezvoltarea încălțămintei pentru diabetici, inclusiv inovații precum introducerea senzorilor inteligenți și alte progrese ale industriei 4.0, abordând totodată barierele în calea asimilării de către pacienți a acestui tip de încălțăminte si provocările în evaluarea rezultatelor pe termen lung. Considerații speciale sunt adresate publicațiilor și autorilor din domeniul cercetării diabetului, deoarece impactul lor continuu dezvoltă cunoștințele și oferă date relevante pentru îmbunătățirea calității vieții pacienților. Constatările arată că încălțămintea pentru diabetici joacă un rol critic în prevenirea complicațiilor piciorului diabetic, dar sunt necesare cercetări suplimentare pentru a standardiza modelele de încălțăminte și pentru a evalua beneficiile pe termen lung.

Cuvinte-cheie: *încălțăminte pentru diabetici, neuropatie, picior diabetic, ulcere, descărcare de presiune plantară, design și proiectare încălțăminte*

Introduction

Diabetes is a long-term condition affecting millions worldwide, often resulting in serious complications, particularly in the lower limbs. Among these, diabetic foot complications, such as neuropathic ulcers, represent a major challenge in diabetes management. These issues frequently lead to significant morbidity and an increased risk of limb amputation. Common conditions associated with diabetes include neuropathy, peripheral arterial disease, and the development of foot ulcers. Diabetic foot ulcers, which affect up to 25% of individuals with diabetes at some point in their lives, remain a critical concern due to their contribution to the high incidence of lower limb amputations. To prevent and manage these complications, appropriate footwear and plantar pressure-relieving devices are essential in minimising strain during walking [1–5]. With a current estimate of over 300 million individuals impacted globally, projections suggest that this alarming figure could potentially double by the year 2030, thereby significantly elevating the occurrence and severity of amputations linked to advanced and untreated foot ulcers.

This literature review explores recent research on diabetic footwear and advancements in plantar devices by providing valuable insight into a variety of biomechanical and neurological disorders. It assesses the effectiveness of these innovations in reducing plantar pressure, preventing ulcerations, and enhancing mobility for individuals with diabetes-related lower limb issues. By reviewing the latest studies, the objective is to highlight current healthcare practices and guide future advancements in the design and prescription of diabetic footwear. The findings emphasise the overall success of modern therapeutic footwear technologies for diabetic patients with various foot deformities. Additionally, extensive clinical trials have shown significant improvements in muscle tone supporting the arches, enhanced trophic nutrition in the feet, and a more balanced foot-loading structure [6–12]. All of these factors contribute positively to the functional capabilities of the footwear and, consequently, to the well-being of diabetic patients. According to recent studies, the use of custom plantar devices has been shown to reduce the risk of foot ulcers by up to 85%, and the recurrence rate of ulcers can drop by 50% when appropriate footwear is used in combination with other preventative measures. Additionally, patient satisfaction with adapted footwear devices is high, with over 90% reporting improved comfort and mobility. The advancements in this area represent a significant step forward in improving the quality of life for individuals suffering from diabetic foot conditions, ensuring better mobility and reduced complications arising from improper footwear [13–27].

To guide readers effectively, the paper is structured as follows:

Introduction

- Overview of the prevalence and challenges of diabetic foot complications, the significance of diabetic footwear, and the objectives of the manuscript.

Methodology

- Description of the literature search strategy and inclusion criteria.

Specific demands on the diabetic foot

- Analysis of the clinical and biomechanical challenges posed by diabetes on foot health.

Structural analysis of diabetic footwear

- Evaluation of footwear design innovations, material performance, and the role of advanced technologies in addressing diabetic foot complications

Customised Smart footwear solutions

- Exploration of intelligent footwear designs incorporating adaptive technologies to optimise therapeutic outcomes

Contributions to the literature review

- Summary of key advancements and their implications for future research and clinical applications.

METHODOLOGY: LITERATURE SEARCH STRATEGY

The literature search used reputable databases such as Web of Science, PubMed, Scopus, and Google Scholar. The primary focus was on key terms related to diabetic footwear and innovations while also including diabetes-related foot complications and the overall quality of life for affected individuals. Key search terms included "diabetic footwear", "neuropathy", "foot ulcers", "pressure offloading", "diabetic foot care" and "footwear design". This strategy was designed to gather a broad and comprehensive selection of studies examining diabetic footwear and its effectiveness in preventing foot-related complications.

Over 60 relevant articles and conference papers were identified across scientific databases, confirming the significance of diabetic footwear as a topic of interest in numerous studies and research groups. However, not all articles were included in this review. The inclusion criteria were limited to peer-reviewed studies published within the past five years, with a focus on clinical trials, meta-analyses, and systematic reviews. Only research that specifically addressed foot complications and the role of diabetic footwear was retained, resulting in 45 peer-reviewed articles. Studies that were not peer-reviewed or unavailable in English were excluded. Additionally, a selection process considered the impact factor and citation count of the relevant papers (figure 1).

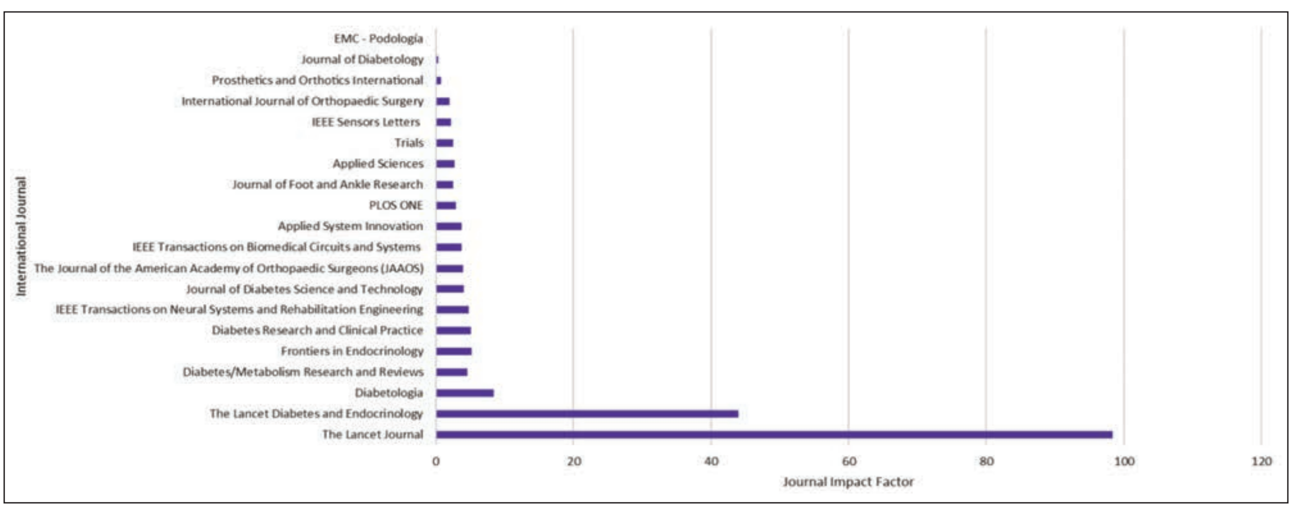

Fig. 1. Impact factor for journals and online publications in the field of diabetic footwear

SPECIFIC DEMANDS ON THE DIABETIC FOOT

According to analysis and projections of the general impact of diabetic foot complications, these represent a formidable challenge in the holistic management of diabetes, imposing substantial health burdens and economic strains on patients and healthcare systems alike [15]. Diabetes mellitus encompasses a range of conditions that predispose individuals to foot ulcerations and potential limb loss. The pathophysiology is further complicated by vascular and neuropathic damage, present in both type 1 and type 2 diabetes, which significantly increases the risk of severe complications such as infections and, in advanced cases, amputations. Chronic hyperglycemia, along with factors like excessive pressure and thermal dysregulation at the skin interface, exacerbates these risks. The combination of poor circulation and impaired wound healing is a critical factor in the development of diabetic foot complications. Vascular insufficiency not only hinders the body's natural healing processes but also significantly increases the risk of deep infections, necrosis, and osteomyelitis. As a result, foot ulcerations become dangerous entry points for infections, heightening the risk of a cascade of severe outcomes [28–31].

Peripheral vascular disease in individuals with diabetes presents a challenging scenario characterised by reduced blood flow and subsequent risk of numerous complications. This vascular insufficiency, coupled with neuropathic changes in the extremities, creates a vulnerable condition for those affected. The development of ischemic conditions, further complicated by the unique anatomical structure of the foot, underscores the urgent need for targeted interventions. Notably, strategies such as compression therapy, advanced wound care techniques, and the use of specialised therapeutic footwear aim to improve circulation and reduce the risk of lesion formation [28, 31]. Both clinicians and patients must recognise that impaired vascular health may necessitate changes in mobility strategies to help maintain functional activity while protecting the locomotor system. This highlights the importance of regular vascular assessments, as even in the presence of neuropathy, poor blood flow can lead to severe ischemic events if not properly managed. Thus, a comprehensive and proactive approach to evaluating vascular health is essential for effectively managing diabetic foot complications [32–37].

Peripheral artery disease (PAD), often a consequence of atherosclerosis, poses a significant challenge in diabetic foot care due to its impact on circulation in the lower limbs. As arterial plaque builds up, blood flow becomes restricted, depriving tissues of vital nutrients – a critical issue for individuals at risk of diabetic foot ulcers. The gradual progression of atherosclerosis often goes unnoticed, but in severe cases of PAD, patients may experience debilitating foot pain or ulceration due to ischemia. To reduce the risk of diabetic foot ulcers, patients must maintain strict glycaemic control and eliminate smoking, both of which contribute to vascular damage. Preventive strategies should focus on those at high clinical risk, emphasising the incorporation of functional foot orthoses into treatment plans. These measures aim to enhance circulation and alleviate pressure on vulnerable areas of the foot, reducing the likelihood of ulcer formation [34–40]. Orthotic interventions designed to align the foot with the specific geometry of a patient's footwear promote an even distribution of plantar pressure. This biomechanical adjustment not only enhances propulsion dynamics but also reduces excessive forces that could otherwise jeopardise sensitive areas of the diabetic foot.

Additionally, specialised footwear aims to minimise high-impact stress, ensuring that energy generated during the push-off phase is efficiently transferred to the ground rather than absorbed by the foot. Given that diabetes-related foot infections are a leading cause of hospitalisation among this population, concerns arise regarding the adequacy of educational efforts aimed at informing high-risk individuals about the importance of foot protection and preventive care strategies. The high prevalence of ulcer formation in diabetic patients underscores the need for greater awareness and proactive management to prevent these complications [41, 42].

The formation of ulcers within the diabetic population represents a significant challenge, characterised by a notably high prevalence of foot ulceration, estimated to be between 15 and 25% over a lifetime in diabetic communities. This statistic is particularly significant when considered in the context of the broader landscape of diabetes prevalence in Europe and beyond, revealing a substantial overall number of individuals affected [1, 43]. When examining the multifaceted factors contributing to foot ulceration in diabetic patients, it becomes clear that the condition results from a complex interplay of influences. The relationship between cause and effect is rarely simple. For instance, abnormal foot pressures, often stemming from reduced pain sensation, can lead to altered gait patterns. Sensory neuropathy, particularly the loss of protective sensation, has long been recognised as a major factor in the development of foot ulcers. Current understanding suggests that the formation of plantar foot ulcers arises from the interaction of various factors, with elevated plantar pressure being a significant contributor. The diabetic foot exemplifies this intricate interplay, where diabetes directly impacts both the microvascular and macrovascular systems. The duration of diabetes further amplifies these effects. The range of contributing issues includes peripheral neuropathy, autonomic dysfunction, peripheral arterial disease, foot deformities, poorly fitting footwear, fragile and dry skin, reduced transcutaneous oxygen levels, a history of previous foot ulcers, and the presence of structural deformities such as hammer toes. This complex combination of factors highlights the need for comprehensive management strategies to prevent the onset of foot ulcers in diabetic patients [44–47].

STRUCTURAL ANALYSIS OF DIABETIC FOOTWEAR

The design of footwear for individuals with diabetes represents a crucial interdisciplinary field of study situated at the intersection of healthcare and innovation. To gain a comprehensive understanding of this field, it is essential to go through a thorough examination of relevant patents and empirical studies, as well as relevant articles. Authors like Bus et al. [2, 6] and Hemler et al. [48] have investigated the multifaceted considerations that shape the creation of functional footwear tailored for individuals with diabetes, as interpreted by medical professionals, industry stakeholders, and design experts. The findings highlight the numerous factors that influence the design, manufacturing, and distribution of these products. A conceptual framework is proposed in their work, illustrating the evolving recognition of the diabetic consumer segment, which begins with personalised clinical solutions, progresses through adaptive manufacturing techniques, and ultimately encompasses prospective diagnostic advancements and cutting-edge technological innovations [49–52].

However, despite the advancements in therapeutic footwear, significant challenges persist in the applied design and design of diabetic footwear and plantar pressure relief devices. The study by Tiwari et al. [53] elucidates the intricacies of diabetic neuropathy and its ramifications for foot biomechanics and plantar pressure distribution innovations. The heterogeneous nature of diabetic neuropathy complicates the standardisation of interventions and makes it difficult to predict outcomes reliably. This underscores the importance of a personalised approach to diabetic foot care involving a multidisciplinary team that includes podiatrists, orthotic specialists, technicians, and other relevant healthcare professionals.

Additionally, patient non-compliance with prescribed footwear devices and inserts, which are designed to correct and relieve plantar pressures, poses a significant challenge. Many patients seek immediate results and struggle to adapt to these devices long-term, limiting the potential therapeutic benefits. Addressing this issue requires not only tailoring interventions but also enhancing patient education and support to improve adherence and ensure sustained outcomes [54–56].

