FABRIC SELECTION FOR THE REFERENCE CLOTHING DESTINED FOR ERGONOMICS TEST OF PROTECTIVE CLOTHING—SENSORIAL COMFORT POINT OF VIEW

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Abstract:

The main purpose of this study is the selection of a proper fabric for the reference clothing for ergonomic tests of protective clothing. For research, seven fabric of different raw material content and different structure were chosen. We studied the handle of fabrics produced from blend of polyester/cotton and polyester/Tencel, which were designated by letters from A to G. The assessment of handle of the fabric was performed based on the mechanical properties of fabrics using Kawabata evaluation system (KES-system).

It was proven that one of the tested fabrics (F) made of polyester and cotton fibers (85% PES / 15% cotton) with the reinforced twill weave is characterized by the highest total hand value (THV). The high THV results from the low value of koshi (stiffness) and the highest value of numeri (smoothness) and fukurami (fullness). However, in terms of physiological comfort, the lower value of fukurami is more preferred. It turned out that the fabric with the higher value of fukurami (including fabric F) is characterized by the lower air permeability and higher water vapor resistance.

At the end, we decided that the reference clothing will be made of cotton/polyester fabric G with the lowest mass per square meter because of the very good physiological comfort parameters and the satisfactory sensorial comfort parameters.

Keywords:

Sensorial comfort, total hand value, reference clothing, protective clothing, ergonomics

1. Introduction

Leaving aesthetics and psychological aspects, we can say that utility comfort of clothing depends on physiological comfort parameters and sensorial comfort parameters [1]. Physiological comfort is determined by the fabric parameters, such as the thermal resistance, water vapor resistance, hygroscopicity, and air permeability. A measure of sensorial comfort is the total hand value (THV) designated with the use of Kawabata evaluation system (KES-system) [1, 2]. The sensorial comfort is a multidimensional concept, and it is impossible to define it through a single physical property. The fabric handle is defined as the total sensations associated with the human being during the manipulation in the fingers of fabric or touching the fabric [3]. This parameter is related to the fabric properties, such as surface contour (roughness, smoothness), density, flexibility, elasticity, resilience, compressibility, surface friction, and thermal character [4]. Raw material, yarn structure, fabric structure, as well as finishing treatment affect the fabric THV [1, 2, 4–6].

Chen et al. [7] compared the handle of two differential-shrinkage (DS) polyester warp knitted fabrics with 100% cotton warp knitted fabric. Research conducted with the use of KES-system shows that the warp knitted fabrics made of DS polyester provide better recovery under low-stress mechanical pressure. The handle of these fabrics was also evaluated subjectively

by 20 women. It turned out that the DS polyester warp knitted fabrics had similar handle to cotton warp knitted fabric in terms of smooth, prickle, comfort, and dry feeling in both dry and wet testing conditions.

Behera et al. [8] studied the handle of fabrics produced from 100% linen and their blends with cotton and viscose. Research shows that 100% linen fabrics were characterized by the highest tensile resilience and bending rigidity, but the addition of cotton or viscose to linen helps to reduce the bending rigidity of these fabrics. Moreover, cotton/linen blended fabrics give comparatively lower surface roughness and surface friction than 100% linen fabrics. By comparing the THV of the fabric, it was found that the 100% linen fabrics exhibit the higher value of this parameter than the 100% cotton fabrics.

A big impact on the fabric stiffness and its handle has a fiber diameter [9, 10]. Hunter et al. [9] ascertained that an increase in the fiber diameter causes increase in the koshi (stiffness), hari (anti-drape), and shari (crispness), but decreases fukurami (fullness) of the fabric. The fabric handle also depends on the cross-sectional shape of fibers [5, 11, 12]. Matsudaria et al. [11] indicated that with an increase in the space ratio in the cross section of the fiber, the fabric becomes soft and deformable.

A direct impact on the fabric handle has also a twist yarn [2, 13, 14]. Several studies [2, 6, 12, 14] shown that fabrics made of

yarns with larger twist are characterized by the higher bending stiffness, less bulkiness, less compressibility, less fiber mobility, and lower surface friction than similar fabrics produced from yarns with the lower twist value [6]. Moreover, research proved that the plied yarns made of two or more single yarns twisted together are stiffer in comparison to the single yarns [12]. Sometimes, in order to improve the handle of filament yarns, these yarns are subjected to texturing process [5]. Thereby the volume of yarn and its stretchiness increase and the fabric becomes more pleasant, less synthetic in touch, softer, and warmer.

Behera et al. [15] compared the fabric hand made of the ring, rotor, and friction spun cotton yarn. Their research shows that fabrics produced from ring yarns are characterized by lower bending, shear rigidity, and hysteresis than the fabrics made of rotor or friction yarns.

Several studies [16, 17, 18, 19, 20, 21] shown that the fabric structural parameters shows a huge impact on the fabric handle. Matsudaria et al. [14] proved that the increase in the weft density results in the increase in koshi (stiffness) and hari (anti-drape), but, at the same time, shari (crispness) decreases. Plain weave fabrics have the higher bending rigidity and shear rigidity in comparison to other fabrics because of the larger number of yarn interlacing [5, 14, 22]. Furthermore, these plain fabrics are characterized by a very compact structure resulting in the lower thickness, whereas twill fabrics are more flexible, smooth, and more compressible [22]. It was confirmed by research conducted by Bensaid et al. [17]. Twill fabrics have the higher fukurami than plain fabrics, so they have the higher THV [22].

Another factor affecting the fabric handle is their finishing treatment [6