Given these challenges, proposals have emerged for the development of intelligent footwear solutions that can manage plantar pressures on an individualised basis. Traditional load-relieving orthotics often lack the flexibility to adapt to dynamically changing plantar pressure patterns, which vary depending on factors like gait speed, foot contact surface, and body support surface. This limitation highlights the need for smart footwear capable of adjusting in real time to the varying demands of different gait stages. Such adaptive footwear could provide more effective pressure relief, enhancing both comfort and therapeutic outcomes for diabetic patients [48, 53, 57–60].

Performance of insole materials for diabetic footwear

A consensus has been reached among podiatric specialists engaged in the study and analysis of treatment conditions associated with diabetic neuropathy and foot ulceration. The consensus pertains to strategies for addressing footwear solutions. The primary objective is to reduce maximum plantar pressures to mitigate the risk of diabetic foot ulcerations or to facilitate the healing and prevention of existing ulcerations. As it is noted in studies by authors such as Haris et al. [60], the impact of factors such as changes in walking speed and changes in the materials used in the manufacture of shoe uppers on plantar pressures is significant. The authors determined that slower walking speeds (approximately 4 km/h) are more suitable for individuals with complications of diabetes mellitus. Ethylene vinyl acetate (EVA) gill material was the most commonly used, and it was also the most effective in reducing maximum plantar pressures in the forefoot area. Moreover, customised multi-density gills comprising multiple densities, softer materials in the hindfoot (EVA), augmented support for the longitudinal arch of the foot, and shock-absorbing support in the metatarsal area demonstrated favourable outcomes in reducing plantar pressures and preventing ulcer recurrence, as evidenced in research by Ahmed et al. and Hemler et al. [13, 48, 61]. In the reviewed literature, it is emphasised that regardless of the route chosen to reduce foot pressures, it is essential to consider patient comfort, the patient's ability to adhere to specialist recommendations, and individual foot characteristics when selecting insole and ankle materials designed to optimise therapeutic benefits.

Papers presented at Conferences in the field of advanced medical and therapeutical footwear such as International Conference on Computer, Control and Robotics (ICCCR) [62], IEEE International Biomedical Instrumentation and Technology Conference (IBITeC) [63], International Conference on Applied Smart Systems (ICASS) [64] and 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO) [65] have presented a hard focus on insole design and construction highlighting the increased significance of footwear components in the overall product.

CUSTOMISED SMART FOOTWEAR SOLUTIONS

In current articles in the field of diabetic footwear, many researchers have directed their attention to smart and intelligent technologies, integrating industry 4.0 concepts, making footwear advancements that will turn the products easy to accept and integrate into daily life by their prospective users. In their 2023 paper, Hemler et al. [48] introduce a novel approach to diabetic foot care: the development of smart footwear designed to relieve plantar pressures during walking. This innovative technology employs the integration of sensors within the modular footwear's modular insole, facilitating real-time monitoring and adjustment of plantar pressure distribution. This optimises the therapeutic efficacy and patient comfort.

The incorporation of self-adjusting soles and insoles, along with adaptive design features, represents a significant advancement in the preventive care of diabetic feet affected by neuropathy. These innovative footwear designs continuously redistribute plantar pressure, shifting the load from the forefoot and midfoot regions to the posterior heel area. Early evaluations have shown promising results in terms of both pressure relief effectiveness and positive user feedback. However, further research is necessary to evaluate the long-term efficacy, durability, and cost-effectiveness of these smart footwear solutions in real-world clinical settings to determine their viability as a standard intervention.

Ahmed Sayed, in collaboration with numerous other researchers, is another of the most prolific authors in the field of diabetic footwear. His articles offer valuable insights into the design characteristics and efficacy of customised insoles for diabetic patients, as well as footwear design features that can reduce the risk of neuropathic foot ulceration. One of the studies conducted [13] emphasises the importance of individualised footwear and insole design features that are specifically tailored to each individual user. This is a crucial aspect to be considered to address specific foot pathologies and various biomechanical abnormalities. The use of customised insoles made from multi-density materials, soft protective cushions in the metatarsophalangeal area and rocker sole footwear designs has been demonstrated to result in significant reductions in plantar pressure and diabetic foot ulcer recurrence rates. However, the technological process is a challenging one, as there is a lack of standardisation in footwear dimensions, and issues such as variability in design parameters and patient adherence to wearing recommendations must be addressed to optimise treatment outcomes. The author also entered into the area of AI-supported technologies. The design principles suggested are universal and address the practical challenges faced by practitioners in creating personalised footwear and insoles for individuals at moderate to high risk of plantar forefoot ulceration. These principles include guidelines for designing and modifying both fully custom-made and prefabricated medical-grade footwear (Pedorthic footwear). Additionally, they emphasise tailoring modifications to ensure affordability, suit specific activities, and improve patient adherence [66].

Other relevant studies refer to authors such as Wang et al., who investigated the efficacy of wearable sensor systems to monitor plantar loading in the assessment of diabetic foot ulcers. The objective was to give readers a comprehensive overview of recent advancements in plantar pressure and stress sensing while also highlighting future needs in this important area of healthcare [67].

According to the research of D'Amico et al. and Deselnicu et al., the CAD-CAM approach delivers superior offloading performance compared to traditional shape-based methods of insole construction. The method enables comprehensive analysis of the entire plantar surface without relying on predetermined anatomical masking. It allows for a detailed evaluation of how and where custom-made insoles redistribute underfoot pressure about the Foot Impression, making the technology particularly valuable in the design phase, guiding modifications needed to optimise insole offloading performance [68, 69].

CONTRIBUTIONS TO THE LITERATURE REVIEW

This paper has focused on work published since 2019. Several papers have continued to contribute to research on diabetic footwear, focusing on improving the design, off-loading techniques and patient adherence. Notable articles and reference works that reflect the principles of continuous improvement in the design and features of diabetic patient footwear are listed below in table 1.

Table 1

LIST OF RELEVANT ARTICLES CONSIDERED FOR THE REVIEW

Reference	Journal	Article	Publication Year	Journal Impact Factor	Article Citations
Hellstrand et al. [14]	Prosthetics and Orthotics International	Clinical guidelines recommending prosthetics and orthotics in Sweden: Agreement between national and regional guidelines	2024	0.8	*Data not available*
Tiwari et al. [53]	Applied System Innovation	A Tunable Self-Offloading Module for Plantar Pressure Regulation in Diabetic Patients	2024	3.8	1
Thimabut et al. [10]	IEEE Transactions on Neural Systems and Rehabilitation Engineering	Novel Vibrating Foot Orthoses for Improving Tactile Sensation in Type 2 Diabetes with Peripheral Neuropathy	2024	4.8	*Data not available*
Ramstrand et al. [70]	Journal of Foot and Ankle Research	Exploring potential risk factors for lower limb amputation in people with diabetes – A national observational cohort study in Sweden	2024	2.5	*Data not available*

Table 1 (continuation)

Reference	Journal	Article	Publication Year	Journal Impact Factor	Article Citations
Kim et al. [71]	Journal of Foot and Ankle Research	The effect of ankle-foot orthoses on gait characteristics in people with Charcot-Marie-Footh disease: A systematic review and meta-analysis	2024	2.5	*Data not available*
Jeffcoate et al. [28]	The Lancet Diabetes and Endocrinology	Causes, prevention, and management of diabetes-related foot ulcers	2024	44	3
Tiwari et al. [72]	IEEE Sensors Letters	A Polyester–Nylon Blend Plantar Pressure Sensing Insole for Person with Diabetes	2024	2.2	*Data not available*
Ahmed et al. [66]	arXiv	AI-Driven Personalised Offloading Device Prescriptions: A Cutting-Edge Approach to Preventing Diabetes-Related Plantar Forefoot Ulcers and Complications	2023	*Data not available*	*Data not available*
Bus et al. [33]	Diabetes/Metabolism Research and Reviews	Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2023 update)	2023	4.6	26
Hemler et al. [48]	Frontiers in Endocrinology	Intelligent plantar pressure offloading for the prevention of diabetic foot ulcers and amputations	2023	5.2	6
Paavana et al. [73]	International Journal of Orthopaedic Surgery	Diabetic foot: Footwear in a management programme	2023	2.05	*Data not available*
Withers et al. [74]	Journal of Foot and Ankle Research	Offloading effects of a removable cast walker with and without modification for diabetes-related foot ulceration: a plantar pressure study	2023	2.5	5
López-Moral et al. [75]	The International Journal of Lower Extremity Wounds	Usability of Different Methods to Assess and Improve Adherence to Therapeutic Footwear in Persons with the Diabetic Foot in Remission. A Systematic Review	2023	1.5	1
An et al. [76]	The Journal of the American Academy of Orthopaedic Surgeons (JAAOS)	Orthotic Devices for the Foot and Ankle	2023	4	2
Ong et al. [15]	The Lancet Journal	Global, regional, and national burden of diabetes from 1990 to 2021, with projections of prevalence to 2050: a systematic analysis for the Global Burden of Disease Study 2021	2023	98.4	493
Barbara and Horton [77]	Canadian Journal of Health Technologies	Custom-Made Foot Orthotics for People with Lower Limb Conditions: CADTH Health Technology Review	2022	*Data not available*	*Data not available*
Jarl et al. [78]	Journal of Diabetes Science and Technology	Personalized Offloading Treatments for Healing Plantar Diabetic Foot Ulcers	2022	4.1	6
Ntella et al. [79]	25th International Conference on Electrical Machines and Systems (ICEMS)	Pressure Offloading Device for Diabetic Footwear Based on Magnetorheological Fluids	2022	*Data not available*	1
Chertenko et al. [17]	Communications in Development and Assembling of Textile Products	Developing lasts with removable toe parts for customized footwear	2022	*Data not available*	*Data not available*
López-Moral et al. [80]	Diabetes Research and Clinical Practice	Effects of wear and tear of therapeutic footwear in patients remission. A 5-year follow-up study	2022	5.1	6
Gonggryp et al. [81]	EMC – Podología	Tratamiento podológico del pie diabético	2022	0.042	*Data not available*

Table 1 (continuation)

Reference	Journal	Article	Publication Year	Journal Impact Factor	Article Citations
McDonogh et al. [82]	Journal of Foot and Ankle Research	Does in-shoe pressure analysis to assess and modify medical grade footwear improve patient adherence and understanding? A mixed methods study	2022	2.5	3
Ahmed et al. [13]	Trials	Footwear and insole design parameters to prevent occurrence and recurrence of neuropathic plantar forefoot ulcers in patients with diabetes: a series of N-of-1 trial study protocol	2022	2.5	1
Iacopi et al. [83]	The International Journal of Lower Extremity Wounds	The Weakness of the Strong Sex: Differences Between Men and Women Affected by Diabetic Foot Disease	2021	1.5	*Data not available*
Pradipta et al. [63]	IEEE International Biomedical Instrumentation and Technology Conference (IBITeC)	Optimization of Insole Shoe for Diabetic Mellitus Type 2 Using Finite Element Analysis	2021	*Data not available*	2
Chen et al. [62]	International Conference on Computer, Control and Robotics (ICCCR)	A Novel Porous Structural Design of the Orthotic Insole for Diabetic Foot	2021	*Data not available*	2
Haris et al. [60]	Applied Sciences	A Review of the Plantar Pressure Distribution Effects from Insole Materials and at Different Walking Speeds	2021	2.7	13
D'Amico et al. [68]	PLOS ONE	Data-driven CAD-CAM vs traditional total contact custom insoles: A novel quantitative-statistical framework for the evaluation of insoles offloading performance in diabetic foot	2021	2.9	6
Wang et al. [84]	IEEE Transactions on Biomedical Circuits and Systems	A Novel Low-Cost Wireless Footwear System for Monitoring Diabetic Foot Patients	2021	3.8	36
Van Netten et al. [44]	Diabetes/Metabolism Research and Reviews	Definitions and criteria for diabetic foot disease	2020	4.6	206
Lazzarini et al. [85]	Diabetes/Metabolism Research and Reviews	Effectiveness of offloading interventions to heal foot ulcers in persons with diabetes: a systematic review	2020	4.6	72
Monteiro-Soares et al. [86]	Diabetes/Metabolism Research and Reviews	Guidelines on the classification of diabetic foot ulcers (IWGDF 2019)	2020	4.6	145
Bus et al. [13, 41]	Diabetes/Metabolism Research and Reviews	Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2019 update)	2020	4.6	263
Schaper et al. [1]	Diabetes/Metabolism Research and Reviews	Practical Guidelines on the prevention and management of diabetic foot disease (IWGDF 2019 update)	2020	4.6	473
Sinha et al. [87]	Journal of Diabetology	Plantar pressure analysis and customized insoles in diabetic foot ulcer management: Case series	2020	0.4	1
Ahmed et al. [61]	Journal of Foot and Ankle Research	Footwear and insole design features that reduce neuropathic plantar forefoot ulcer risk in people with diabetes: a systematic literature review	2020	2.5	49
Zwaferink et al. [88]	PLOS ONE	Optimizing footwear for the diabetic foot: Data-driven custom-made footwear concepts and their effect on pressure relief to prevent diabetic foot ulceration	2020	2.9	28

Table 1 (continuation)

Reference	Journal	Article	Publication Year	Journal Impact Factor	Article Citations
Hobabagabo et al. [43]	The Lancet Diabetes and Endocrinology	Forced migration and foot care in people with diabetes	2020	44	3
Wang et al. [67]	IEEE Transactions on Biomedical Engineering	A Review of Wearable Sensor Systems to Monitor Plantar Loading in the Assessment of Diabetic Foot Ulcers	2020	*Data not available*	38
Albathi et al. [65]	2019 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO)	Design of a smart in-sole to model and control the pressure under diabetic patients' feet	2019	*Data not available*	2
Bus et al. [89]	Diabetes/Metabolism Research and Reviews	Guidelines on offloading foot ulcers in persons with diabetes (IWGDF 2019 update)	2019	4.6	132
Bus et al. [90]	Diabetes/Metabolism Research and Reviews	State of the art design protocol for custom made footwear for people with diabetes and peripheral neuropathy	2019	4.6	34
Chatwin et al. [91]	Diabetes/Metabolism Research and Reviews	The role of foot pressure measurement in the prediction and prevention of diabetic foot ulceration – A comprehensive review	2019	4.6	74
Crawford et al. [45]	Diabetologia	Preventing foot ulceration in diabetes: systematic review and meta-analyses of RCT data	2019	8.4	40
Bencheikh et al. [64]	2018 International Conference on Applied Smart Systems (ICASS)	A low Cost Smart Insole for Diabetic Foot Prevention	2018	0.71	6

CONCLUSIONS

The findings from this study indicate that diabetic foot disorders are of critical significance, not only due to the substantial financial resources allocated to managing this condition but also because effective foot care measures can largely prevent its onset and mitigate the risks associated with this serious health issue. Identifying individuals at risk for foot ulcers and implementing timely and appropriate corrective actions can significantly reduce the incidence of serious complications, including amputations that are frequently associated with this ailment. Moreover, the ramifications extend far beyond the profound personal impact on patients and their families, translating into considerable economic savings by avoiding complex complications and ensuring that adequate and proper care is provided for those already affected by diabetic foot problems and their associated challenges. In five years, the number of severe cases and amputations caused by untreated foot ulcers could double compared to the present. Furthermore, individuals afflicted by this condition are likely to face a deteriorating quality of life following amputations, which correlates with a heightened incidence of severe comorbidities that could detrimentally influence their overall health and well-being, creating a vicious cycle that is difficult to break and affect not just the patients, but also places an enormous burden on healthcare systems worldwide. For the benefit of the afflicted individual, continued research and interdisciplinary collaboration are essential to further refine these interventions and improve outcomes for people with diabetes.

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Investigation of atmospheric plasma in textile finishing

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ABSTRACT – REZUMAT

Investigation of atmospheric plasma in textile finishing

This study aims to investigate the usability of plasma pretreatment before bleaching in textile finishing. Atmospheric pressure air plasma treatment was applied to 100% cotton rib raw fabrics. Samples were bleached at three different temperatures (90–100–110°C) and two different duration (30–60 minutes). Hydrophilicity and whiteness values, which were intended to be imparted to the sample by bleaching, were measured. Bleached samples were pre-mordanted using Potassium aluminium sulfate (alum) and dyed using chlorophyll natural dye. Colour measurements of the dyed samples were made. Air plasma applied to the fabrics has shortened the samples' sinking time and improved their hydrophilicity. While bleaching temperature has an effect on the whiteness measured after bleaching, the effect of plasma treatment has not been statistically significant. Colour and K/S values were measured after dyeing 5% and 10% pre-mordanted samples with chlorophyll natural dye. It's been found that the colour values are similar, and there is no statistical difference observed between the K/S values.

Keywords: *pretreatment, dyeing, hydrophility, whiteness, colour*

Investigarea plasmei atmosferice în finisarea materialelor textile

Scopul acestui studiu este de a investiga utilitatea pretratării cu plasmă înainte de albire în finisarea materialelor textile. Tratamentul cu plasmă de aer la presiune atmosferică a fost aplicat tricoturilor patent din bumbac brut 100%. Probele au fost albite la 3 temperaturi diferite (90–100–110°C) și 2 durate diferite (30–60 minute). Au fost măsurate valorile hifrofiliei și gradului de alb care urmau să fie conferite probei prin albire. Probele albite au fost premordansate cu sulfat de potasiu și aluminiu (alaun) și vopsite cu colorant natural de clorofilă. Au fost efectuate măsurători ale culorii probelor vopsite. Plasma de aer aplicată pe tricoturi a scurtat timpul de scufundare a probelor și a îmbunătățit hidrofilia acestora. În timp ce temperatura de albire are un efect asupra gradului de alb măsurat după albire, efectul tratamentului cu plasmă nu a fost semnificativ din punct de vedere statistic. Culoarea și valorile K/S au fost măsurate după vopsirea cu colorant natural de clorofilă a probelor premordansate 5% și 10%. S-a constatat că valorile culorii sunt similare și nu se observă nicio diferență statistică între valorile K/S.

Cuvinte-cheie: *pretratament, vopsire, hidrofilie, grad de alb, culoare*

INTRODUCTION

Some dyeing production requires heavy metals like mercury, chromium, cadmium, lead, or arsenic. About 70% of dyes used in fabric dyeing are incompletely absorbed by the fabric, leading to their discharge into wastewater. Untreated wastewater release poses risks to humans and animals throughout the food chain. Adopting eco-friendly wastewater treatment is crucial for conserving and restoring water resources [1]. Sustainability in all applied fields, particularly in textiles, is to protect our globe, environment, and community, where green-dyed products are playing their role [2]. The surface modification of textile fibres plays a crucial role in delineating their moisture management, dyeing properties, and overall performance. Given that these surface attributes directly influence the hygroscopic tendencies of fibrous substrates, various techniques have been developed for the surface modification of textiles.

Microwave technology is used in textile finishing and the extraction of natural pigments from plants. It accelerates chemical reactions, improves pigment dispersion, and enhances dye adsorption onto fibres. This method improves dyeing conditions, fastness, and colour yield while reducing mordant and solvent usage, providing economic and time-saving benefits [3–5]. Literature studies have focused on determining optimum dyeing conditions by combining different dyeing parameters with mw irradiation. MW radiation is used to investigate the natural dyeing potential of tea leaves [5]. arjun bark [6], acid red 138 [7], cassia obovata [8], red sandal wood (RSW) [4], and cassia fistula pods [3]. The main application areas of ultrasound technology in textile and apparel can be listed as follows: pre-treatment, washing, dyeing, ultrasound drying, use of ultrasound waves in various painting methods, and ultrasonic stitches in garments. Cavitation, generated within the liquor, is the main contributor to the effects of ultrasound in wet finishing procedures. Cavitation occurs due to the explosion of small energetic bubbles formed due to the movement of ultrasound waves in the liquor. As a result of cavitation occurring at the solid/liquid interface, an increase in mass transfer from liquid to solid is observed [9]. Studies on ultrasonic radiation have focused on improving dyeing conditions and investigating the use of bio-mordants. In their study, Adeel et al. applied US to silk material for 60 minutes [10], while Adeel et al. applied US radiation to silk material for 30 minutes [2], and Azeem et al. applied US radiation to wool material for 15–60 minutes [11]. Here, the processing time is longer than other surface modification techniques. Ultraviolet (UV) waves have shorter wavelengths than visible light. Scientists have divided the ultraviolet part of the spectrum into three: near UV, far UV and very far UV. It is expressed in terms of the wavelength energy of UV light. While UV A and UV B are used in lighting systems in industry, UV C is used in surface modification. [12]. As we move from visible light to UV radiation, the wavelength decreases while the energy and frequency increase. This change allows the beam to penetrate surfaces more effectively. These beams are undetectable and non-ionizing. When non-ionizing rays are absorbed by molecules, they cannot ionise them into positive or negative ions [13]. Under aerobic conditions, UV light (100–400 nm) oxidises fibre surfaces, forming reactive groups like carboxyl, aldehyde, hydroxyl, and carbonyl. This enhances dye-fibre affinity, improving natural dyeing efficacy [14]. In their study, Adeel et al. reduced the dyeing temperature by exposing the polyester fabric and dye solution to Ultraviolet radiation for 30–45 minutes [15]. Haggag et al. dyed silk fabric with mulberry leaf extract. High colour strength and satisfactory fastness towards light, washing, perspiration and crocking were achieved [16]. UV polymer technology on textiles faces challenges in formulation, component selection, and surface integration. Textile's high hydrophilicity enables liquid polymer penetration, altering inner layers. Concerns include residual odours, garment use restrictions, and polymer effects on texture and drape, with excessive cross-linking stiffening the fabric, reducing comfort [12].

Gamma rays, emitting high-energy photons, penetrate deeply. Being electrically neutral and massless, they don't alter the nucleus. Typically, gamma emission follows alpha and beta decay. Despite travelling far in air and lead, they're not fully absorbed. Examples of gamma-emitting substances are caesium (Cs-137), krypton (Kr-88), and cobalt (Co-60) [17]. Gamma rays from isotopes like Cs-137 or Co60 produce ionising radiation, interacting with fabric surfaces to create free radicals, altering surface properties and chemical composition [14]. Gamma radiation can crosslink and graft polymers by generating radicals on substrate surfaces in the presence of oxygen. These radicals react with atmospheric oxygen to form functional groups needed for grafting, altering fundamental properties due to deep penetration and causing material degradation due to gamma rays' exceptional penetrative ability [13]. Gamma radiation is applied to dye powders and textile materials at different doses. Batool et al. stated that the best-absorbed dose for cotton fabric and chicken gizzard leaf powder was 10 kGy. They revealed the optimum conditions for dyeing [18]. In their study, Bhatti et al. found that the best dose applied to sdelulosic fabric and Vat Green 1 dye was 6 kGy [19]. Gulzar et al. observed that 20 kGy is the optimum absorbed dose for surface modification of cotton [20]. Khan et al. indicated that gamma-ray treatment of 15 kGy was the effective absorbed dose for extraction of dye and surface modification of cotton fabric [21]. In addition to optimising dyeing conditions, microwave technology finds applications in the reuse and recycling of textile wastewater, as well as in the sterilisation processes of textiles [22]. Plasma, the "fourth state of matter", is an electrically neutral ionised gas with a significant number of charged particles that are not bound to an atom or molecule. Plasma technology can assist in designing and removing natural or synthetic grease and wax from textile fibres, increasing the dyeing rates of textile polymers, and improving the diffusion of dye molecules into fibres to increase colour intensity and wash fastness. This treatment promotes surface modification of polymeric/textile substrates, improves hydrophilic properties (chemical changes) and increases the surface properties (physical changes) of fibres/textile substrates. This surface modification increases the dyeability of the fibre and is an effluent-free and environmentally friendly process [1]. Plasma treatment stands out as one of the most promising technologies, serving as an alternative for several wet processes in textiles while concurrently diminishing energy, water, and chemical usage. Through meticulous choices in plasma gas and processing conditions, a spectrum of surface modifications becomes achievable, encompassing tasks such as contamination removal, bond breaking (resulting in the creation of free radicals), crosslinking, etching (yielding surface roughness), functionalisation, polymerisation, and post-irradiation grafting [23]. Through the utilisation of the plasma process, textile fibres can acquire characteristics such as wettability [24–28], thermal comfort [29], desizing&decoloration [30–32], flame retardant [33], water proof&oil repellent [34–38], antibacterial properties [39, 40] and anti-static properties [41]. Atmospheric plasma treatment is based on the principle of ionising the oxygen and nitrogen in the air and applying it to the surface. The plasma ionisation process is the disintegration of gases under the influence of high voltage by passing them between two electrodes and the transformation of gas atoms into ions with a high energy effect [42]. Atmospheric Pressure Plasma Treatment (APPT) causes the oxygen content on the surface of cotton fibres to increase [43]. Oxidation of the cotton fibre surface caused by reactive oxygen species adds new oxygen-containing functional groups such as -OH and -C-O, greatly increasing the adhesion force between the polymer surface and water molecules [44]. Air plasma increases hydrophilicity in cotton fabrics [45]. There are various studies in the literature on the investigation of the dyeability of different fibres with plasma treatment

[46–54]. The possibility of using atmospheric pressure plasma as a dry process to remove foreign substances and yellowness in 100% raw cotton knitted fabrics was investigated in a study. They stated that atmospheric pressure plasma treatment can effectively remove impurities in 100% raw cotton knitted fabrics and significantly increase the water absorption property [55]. Plasma treatment was applied to raw cotton fabrics with different combinations of plasma parameters using helium and oxygen gases in another study. They stated that the wettability of raw cotton fabrics increased significantly after plasma treatment and gave better results than traditional desizing and cleaning [56]. Argon and air-atmospheric plasma were treated to knitted and naturally coloured cotton fabrics. Researchers stated that atmospheric plasma treatments could alter the surface of naturally coloured cotton fabrics without significant loss in colour strength or fastness and thermal properties [57]. In another study, researchers applied low-pressure non-equilibrium gaseous plasma to raw cotton fabrics to enhance the adsorption of natural dyes and improve the ultraviolet (UV) protection factor. They stated that the ultraviolet protection factor (UPF) was found above 50, indicating excellent protection due to improved adsorption of the dye on samples treated with ammonia plasma [58]. Haji et al. were dyed wool fibres using grape leaves. To improve the dyeability, wool fibres were pre-treated with oxygen plasma. The results revealed that plasma treatment has partially removed the surface scales of wool and enhanced the penetration of the natural dye into the fibres. Plasma treatment power showed the highest effect on fibre modification [54].

This study aims to investigate the effect of atmospheric plasma treatment on the hydrophilicity, whiteness value after bleaching and colour values of fabrics after dyeing.

MATERIALS AND METHODS

Materials

100% carded cotton ring spun yarn with Ne 20/1 yarn count was knitted with flat knitting machines of 10 gauge thus, 100% cotton 1 × 1 rib fabrics were used in the study. Hydrogen peroxide 35% EMPLURA® (Sigma-Aldrich, Germany), Sodium Hydroxide EMSURE® (Sigma-Aldrich, Germany), Oil remover soap BELFİX BTD (Belice Chemical, Türkiye), Anti-crease agent BELFALT OYT (Belice Chemical, Türkiye), Ion trapping BELPİN RT (Belice Chemical, Türkiye), Wetting agent BELWETT HM-Y (Belice Chemical, Türkiye), Peroxide stabiliser BAY STAP-CH (Bayka Chemical, Türkiye), Anti-peroxide DK ANP 4 (Derin Chemical, Türkiye), Aluminum potassium sulfate (Carlo Erba Reagents GmbH, Germany), Chlorophyll S-10 (Tito Co. Ltd., Türkiye) liquid was provided.

Methods

Within the scope of this study, fabrics treated with atmospheric plasma were bleached and subsequently dyed with chlorophyll natural dye. Initially, atmospheric air plasma was applied to the samples at various speeds, and SEM analyses were conducted to observe changes in the surface morphology of the fibres. Hydrophilicity and whiteness values of the bleached fabrics were measured. Finally, the bleached fabrics were dyed using chlorophyll natural dyestuff, and colour measurements of the dyed samples were taken (figure 1).

Atmospheric pressure plasma

Atmospheric pressure plasma jet (APJ) treatments were applied to 100% cotton knitted fabrics at Plasmatreat GmbH. The objective was to activate the surface of cotton fabrics and enhance their hydrophilicity using atmospheric pressure air plasma. Table 1 outlines the parameters of the atmospheric pressure plasma treatment.

Openair® plasma systems operate at atmospheric pressure and generate plasma by spraying it onto the

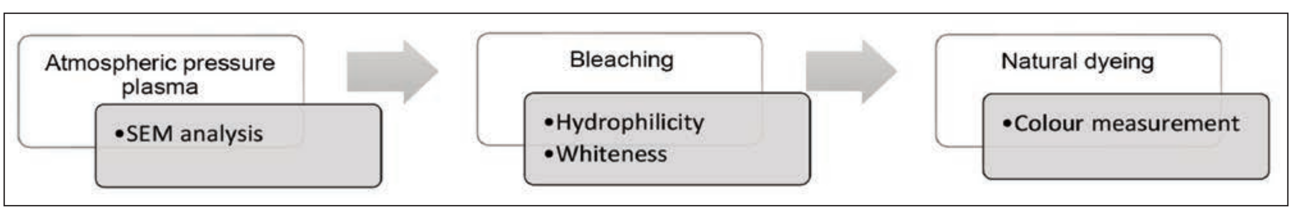


Fig. 1. Flow chart

Table 1

PARAMETERS OF THE ATMOSPHERIC PRESSURE PLASMA							
Jet	**Voltage (V)**	**Frequency (kHz)**	**Power (Watt)**	**Distance (mm)**	**Pressure (bar)**	**Ionisation gas**	**Speed (m/min)**
RD1010	280	21	600	10	3	Air	5
RD1010	280	21	600	10	3	Air	10

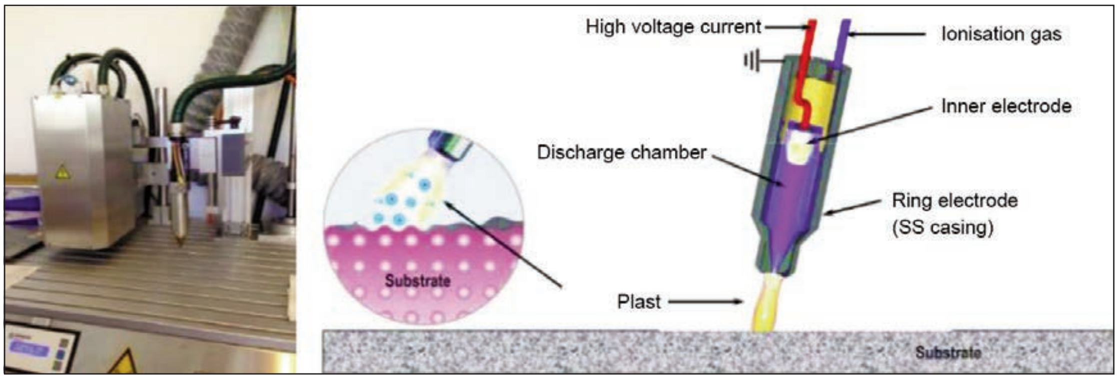


Fig. 2. Atmospheric Pressure Plazma (APJ) (Openair®plazma) [59]

fabric with the help of a jet-fired arc and processing gas, typically air. This plasma contains a sufficient level of induced particles to initiate the desired effect on the surface (figure 2).

Bleaching process

The bleaching processes were applied to cotton fabrics using the exhaust method. This involved treating the fabrics with a solution containing 6% H2O2, 4g/l (46°Be) NaOH, 0.5 g/l oil remover soap, 0.5 g/l anti-creasing agent, 0.8 g/l ion trapping agent, 0.5 g/l wetting agent, and 0.8 g/l peroxide stabiliser in a laboratory-type machine, with a liquor ratio of 20:1. The bleaching process was conducted at three different temperatures and two different durations. The parameters of the bleaching process and the corresponding sample codes are presented in table 2.

After the bleaching processes, the samples were rinsed for 10 minutes. At the end of the bleaching process, anti-peroxide treatments were applied to remove peroxide residues remaining on the samples. These processes were carried out for 20 minutes at 50°C in a liquor prepared using 0.2 g/l catalase enzyme and 0.5 cm^3/l acetic acid. Hydrophilicity assessments of the samples were conducted using the sinking method. A sample measuring 5 cm × 5 cm was immersed in pure water, and the stopwatch was initiated upon contact with the water. The stopwatch was stopped when the sample was completely submerged in water, and the sinking times were recorded. Whiteness values (Berger) of the samples were measured with a spectrophotometer (Datacolor).

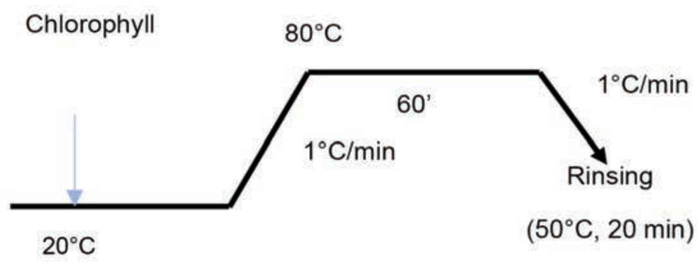
Natural dyeing

After the pre-mordanting process, dyeing processes utilising 10% owf chlorophyll were conducted at 80°C for 60 minutes, with a liquor ratio of 30/1. The dyeing liquors, prepared at a room temperature of 20°C, were contained in tubes. The pH value of the dye bath was measured as 11.02. The exhausting apparatus was programmed according to the diagram illustrated in figure 3. The dyeing liquors were gradually heated to 80°C, increasing by 1°C per minute.

Table 2

BLEACHING PROCESS PARAMETERS AND SAMPLE CODES

Sample code	Plasma type	Temperature (C°)	Time (min)
R-90-30	Reference (plasma free sample)	90	30
A5-90-30	Air plasma (5 m/min)		
A10-90-30	Air plasma (10 m/min)		
R-100-30	Reference (plasma free sample)	100	
A5-100-30	Air plasma (5 m/min)		
A10-100-30	Air plasma (10 m/min)		
R-110-30	Reference (plasma free sample)	110	
A5-110-30	Air plasma (5 m/min)		
A10-110-30	Air plasma (10 m/min)		
R-90-60	Reference (plasma free sample)	90	60
A5-90-60	Air plasma (5 m/min)		
A10-90-60	Air plasma (10 m/min)		
R-100-60	Reference (plasma free sample)	100	
A5-100-60	Air plasma (5 m/min)		
A10-100-60	Air plasma (10 m/min)		
R-110-60	Reference (plasma free sample)	110	
A5-110-60	Air plasma (5 m/min)		
A10-110-60	Air plasma (10 m/min)		



Natural dyestuff	Amount (%owf)
Chlorophyll	10
Liquor ratio	30/1

Fig. 3. Dyeing diagram

The temperature was maintained at 80°C for 60 minutes while the dyeing process occurred.
Subsequently, the bath was cooled to 50°C, emptied, and the samples were rinsed under tap water for 2 minutes. Colour measurements of the dyed samples were conducted using a spectrophotometer (Datacolor).

RESULTS AND DISCUSSION

SEM Analysis

Figure 4 illustrates that the surface morphology of cotton knitted fabric undergoes changes when exposed to air plasma, and these changes become more pronounced with longer treatment times. From the SEM images, it is evident that the surface of the plasma-treated sample fabrics has undergone significant modification, in contrast to the reference samples, which exhibit a smoother surface texture. The plasma-treated samples display notable microcracks on their surfaces. These surface modifications due to plasma treatment were further confirmed through subsequent hydrophilicity tests, which demonstrated an increase in the hydrophilicity of the fabrics following air plasma treatment. The modification occurring on the surface of the sample treated with plasma at a speed of 5 m/min was more intense (figure 4). Therefore, it can be concluded that as the contact time of the plasma treatment with the sample fabric increases, the hydrophilicity of the sample fabric also increases.

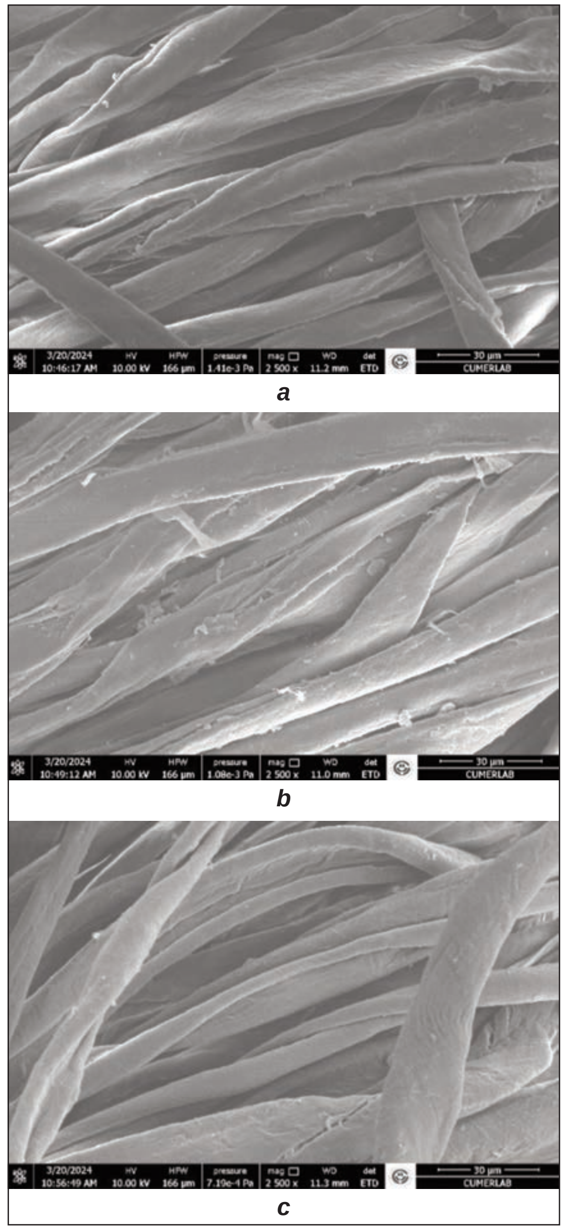


Fig. 4. SEM İmages: *a* – reference (plasma-free); *b* – air plasma (5 m/min); *c* – air plasma (10 m/min)

Hydrophilicity results

The hydrophilicity of the samples was assessed using the sinking method. Sinking times, measured according to this method, are presented in figure 5. As anticipated, sinking times decreased with increasing temperatures for bleached samples at equivalent temperatures and durations. Significantly reduced sinking times were observed for plasma-treated samples compared to the reference (plasma-free) sample treated under identical temperature and time conditions. The plasma treatment effectively enhanced the fabric's hydrophilicity.
Analysis of variance was performed for the dependent variable hydrophilicity, taking plasma type and temperature as independent variables (table 3). No statistical difference was observed between the subgroups of the temperature variable in terms of hydrophilicity (batma süresi) values obtained at the end of the 30-minute bleaching process. However, a statistical difference was found between subgroups of plasma type at the end of the 30-minute bleaching process. A notable decline was observed in similar samples with rising temperatures. However, plasma pretreatment led to a significant reduction in sinking times. It is observed that there is a statistical difference

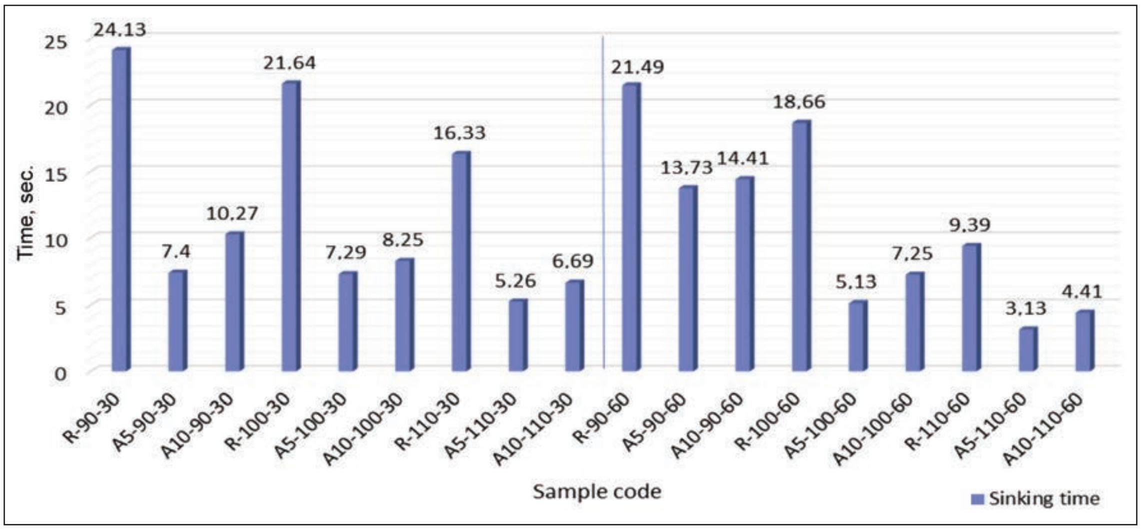


Fig. 5. Hydrophilicity test results (sinking time)

Table 3

ANALYSIS OF VARIANCE

Duration	Source	Type III Sum of Squares	df	Mean Square	F	Sig.	R square	Adjusted R Squared
30 minutes	Temperature	31.483	2	15.741	6.552	0.055	0.976	0.951
	Plasma type	351.685	2	175.842	73.189	0.001		
60 minutes	Temperature	179.330	2	89.665	20.687	0.008	0.950	0.899
	Plasma type	147.388	2	73.694	17.002	0.011		

between the subgroups of the temperature variable and the subgroups of the plasma type variable in terms of hydrophilicity values obtained at the end of the 60-minute bleaching process. Increasing the temperature and applying plasma pretreatment during the 60-minute bleaching process significantly reduced the sinking time of the samples.

The Tukey HSD test was employed as a post hoc test to examine differences between subgroups. In the output of homogeneous subsets, the subgroups of the temperature variable were consolidated into a single subset after 30 minutes of bleaching (table 4). Plasma-treated samples were grouped into one subset, while the reference sample appeared in a separate subset. Consequently, it can be inferred that the plasma treatment influences the hydrophilicity values after 30 minutes of bleaching (table 5). Sinking data measured after bleaching at 100°C and 110°C were aggregated into the same subset, while sinking data measured after bleaching at 90°C were presented in a distinct subset. Hence, it can be deduced that the hydrophilicity values of the samples bleached at 110°C and 100°C for 60 minutes are similar, and these two groups do not exhibit statistically significant differences (table 6).

It can be concluded that there is no statistical difference between the hydrophilicity values of the samples treated with plasma at a speed of 5 m/min for 60 minutes and those treated at a speed of 10 m/min for 60 minutes.

Berger whiteness index results

Whiteness measurements of the samples were conducted using the Berger whiteness index. Plasma

Table 4

SUBSETS OF TEMPERATURE FOR 30 MINUTES

Temperature	30 minutes	
	N	Subset
		1
110°C	3	9.4267
100°C	3	12.3933
90°C	3	13.9333
Sig.		0.05

Table 5

SUBSETS OF PLASMA TYPE FOR 30 MINUTES

Plasma type	30 minutes		
	N	Subset	
		1	2
Air plasma 5	3	6.65	
Air plasma 10	3	8.4033	
Plasma free	3		20.7
Sig.		0.429	1

Table 6

SUBSETS OF TEMPERATURE FOR 60 MINUTES			
Temperature	**60 minutes**		
	N	**Subset**	
		1	**2**
110°C	3	5.6433	
100°C	3	10.3467	
90°C	3		16.5433
Sig.		0.104	1

Table 7

SUBSETS OF PLASMA TYPE FOR 60 MINUTES			
Plasma type	**60 minutes**		
	N	**Subset**	
		1	**2**
Air plasma 5	3	7.33	
Air plasma 10	3	8.69	
Plasma free	3		16.5133
Sig.		0.723	1

pretreatment applied to the samples did not result in a consistent increase or decrease in whiteness values (figure 6). When the Berger whiteness index values obtained after the pretreatment process for 30 and 60 minutes were compared, the whiteness index values were higher in the bleaching process for 60 minutes, as expected. No significant difference was observed between plasma-treated samples bleached at the same temperature and time and the reference sample. However, a notable increase in whiteness values was observed when the bleaching temperature was raised to 110°C for both 30 and 60 minutes of bleaching.

Analysis of variance was conducted for the dependent variable whiteness, with plasma type and temperature as independent variables. A statistical difference was found between the subgroups of the temperature variable regarding the whiteness values obtained after the bleaching process for both 30 and 60 minutes (p value < 0.05). However, there was no statistical difference observed in the subgroups of the plasma type concerning the whiteness values obtained after the bleaching process for 30 and 60 minutes (p value > 0.05) (table 8). Although the plasma process did not demonstrate a statistically significant effect on the whiteness values, the temperature variable notably influenced the whiteness values statistically.

Tukey HSD test was used as a post hoc test to see the differences between subgroups. In the homogeneous

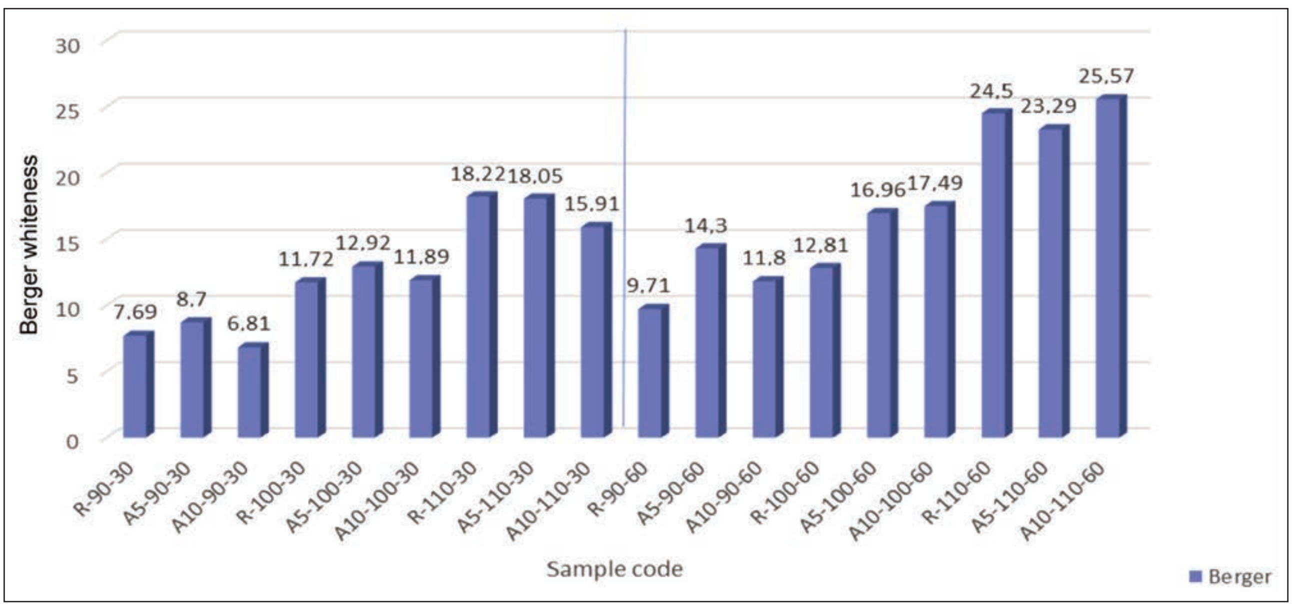


Fig. 6. Berger whiteness ındex values

Table 8

ANALYSIS OF VARIANCE								
Duration	**Source**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**R square**	**Adjusted R Squared**
30 minutes	Temperature	140.272	2	70.136	172.497	0.000	0.989	0.978
	Plasma type	4.321	2	2.160	5.313	0.075		
60 minutes	Temperature	246.924	2	123.462	37.528	0.003	0.952	0.904
	Plasma type	13.140	2	6.570	1.997	0.250		

Table 9

SUBSETS OF TEMPERATURE FOR 30 MINUTES				
Temperature	**30 minutes**			
	N	**Subset**		
		1	**2**	**3**
90°C	3	7.7333		
100°C	3		12.1767	
110°C	3			17.3933
Sig.		1.000	1.000	1.000

Table 10

SUBSETS OF PLASMA TYPE FOR 30 MINUTES		
Plasma type	**30 minutes**	
	N	**Subset**
		1
Air plasma 10	3	11.5367
Plasma free	3	12.5433
Air plasma 5	3	13.2233
Sig.		0.067

Table 11

SUBSETS OF TEMPERATURE FOR 60 MINUTES			
Temperature	**60 minutes**		
	N	**Subset**	
		1	**2**
90°C	3	11.9367	
100°C	3	15.7533	
110°C	3		24.4533
Sig.		0.126	1.000

Table 12

SUBSETS OF PLASMA TYPE FOR 60 MINUTES		
Plasma type	**60 minutes**	
	N	**Subset**
		1
Plasma free	3	15.6733
Air plasma 5	3	18.1833
Air plasma 10	3	18.2867
Sig.		0.291

subsets output, the subgroups of the temperature variable were divided into three subsets (table 9). The temperature had a statistical effect on whiteness values after 30 minutes of bleaching. Subgroups of the plasma type were collected in a single subset. From this, it was concluded that the plasma treatment did not affect the whiteness values after 30 minutes of bleaching (table 10). After 60 minutes of bleaching, 90°C and 100°C of the subgroups of the temperature variable were collected in the same subset, while 110°C was put in a different subset. It was concluded that the 110°C subgroup is statistically different (table 11). Since all subgroups of the plasma type variable were collected in a single subset after 60 minutes of bleaching, it was concluded that there was no statistical effect of the plasma treatment on whiteness (table 12).

Colour measurements

Colour measurements of the samples were measured according to the CIE lab system. Colour and K/S values of 5% and 10% pre-mordanted samples were found to be close to each other (table 13).

Table 13

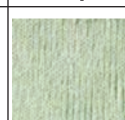
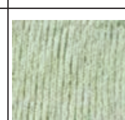
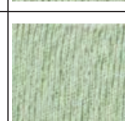
COLOUR MEASUREMENT												
Sample code	**%5 mordan**						**%10 mordan**					
	L	**a**	**b**	**Δe**	**K/S**	**Sample**	**L**	**a**	**b**	**Δe**	**K/S**	**Sample**
R-90-30	71.58	–6.40	12.46	1.38	7.17		68.04	–7.50	13.51	1.43	5.15	
A5-90-30	70.62	–6.34	12.89	0.93	6.84		69.65	–7.82	12.43	2.24	6.00	
A10-90-30	72.22	–6.13	12.12	1.64	7.64		70.92	–7.54	12.39	2.32	6.52	
R-100-30	69.58	–7.49	12.70	1.57	5.96		70.26	–7.76	12.14	2.43	6.23	

Table 13 (continuation)

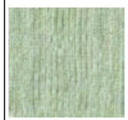
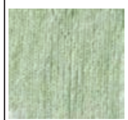
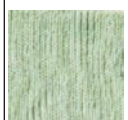
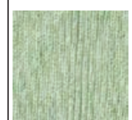
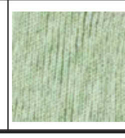
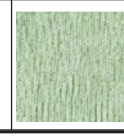
Sample code	%5 mordan						%10 mordan					
	L	a	b	Δe	K/S	Sample	L	a	b	Δe	K/S	Sample
A5-100-30	69.47	–7.46	12.68	1.53	5.93		69.80	–7.73	12.32	2.24	6.12	
A10-100-30	69.84	–7.67	12.62	1.79	6.05		69.96	–8.03	12.28	2.51	6.03	
R-110-30	70.48	–7.73	12.95	1.85	6.00		71.68	–8.09	12.18	2.96	6.67	
A5-110-30	70.24	–7.37	12.88	1.52	5.08		69.37	–8.43	13.10	2.48	5.57	
A10-110-30	69.95	–8.01	13.12	1.99	5.70		70.21	–8.72	13.36	2.8	5.54	

Table 14

INDEPENDENT SAMPLES TEST							
Value	t	df	Sig. (2-tailed)	Mean difference	Std.Error difference	95% Confidence interval of the difference	
						Lower	Upper
KS	–0.184	34	0.855	–0.04000	0.21723	–0.48146	0.40146

The difference between the K/S values of the samples premordanted using 5% and 10% owf of potassium aluminium sulfate (alum) was examined with the Independent Samples t-test (table 14). No statistical difference was observed between K/S values (p value > 0.05).

CONCLUSION

This study aimed to investigate the usability of plasma pretreatment before bleaching in textile finishing. Atmospheric pressure air plasma treatment was applied to 100% cotton rib raw fabrics. SEM analyses were performed to see the effect (surface characterisation) of the plasma treatment on the fabrics. According to the SEM analysis results, it was concluded that slow application of plasma pretreatment (5 m/min) causes more intense surface modification and microcracks on the sample surface.

Then, samples were bleached at three different temperatures (90°C – 100°C – 110°C) and two different times (30–60 minutes). Hydrophilicity and whiteness values, which were intended to be imparted to the sample by bleaching, were measured. The sinking times of plasma-treated samples decreased significantly compared to the reference (plasma-free) sample treated at the same temperature and time. Plasma treatment enhanced the fabric's hydrophilicity. Statistical analysis further confirmed that plasma treatment influenced the hydrophilicity values of samples bleached at various temperatures for 30 and 60 minutes. When comparing the whiteness values of samples bleached at various temperatures for 30 and 60 minutes, both the plasma-treated samples and the reference sample were statistically grouped. Therefore, plasma pretreatment did not have a significant effect on the whiteness values of the samples. Nevertheless, statistically significant differences emerged in the whiteness values of samples bleached at 90°C – 100°C and 110°C compared to those bleached for 30 minutes. Similarly, a statistical discrepancy was observed among samples bleached for 60 minutes, particularly with a temperature increase to 110°C within the same group as those at 90°C and 100°C. The whiteness data obtained after bleaching at 90°C, 100°C, and 110°C for 30 minutes were categorised into different subsets. For the bleaching process conducted within 30 minutes, it was observed that each temperature level exerts an influence on whiteness. However, with the extension of bleaching time to 60 minutes, the whiteness data obtained after bleaching at 90°C and 100°C were grouped into the same subset, whereas the whiteness data obtained after bleaching at 110°C were placed in a separate subset. Consequently, it is evident that the temperature variable significantly impacts whiteness.

Bleached samples were pre-mordanted using Potassium aluminium sulfate (alum) and dyed using chlorophyll natural dye. Colour measurements of the dyed samples were made. Chromaticity coordinates (L*, a*, b*) and Kubelka-Munk (K/S) values of the samples showed negligible difference. An investigation of the difference between the K/S values of samples subjected to pre-mordanted utilising 5% and 10% on weight of fabric (owf) of potassium aluminium sulfate (alum) was conducted employing the Independent Samples t-test (Table X). No statistical difference was observed between K/S values (p value > 0.05).

In this study, the usability of atmospheric pressure air plasma in textiles was investigated. Plasma pretreatment was applied to textile materials as a pre-treatment before bleaching and natural dyeing processes. Plasma pretreatment induced modifications on the fabric surface. The integration of plasma technology in textile dyeing is expected to reduce both chemical and water consumption required for subsequent processes such as bleaching and dyeing. Consequently, the amount of wastewater discharged into the environment is anticipated to decrease, along with a reduction in energy consumption.

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Therapeutic management of burns affecting major joints of the limbs and the role of medical textiles in enhancing the rehabilitation process: 1 year retrospective study

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ABSTRACT – REZUMAT

Therapeutic management of burns affecting major joints of the limbs and the role of medical textiles in enhancing the rehabilitation process: 1 year retrospective study

Burn injuries rank among the most severe forms of trauma, posing a significant global public health challenge due to their high morbidity and mortality, even within specialised burn care facilities. Effective treatment for severe burns necessitates comprehensive critical care and early identification of complications, which can improve patient survival and functionality. A comprehensive set of criteria has been established for admitting burn patients to specialised burn centres, ensuring that those with extensive, complex, or specific types of burns receive appropriate multidisciplinary care. Burns involving major joints are particularly challenging due to risks of scarring, contractures and functional limitations that demand adequate surgical treatment and rigorous rehabilitative care. This one-year retrospective study analysed burn injuries to major joints in adult patients admitted to the Burn Unit at Clinical Emergency Hospital Bucharest in 2023. Inclusion criteria were the burns affecting the shoulder, elbow, wrist, hip, knee or ankle. Collected data included demographics, injury details and outcomes. Therapeutic management was also assessed, focusing on systemic support and treatment of complications, wound dressings and surgical treatment. Findings will aid in understanding the pathophysiology, etiology, and therapeutic strategies for burns involving major joints, emphasising the importance of early, targeted interventions to improve recovery and patient quality of life.

Keywords: *burns, major limb joints, dressings, surgical treatment, rehabilitation, medical textiles*

Managementul terapeutic al arsurilor ce afectează articulațiile majore și rolul textilelor medicale în procesul de recuperare: studiu retrospectiv pe 1 an

Arsurile se numără printre cele mai grave forme de traumatism, reprezentând o provocare semnificativă pentru sănătatea publică la nivel global din cauza ratei ridicate de morbiditate și mortalitate, chiar și în unitățile specializate de îngrijire a arșilor. Tratamentul eficient al arsurilor severe necesită îngrijire multidisciplinară, precum și identificarea timpurie a complicațiilor, ceea ce poate îmbunătăți supraviețuirea și funcționalitatea pacienților. A fost stabilit un set cuprinzător de criterii pentru admiterea pacienților cu arsuri în centre specializate, asigurându-se că acei pacienți cu arsuri extinse, complexe sau de etiologie mai rară beneficiază de îngrijire multidisciplinară adecvată. Arsurile care implică articulațiile majore sunt deosebit de provocatoare din cauza riscurilor de cicatrizare vicioasă, contracturi și limitări funcționale, necesitând tratament chirurgical adecvat și îngrijire riguroasă de recuperare.

Acest studiu retrospectiv pe un an a analizat leziunile de arsură ale articulațiilor majore la pacienții adulți internați în Secția Îngrijire a Arșilor Gravi a Spitalului Clinic de Urgență București în 2023. Criteriile de includere au fost reprezentate de prezența arsurilor ce afectează umărul, cotul, articulația radio-carpiană, șoldul, genunchiul sau glezna. Datele colectate au inclus informații demografice, detalii despre leziuni și rezultate. Managementul terapeutic a fost de asemenea evaluat, concentrându-se pe suportul sistemic și pe tratamentul complicațiilor, pansamentele utilizate pentru plăgi, precum și tratamentul chirurgical. Rezultatele vor ajuta la înțelegerea fiziopatologiei, etiologiei și strategiilor terapeutice pentru arsurile care implică articulațiile majore, subliniind importanța intervenției timpurii și direcționate pentru îmbunătățirea recuperării și calității vieții pacienților.

Cuvinte-cheie*: arsuri, articulațiile mari ale membrelor, pansamente, tratament chirurgical, recuperare, textile medicale*

INTRODUCTION

Burns represent one of the most severe types of trauma, imposing a substantial global public health burden due to their high morbidity and mortality rates, even in specialised burn centres. Effective management of severe burns requires comprehensive critical care and local treatment delivered by a multidisciplinary team. Early detection of complications is crucial, guiding precise treatment approaches that improve both survival and functional outcomes for patients. Survivors of major burns frequently face lasting physical and psychological challenges, requiring serial surgical procedures, ongoing physical therapy for functional disabilities, and long-term psychological support for lasting mental health impacts [1–5].

American Burn Association established the guidelines accepted worldwide for referral of burned patients to specialised Burn Centres based on the severity of the lesions. The following criteria impose hospitalisation in a burn centre: full-thickness burns on any surface, partial-thickness burns covering ≥10% of Total Body Surface Area (TBSA), deep partial or full-thickness burns affecting the functional areas (face, hands, genitalia, feet, perineum or areas over joints), patients with burns accompanied by other comorbidities or with concurrent traumatic injuries, inability to manage pain, inhalation injuries, pediatric burns, chemical and electrical injuries. Using these referral criteria for burn patients enhances outcomes by ensuring patients receive care aligned with the latest evidence-based practices and they benefit from the expertise of a properly trained team while still respecting the proper allocation of resources [6, 7].

One of the severity criteria established by ABA is the involvement of functional areas, which include the major joints. Burns on the joints present a unique challenge in clinical management due to their potential impact on mobility and function. The skin around joints is often thinner and more sensitive, making it more susceptible to deeper burns that can compromise underlying structures. When burns occur in these areas, they can lead to complications such as scarring, contractures, and limited range of motion, which may require extensive rehabilitation.

Contractures of the shoulder, elbow, hip, and knee joints are commonly seen after burn injuries. While burns affecting the limbs and joints can directly cause these deformities, improper positioning and insufficient physical exercise during recovery can worsen the condition. Effective treatment is essential, often involving advanced wound care techniques, pain management, and sometimes surgical interventions to promote healing and restore function [8–10].

This study aimed to analyse burns affecting the major joints of the limbs, which are a frequent encounter in burn patients. We sought to highlight the pathophysiology, etiology, and severity of these injuries – key aspects that guide therapeutic approaches and subsequent recovery. Involvement of joint areas can lead to severe functional deficits, some of which may be irreversible, significantly impacting patients' quality of life and their ability to reintegrate socially and professionally. Furthermore, the role of medical textiles in treating burn patients was thoroughly assessed as recent advances in this field provide optimal local care during all the evolutive phases of the burn lesions, from emergency settings to long-term rehabilitation.

MATERIAL AND METHOD

We performed a retrospective study including the patients admitted to the Burn Unit of the Clinical Emergency Hospital Bucharest for one year, from the 1st of January 2023 to the 31st of December 2023. The inclusion criteria were age ≥18 years and burns to the major joints of the limbs, such as the shoulder, elbow, wrist, hip area, knee and ankle joints. The exclusion criteria comprised the absence of burns at the joint level, incomplete medical records, and transfer to a different facility. The following data were obtained: age and gender of patients, mechanism of injury, burned surface area, presence of third-degree burns, localisation of affected joints, presence of inhalation injuries, length of stay (LOS), surgical and conservative treatment applied and outcome. The Abbreviated Burn Severity Index (ABSI) score was calculated to assess prognosis. The collected data were integrated into an Excel database for analysis and management.

This study received approval from the hospital's ethics committee and was conducted following all principles outlined in the Declaration of Helsinki.

RESULTS

Out of the total of 140 patients who were admitted between the 1st of January 2023 and the 31st of December 2023, 10 patients were transferred to another clinic, and 18 patients didn't present burns of the major joints and were excluded from the study. The remaining 112 patients were further analysed, and their characteristics are presented in table 1.

The majority of the patients were male, totalling 82 individuals (73.2% of the overall cohort). The mean age of the patients was 50.52 years old, while the mean total body surface area (TBSA) burned was 24.7%, with 36.6% of patients sustaining burns covering a maximum of 10% of body surface area and 26.8% of patients falling within the 11–20% range. Third-degree burns were present in 69 patients (61.6% of the total cases).

Concerning the mechanism of burn injury, 82 out of the 112 cases (73.2% of patients) were attributed to flame injuries, 23 (20.5%) were due to scalds, while 5 cases (4.5%) resulted from electrocution and 2 cases (1.8% of patients) were classified as chemical burns. Inhalation injury was present in 30 cases, representing 26.8% of the total. Tracheostomy was performed in 8 cases (7.1% of patients).

The ABSI score was calculated, with the distribution shown in figure 1. Among the 112 patients, 36 patients had an ABSI score of 4 or 5, corresponding to a probability of survival of 98%, 29 patients had a score of 6 or 7 (probability of survival of 80–90%); 19 patients had a score of 8 or 9 (probability of survival 50–70%), 12 patients had a score of 10 or 11 (probability of survival 20–40%), and 9 patients had a score equal or above 12, corresponding to a probability of survival equal or smaller than 10%. Mortality in the study group was 18.8%. The mean registered

Table 1

CHARACTERISTICS OF STUDY PATIENTS			
Variables	**Classification**	**Cases**	**Proportion (%)**
Sex	Male	82	73.2
	Female	30	26.8
Age	18–30	17	15.2
	31–40	17	15.2
	41–50	20	17.9
	51–60	22	19.6
	61–70	20	17.9
	71–80	13	11.6
	>80	3	2.7
Burn mechanism	Flame	82	73.2
	Scald	23	20.5
	Electrocution	5	4.5
	Chemical	2	1.8
%TBSA	1–10%	41	36.6
	11–20%	30	26.8
	21–30%	12	10.7
	31–40%	5	4.5
	41–50%	9	8
	51–60%	4	3.6
	61–70%	4	3.6
	71–80%	2	1.8
	81–90%	3	2.7
	91–100%	2	1.8
3rd-degree burns		69	61.6

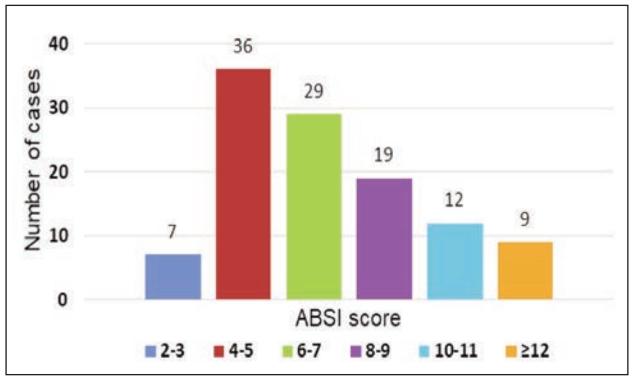

Fig. 1. Distribution of ABSI score in the study group

Table 2

THE NUMBER OF CASES PER JOINT AND THE TOTAL NUMBER OF CASES FOR EACH ANATOMICAL REGION				
Body segment	**Unilateral right side**	**Unilateral left side**	**Bilateral**	**Total**
Upper limb				146
Shoulder	10	5	15	30
Elbow	7	7	22	36
Wrist	13	13	54	80
Lower limb				78
Hip	2	6	13	21
Knee	10	2	12	24
Ankle	6	5	22	33

Length of Stay (LOS) of the patients was 22.9 days.

An analysis of burn localisation revealed involvement of 146 major joints in the upper extremity, with the wrist being the most affected (80 times), followed by the elbow (36 times) and shoulder (30 times). In the lower limbs, major joints were affected 78 times, with a higher incidence of burns also being reported for the distal joints – 33 times for the ankle and 24 and 21 times, respectively, in the case of the knees and the hips (table 2).

For all patients, dressing of the burn wounds was carried out regularly, employing suitable dressings according to the depth of the burns, the clinical presentation and the local progress, with notable examples depicted in figures 2 and 3.

In figure 2, the dressing has the ability to promote epithelisation while hydrating the burn lesion. Figure 2, *e* and *f* depict a case of a partial thickness burn lesion caused by a flame in the knee region epithelised with Epicite®. Figure 2, *g* and *h* present Aquacel® Ag for a temporary cover of a shoulder burn, absorbing the exudate while providing an antimicrobial effect. Figure 2, *i* illustrates a

Fig. 2. Dressing of the burn wounds: *a* to *d* – Epicite® used in a female patient with superficial burn lesions; *e* and *f* – burn lesion epithelioid with Epicite®; *g* and *h* – Aquacel® Ag used for a temporary cover; *i* – TenderWet Plus® used for absorbing the fluids; *j* and *k* – Mepilex Ag used for a wrist burn; *l* – Grassolind dressing

TenderWet Plus® used for absorbing the fluids in an elbow burn. Figure 2, *j* and *k* show the aspect of Mepilex Ag and its use in the case of a wrist burn, keeping the lesion moist while preventing bacterial contamination. Figure 2, *l* displays a Grassolind dressing, which has a greasy composition, thus promoting epithelisation.

The most severe cases with extensive burn lesions require daily lavage performed in a sterile manner with elaborate dressings to limit the liquid, protein and thermic losses while trying to repel any contamination of the burned wounds. Such type of dressing is exemplified in figure 3.

Fig. 3. Severe case with extensive burn lesions

Our standard protocol pays great attention to the local treatment of burn lesions. After thoroughly cleansing the wounds with antiseptic solutions, we always perform the dressings with Burnshield® in the initial phase. This type of dressing is used in the first 24 hours after burn injury, being a non-adherent, sterile, non-toxic, and non-irritant hydrogel. It has a soothing and cooling effect on the patient, reducing inflammation and providing pain relief while minimising the risk of infection. The burn lesions are assessed the next day. The initial depth and the evolution of the lesions dictate the type of dressings that we use in the following days.

In our Burn centre, burn care involves selecting appropriate treatments and dressings based on the depth of the burn and the stage of healing. For superficial partial-thickness burns, the primary goals were to promote epithelialisation, minimise fluid loss, and reduce the risk of infection. Dressings selected in these cases are non-adherent, protecting the fragile new epithelial layer and allowing painless removal, hydrating to maintain a moist environment that accelerates skin regeneration. Absorbent dressings were used to manage low to moderate levels of exudate while keeping the wound bed clean. These dressings aim to support rapid healing and also enhance patient comfort by reducing the need for frequent dressing changes. For deep partial-thickness burns, our focus was to maintain hydration, effectively manage exudate, and prevent infection to avoid complications. Moisture-retentive dressings help prevent tissue desiccation and support cellular activity essential for healing, while antimicrobial dressings reduce bacterial load and protect against infection. Dressings with high absorbency are used for managing moderate to heavy exudate, ensuring a balanced wound environment that promotes recovery. In cases of full-thickness burns, pre-surgical care aims to keep the wound clean and infection-free while preparing for surgical interventions like excision and grafting. Antimicrobial or barrier dressings were applied to create a bacteriostatic environment, and in complex cases where donor sites are insufficient, negative pressure wound therapy is taken into consideration to promote granulation tissue formation. Hydrophilic foam dressings may also be used to provide cushioning and absorb excess exudate from heavily draining wounds.

In the final phase of healing, scar remodelling was supported through silicone-based products that hydrate and soften scar tissue, compression garments that reduce collagen deposition and improve circulation, and emollient or vitamin-enriched products that maintain skin hydration and enhance texture. Throughout all stages of burn care in our Burn Centre, textile bandages play an essential role by securing primary dressings in place, providing gentle compression to manage edema or support scar remodelling, and adding padding to protect wounds from external mechanical forces. They are versatile and adaptable to various wound sizes and locations but should be carefully applied to avoid excessive pressure that could compromise circulation. Dressing choices and care strategies are regularly reassessed and tailored to the burn's depth, exudate levels, and healing phase to optimise outcomes.

Of the total lot of 112 patients, 79 patients (70.5%) required surgical treatment to cover the defects. Regarding the debridement of burns, 75 patients had a surgical excision performed either tangentially or in a fascial plane, depending on the severity of the lesion, while in 4 cases, enzymatic debridement using Bromelain was employed. After the debridement, these patients required permanent coverage with skin autografts. Out of the total cases, 7 patients had high-severity burns of the limbs, which required amputations. Defect covering using flaps was mostly reserved for the sequelae cases and consisted of 3 cases of Z-plasties, 1 random flap, 1 pedicled abdominal flap and 1 pedicled latissimus dorsi flap. Figures 4 and 5 exemplify the therapeutic strategy applied in two of our cases.

A 72-year-old female patient who had a full-thickness burn lesion of the arm, elbow, and forearm and a deep partial thickness burn of the distal third of the forearm is illustrated in figure 4, *a*. Figure 4, *b* depicts the aspect after the excision of the burn eschar in a fascial plane and a tangential excision in the distal aspect of the forearm and the wrist. The coverage of the resulting defect with a split-thickness skin graft (figure 4, *c*) and the evolution at 3 weeks (figure 4, *d*) with 90% of the graft integrated and healed, except for a small region near the elbow, which was successfully managed using negative pressure wound therapy (figure 4, *e*).

Figure 5 presents a 43-year-old patient with an axillary scar after a burn injury with significant retraction of the anterior axillary fold. Figure 5, *b* presented the immediate postoperative aspect: the contracture was managed by the release of the scar by Z plasties. Figure 5, *c* depicts the result with a significant functional improvement of the shoulder abduction.

According to the protocol in our clinic, all the patients in the study benefited from the systemic support of the vital functions, the local treatment of the burned lesions, thromboprophylaxis, and prevention of associated contractures of the joints by following a daily kinetotherapy program along with elevation of the affected limbs and means of anticontracture posture. After the complete healing of the burn wounds, patients were discharged with recommendations to wear compressive garments made from breathable, elastic materials that allow for comfort and flexibility while providing adequate compression (figure 6).

Figure 6 depicts a male who suffered burns by flame to the right upper limb and the lower limbs, which required coverage with skin grafts. This stage presents the healed grafts the patient wearing compressive garments to prevent the formation of vicious scars.

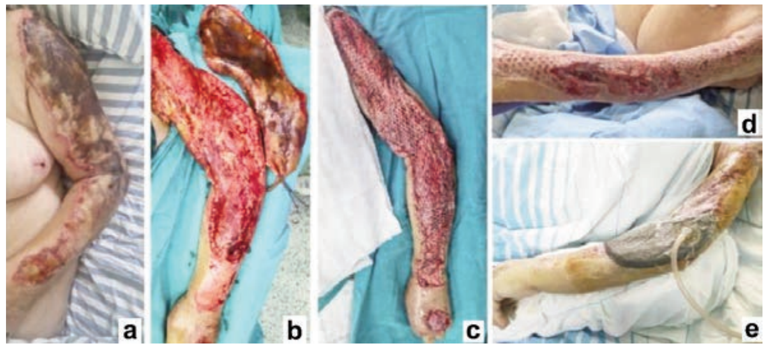

Fig. 4. 72-year-old female patient with: *a* – full-thickness burn lesion of the arm, elbow, and forearm; *b* – aspect after the excision of the burn eschar; *c* – split-thickness skin graft; *d* – evolution at 3 weeks; *e* – 90% of the graft integrated and healed

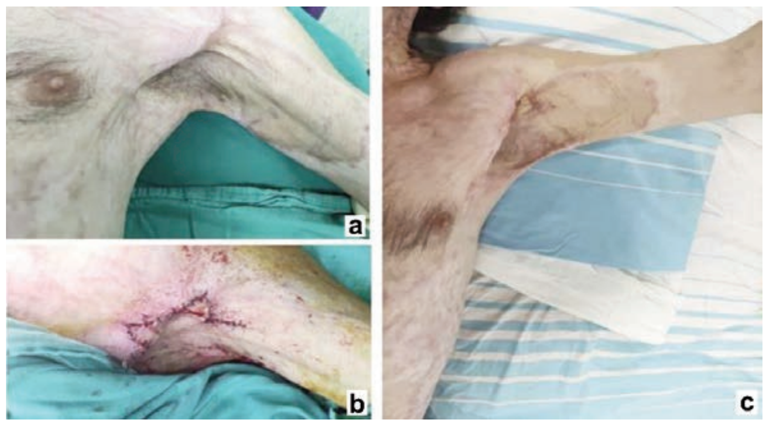

Fig. 5. 43-year-old patient with: *a* – axillary scar after burn injury; *b* – the scar by Z plasties; *c* – significant functional improvement of the shoulder abduction

Fig. 6. Male that suffered burns by flame to the right upper limb and the lower limbs

DISCUSSION

Assessment of burn severity

Burns represent a particularly severe form of trauma, with a high risk of mortality even in developed countries, having the potential to significantly impact the quality of life of survivors. The involvement of functional areas is one of the admission criteria in specialised burn centres, as it represents a severity factor that worsens the vital and functional prognosis of patients [1, 5].

In this study, we focused on burns affecting the major joints of the limbs, as their involvement poses unique challenges for specialised surgical treatment, both in the acute phase and throughout the patient's long-term recovery. Such cases demand an intensive, sustained rehabilitation program to restore quality of life and achieve an optimal functional outcome.

Out of the 140 total patients, only 112 met the eligibility criteria for this study, having burned joints. Male patients made up a significantly higher percentage, with 82 cases (73.2%), compared to only 30 female patients (26.8%), the percentage of male patients being similar to what other studies have described [11, 12]. The mean age was 50.52, with 17 patients being younger than 30 years of age, 17 in the 31–40 interval, 20 between 41–50, 22 between 51 and 60, 20 between 61 and 70 and 13 between 71 and 80 with only 3 cases older than 80.

Of critical importance in assessing the severity of the cases is the lesional mechanism that affects the prognosis of recovery. Extensive flame burns, which were the most frequent in this study (82 cases), affect multiple anatomical regions and cause inhalation injuries (27 of the total 30 inhalation injuries noted) while leading to severe systemic complications that will require prolonged health care by a multidisciplinary team [1]. The more infrequent etiologies are the chemical burns and the electrocutions. Chemical burns represent dynamic lesions caused by various substances, frequently determining deep burns that require excision and coverage by skin grafts. Electrocutions, in particular those caused by high voltage, lead to extensive tissue damage on the electric current passage with severe muscle destruction, rhabdomyolysis, nerve and artery destruction with ischemia events, compartment syndrome formation as well as potentially fatal systemic complications, such as acute kidney failure. Consequently, decompression fasciotomies and rapid excision of the devitalised tissues become mandatory [13]. Since the lesions may progress during the following days, serial debridements frequently become necessary. As such, this type of lesion produces complex defects involving the skin, musculotendinous system, neurovascular elements and even bone and joint involvement. Therapeutic strategies in these cases require elaborate reconstructive procedures.

One of the most important indicators was calculating the mean TBSA burned. A larger value is likely involving multiple joints, frequently accompanied by a longer hospital stay and leading to a significantly higher risk of developing contractures. In the same study performed by Tan et al., they found a higher incidence of contractures in the severely burned patients than in the less affected ones [11]. The mean TBSA calculated in this study was 24.7%, with the majority of patients having small burned surfaces, 41 patients (36.6%) having less than 10% burned surface, and another 30 patients (26.8%) had between 11 and 20% burned TBSA. Although the mean burned TBSA was not particularly high, the severity of the lesions was increased by the depth of the lesion. Hence, the percentage of 3rd-degree burns was noted in 61.6% of the cases having severe burns, while another 95 cases (84.8%) also associated deep intermediate burns. Another severity factor studied was the presence of inhalation injuries, as it increases the risk of mortality ranging from 45% to 78% [14, 15]. In our study group, 30 of the total cases (26.8%) had inhalation injuries, 8 of which also required tracheostomy.

Prognostic scores are an important tool for predicting the evolution of burn patients. One of the most widely used prognostic scores is the ABSI score, which assesses burn severity and estimates mortality risk, including total body surface area burned, burn depth, age, sex, and the presence of inhalation injuries [16]. According to the ABSI score, 21 out of the 112 patients (18.8%) faced a severe (score of 10–11) or a maximum (score ≥12) threat to life, statistically giving them the lowest chances of survival. This aligns with the 21 patients who did not survive, representing 18.8% of the total patient group.

Out of the total patient group, 59 had additional health issues. Due to the elevated risk of low adherence to treatment recommendations with some of these issues, it was important to highlight the ones most likely to impact the evolution: 18 patients had cardiac conditions such as heart failure or valvular disease, 3 had cancer, 29 had HBP (high blood pressure), 12 were diabetic and 20 obese. The greatest adherence challenges were observed among psychiatric patients (23 cases) or with those with chronic alcohol abuse (15 cases), totalling 38 patients (33.9%). Studies approximate that half of the patients with a psychiatric disorder do not adhere to the treatment recommendations [17–19].

Despite significant advances in therapeutic modalities, burns often lead to a range of complications, which can be broadly categorised into systemic and burn wound-specific issues. Systemic complications may involve multiple organs and systems and may include multisystem organ dysfunction, specific organ failures such as acute kidney injury with acute tubular necrosis, pulmonary failure, cardiac and hepatic failure, gastrointestinal system failure, hematologic complications (including anemia, thrombocytopenia, increased thromboembolic risk), central nervous system impairment and severe infectious complications (highly aggressive, multi-drug-resistant pathogens are frequently involved, including the ESKAPE group). Systemic dysfunctions can complicate the patient's recovery and increase mortality risk [4, 20–23].

Patients also experience persistent hypermetabolism, which places a considerable burden on nutritional and energy reserves, requiring long-term intensive metabolic support to meet the increased demands for recovery [24]. In addition to systemic complications, burn lesion-related problems are common and can significantly impact long-term outcomes. Burn wound infections and sepsis are frequent and serious complications that require permanent monitoring and prompt therapeutic management [20, 25]. Furthermore, burns frequently lead to abnormal wound healing, resulting in hypertrophic scarring, keloid formation, and, in some cases, heterotopic ossification, with bone formation in soft tissue areas. These burn-specific complications can alter mobility, impact quality of life, and require additional surgical interventions [26, 27].

Burn wound local treatment: modern dressings including textile technologies and surgical strategies

For deep burns, early excision and grafting have been the standard of care since the 1970s, using autografts for coverage, but patients with more extensive burns may require temporary coverage with allografts, xenografts, and dermal substitutes. For patients with partial-thickness burns, numerous options are available for dressings, with the choice depending on the depth of the burns, the location and the amount of exudate of the burn wounds, the desired frequency of dressing changes, and associated costs [28].

Burn wounds present unique challenges in wound management, and the selection of appropriate dressings is critical for successful treatment. Due to the complexity of these lesions, there is no universal dressing that can effectively address all types and stages of wound healing. Choosing the most suitable dressing for a burn wound requires a thorough clinical assessment. Key characteristics of an ideal burn dressing include the ability to alleviate pain, absorb wound exudates, prevent infection, and protect the wound from microorganisms. Additionally, the dressing should maintain a moist healing environment, provide optimal gas exchange, regulate temperature and pH, and have the ability to be non-toxic [29, 30].

Modern advancements in wound dressing materials have led to the development of composite dressings, incorporating layers with specific properties like elasticity and antibacterial activity to manage burns effectively. These advanced dressings often include bioactive compounds, such as collagen, colloidal silver, and hyaluronic acid, which enhance healing by supporting fibroblast proliferation, angiogenesis, and infection control. Furthermore, ideal dressings for burn wounds are designed for flexibility, ease of application and comfort, as pain management is crucial. Further research is carried out in textile technology to optimise the properties of wound dressings [30, 31] by designing and creating tri-layered structures to obtain a varied range of possible special effects. The three-layered structure consists of outer layer I, which plays the role of carrier, insulator and protector of the underlying layers, being elastic, resistant and sub-micro-porous (to block the physical access of microorganisms to the lesion), (layer II) – intended management of liquid compositions in the lesion area, macroporous and compressible, with open pores with high tortuosity and layer III – impermeable substrate – non-adherent, biologically inert and microporous. Antimicrobial properties are frequently integrated into burn dressings to inhibit the growth of bacteria such as Staphylococcus aureus and Escherichia coli and fungi like Candida albicans, helping to prevent infection, which represents a significant risk in burn wounds. Additionally, the hemocompatibility of these materials is crucial, ensuring minimal damage to blood cells while providing compatibility with the patient's tissues. Modern burn dressings are not only passive barriers; they are active, multifunctional materials that play an important role in facilitating wound healing and protecting patients from systemic complications [30, 32].

Textile dressings, being currently the most used type of local therapeutic strategy in burn care, offer several advantages, including widespread availability, ease of use by all healthcare workers, and affordability due to their low cost. Additionally, they allow for easy inspection of wound secretions, making them practical for monitoring wound healing progress [30, 33].

Traditional dressings serve essential functions, such as absorbing exudate, protecting the wound from contamination, and therefore supporting healing by keeping the wound environment clean. [31] While traditional dressings are still widely used, modern wound dressings represent an evolution in wound care technology; they are designed to create a moist healing environment, effectively manage wound exudate, support the body's enzymes in breaking down damaged tissue through autolytic debridement, and encourage tissue regeneration [34, 35]. This category includes hydrocolloids, hydrogels, foams, films, and hydrofibers [33, 36]. Film dressings are transparent, flexible coverings that conform to any wound shape without needing additional dressing material, allowing for wound inspection without removal. They can absorb small amounts of exudate, maintaining an optimal moisture balance for healing. Medicated films can also be preloaded with drugs. Hydrocolloids are specialised wound dressings with a dual-layer structure consisting of an impermeable outer layer that serves as a protective barrier for the inner hydrocolloid layer [33]. Hydrocolloid dressings are transparent or translucent and suitable for wounds with minimal to moderate exudate. These dressings are biodegradable, non-toxic, and breathable but are not recommended for deeper wounds, wounds with heavy exudate, or those needing free oxygen flow for healing [37]. Hydrofibers are particularly suitable for wounds with moderate to high exudates thanks to their fibrous scaffold of synthetic polymers such as polycaprolactone, polylactic acid, or carboxymethyl cellulose. When they are exposed to wound fluid, hydrofibers transform into a gel-like matrix with effective absorption capacity for wound exudates, preventing dryness and promoting a clean healing environment [38, 39]. Foams have an outer layer of polyurethane sheet, which forms pores in response to moisture-regulating gas exchange and water evaporation [40]. The inner matrix consists of polyols or polyacrylates, which enhance moisture resistance and water absorption capabilities [32]. Hence, they are the preferred choice for surgical wounds with high exudate levels and diabetic foot ulcers, and they should be avoided in wounds with low exudation, dry scars or similar conditions [38–41]. Hydrogels are made from a three-dimensional polymeric network. These are composed of a cross-linked network of hydrophilic polymers capable of absorbing and retaining huge volumes of water or wound exudate [32].

Recent advancements in wound dressing materials have led to the development of composite dressings, incorporating layers with specific properties like elasticity and antibacterial activity to manage burns effectively. These advanced dressings often include bioactive compounds, such as collagen, colloidal silver, and hyaluronic acid, which enhance healing by supporting fibroblast proliferation, angiogenesis, and infection control. Furthermore, ideal dressings for burn wounds are designed for flexibility, ease of application and comfort, as pain management is crucial. Further research is carried out in textile technology to optimise the properties of wound dressings [30, 31] by designing and creating tri-layered structures to obtain a varied range of possible special effects. The three-layered structure consists of outer layer I, which plays the role of carrier, insulator and protector of the underlying layers, being elastic, resistant and sub-micro-porous (to block the physical access of microorganisms to the lesion), (layer II) – intended management of liquid compositions in the lesion area, macroporous and compressible, with open pores with high tortuosity and layer III – impermeable substrate – non-adherent, biologically inert and microporous. Antimicrobial properties are frequently integrated into burn dressings to inhibit the growth of bacteria such as *Staphylococcus aureus* and *Escherichia coli* and fungi like *Candida albicans*, helping to prevent infection, which represents a significant risk in burn wounds. Additionally, the hemocompatibility of these materials is crucial, ensuring minimal damage to blood cells while providing compatibility with the patient's tissues. Modern burn dressings are not only passive barriers; they are active, multifunctional materials that play an important role in facilitating wound healing and protecting patients from systemic complications [30, 32].

Advancements in various technological fields have highlighted the promising role of textile technologies in the medical sector. These technologies have been utilised in the development of a wide range of materials for complex reconstructive applications, including skin substitutes, vascular prostheses, implants, and nerve conduits. Textile-based materials are particularly advantageous due to their cost-effective production, versatile fabrication processes, and favourable structural and biomechanical properties, making them a valuable asset in modern medical applications [42–44].

Smart textiles are revolutionising wound care by integrating sensors, drug delivery systems, and responsive materials to actively monitor and enhance the healing process. These advanced fabrics can track key wound parameters such as moisture, pH, temperature, and infection, enabling real-time feedback and personalised treatment. Their ability to release therapeutic agents, maintain optimal conditions, and support tissue regeneration makes them highly effective for chronic and acute wounds. With cost-effective production, flexibility, and remote monitoring capabilities, smart textiles offer a promising solution to improve patient outcomes and reduce healthcare burdens [45, 46].

Nanostructured textiles, particularly those developed using electrospinning technology, offer significant potential in treating severe burn injuries by providing bio-responsive scaffolds that enhance cell adhesion, proliferation, and tissue regeneration. These advanced materials are biocompatible, biodegradable, and non-toxic, ensuring safe clinical use without inducing chronic inflammation. Their high porosity and permeability facilitate nutrient and oxygen exchange, promoting wound healing while reducing scar formation and tension. Electrospun mats improve handling and can be functionalised with growth factors or antibiotics, determining enhanced cell growth with less tension and smoother skin surface than traditional regenerative solutions. In addition, they also improve the scar quality and enhance angiogenesis in preclinical trials. Supported by textile re-industrialization efforts and funding programs, these materials are scalable and cost-effective, with ongoing clinical evaluations aiming to validate their efficacy further. Nanostructured textiles represent a promising innovation in burn care, offering personalised, efficient, and sustainable solutions for better rehabilitation of these complex patients [47–49].

In our study, a high incidence of full-thickness and deep partial-thickness burns was collected, most of which were on the joints or the limbs, with a majority of the patients requiring surgical treatment. In the acute setting, incisions and fasciotomies were carried out for compartment syndrome release in 27 cases. As the gold standard for the treatment of 3rd-degree burns remains that of the excision of the entirely affected region and closure with skin grafts, this practice has been shown to significantly reduce the mortality rates and the length of stay [1, 50]. Thus, this became the most commonly performed operation, being used in 50 patients once, 11 patients required 2 grafting sessions, while the more severe cases required 3 or 5 subsequent graftings in 3, respectively, one case. The severity of the trauma in 7 patients with fixed joints and non-contractile muscle mass in the setting of increasing vasopressor support imposed the necessity of amputating a limb in 5 cases, while 2 other patients required 2 simultaneous amputations. The sequelar stages were treated using local flaps such as Z plasties in 3 cases, 1 local random flap in another case, a pedicled abdominal flap and the use of a locoregional latissimus dorsi flap for the reconstruction of the elbow.

Negative pressure wound therapy (NPWT) is another therapeutic strategy that is also useful for burn injuries. NPWT typically includes an open-pore polyurethane ether foam sponge covered with an adhesive film to form a semi-occlusive dressing and a negative pressure source consisting of a fluid collection system and a suction pump that generates negative pressure and removes excess fluid. NPWT uses controlled suction to remove excess fluid from partial-thickness burn wounds, helping to accelerate healing and reduce further wound progression [51–53].

Particularities of major joints of the limbs involved in severe burns

The issue of joint involvement is a particular one in the burned patient as they can be directly involved by the injury – which was described in 112 of the total cases (80 of these having hand burns), or they can be involved as well in patients with extensive burns without a direct injury of these joints. A large burn injury typically requires an extended length of ICU stay, which, alone, is associated with a significant incidence of contracture [8, 54, 55].

The direct involvement of the joint frequently is treated by the aforementioned therapeutical principles using dressings and by surgical resolve. Of particular interest is the importance of prophylaxis of the contractures, which is achieved by using non-meshed good-quality skin grafts if the donor sites are sufficient. The use of dermal substitutes may prove useful in these cases when the donor sites are scarce. A meticulous operative technique that determines the adherence of the graft to the bed is essential, as well as the post-operative splinting, with all patients benefiting from a strict kinetotherapy program [56, 57]. Aside from the systemic management of these patients, in cases of joint involvement in patients with a high burned TBSA, it is crucial to conduct a correct assessment of the depth of the burned lesions, which may lead to the following therapeutic conduct. Superficial partial thickness may be managed conservatively by aiding the epithelisation using different dressings according to the lesional characteristics. Deep partial-thickness and full-thickness burns require excision and rapid coverage to avoid local complications and sequential functional deficit. The surgical excision can be performed either tangentially using the dermatome or may require excision down to the fascial plane, thus limiting the blood loss but determining more important functional sequelae. Alternative methods are represented by hydro-surgical debridement (Versajet®) or enzymatic debridement using Nexobrid® [58]. The decisive coverage is done with thick, non-meshed skin grafts to avoid scar contracture. Dermal substitutes such as Integra® and Alloderm® may be used to improve functionality but must also be covered with skin grafts [59].

The most severe lesions that lead to exposure of the articular surfaces or the bone will require complex reconstructive methods using flaps [60]. Most of these cases involve electrocution injuries, and therefore, these patients require flap coverage. In one case, a latissimus dorsi flap was used, while two other patients received coverage with random circulation flaps.

Burn contractures affect almost one-third of the total burn patients, leading to a major functional impairment and increasing costs while affecting the patient's physical function, pain and quality of life [61]. Therefore, the importance of effective prevention with treatment strategies aimed at decreasing morbidity and expenses as well as proper body positioning and splinting of the joint structures [62].

Recently, Raborn and Janis published a review paper analysing the latest available data on burn contractures. Despite the extensive number of articles reviewed, they concluded that the literature lacks robust evidence to support the development of an anatomically based algorithm for contracture management. Each anatomical site has its particularities with several reconstructive options but few comparisons between the options. However, they could derive some conclusions: flaps have better outcomes with a lower risk of re-contracture compared to grafts, acellular dermal matrices may decrease the risk of graft contracture, laser therapy mildly reduce contractures and several drugs have been proven to inhibit contracture formation [61]. When establishing a protocol for the surgical treatment of burn patients, prioritising functional zones such as the joints is essential.

A prolonged interval of physical inactivity, which is associated with the burn treatment and the contraction of the scar tissue surrounding the joint, is highly likely to impede joint mobility and recovery. Even though every joint in the body may suffer modifications, the most prone to the formation of contractural deformities are the shoulder, the elbow (most often), the hip and the knee [8]. Studies have shown the fact that wearing splints drastically reduces the incidence of contracture formation from 79% to 26% in the case of the axilla, respectively from 55% to 12% in the case of the elbow, with an even more drastic reduction in incidence if the splints were worn more than 6 months. Consequently, in their study, more than 90% of the 219 individuals who did not use splints necessitated reconstructive surgery, while the incidence of surgery in the lot who used decreased dramatically to 25% [63].

The management of joint contractures can be divided into three stages: acute, intermediate phase of the recovery and established contractural deformities. In the first phase, the main factors leading to contractural deformities are inadequate physical exercise as well as lack of joint splinting. In this setting, splinting of the joints and proper body positioning become necessary. The second phase spreads from the second to the fourth month following burn injury with a physiologically active cicatricial process having the highest collagen synthesis rate and an increase in the myofibroblast population thus being recommended the continuous use of splinting alongside pressure to support the joints and the burned sites [26]. Compression garments prevent the formation of hypertrophic scars if they have not formed yet [64]. The contractural deformities usually require surgical reconstruction, although there also are cases that can be treated by a nonoperative approach, usually after a long period of inactivity and less from scar contracture [8,65,66].

The classic recommendation is that surgical treatment for contractures should be undertaken after the active phase of healing has ceased, usually nearly 1 year when the scar is mature, supple and avascular. Operation on a still active scar, which is in the phase of contraction, may insult the traumatised tissues, leading to a further contraction, ignoring the fact that in this stage, physical therapy approaches may significantly improve the condition. There are some exceptions to this rule, on the subject at hand worth mentioning would be the crippling contractures of the hand, especially those leading to hyperextension of the metacarpophalangeal joints with permanent damage of the extensor mechanism and the contractures of the knees, affecting the upright human position as well as any incapacitating contracture which does not improve by physical therapy [64].

Summarising the aforementioned data, two primary causes of joint injury are highlighted: direct burns and articular contractures, both of which can lead to complex, progressive lesions that may impact various joint structures. Currently, there is no clear consensus on the optimal treatment for these lesions. As a result, prioritising preventive measures, early therapeutic intervention, and a continuous rehabilitation program are essential to reducing morbidity, minimising functional loss, and improving quality of life.

CONCLUSIONS

Burns are among the most severe types of trauma, with high mortality risks even in developed countries and a profound impact on the quality of life for survivors. When functional areas, such as major joints, are affected, these injuries are considered particularly severe, requiring specialised care due to their negative impact on acute recovery and long-term functional outcomes. This study focuses on burns involving major limb joints, which present unique challenges for specialised surgical treatment during the acute phase and throughout long-term recovery. Managing such cases requires intensive, sustained rehabilitation to restore functionality and enhance the patient's quality of life. Our findings emphasise the importance of early intervention and individualised therapeutic strategies for joint-involved burns. By implementing focused surgical and rehabilitative approaches, healthcare providers can address the complex pathophysiology of these injuries, reduce the risk of debilitating complications, and optimise recovery outcomes for burn survivors. The importance of the local treatment has been proven in the evolution of the burned patient, more so when treating the functional ones. Textile technologies represent a promising field for burn wound care in the acute setting as well as during patient rehabilitation.

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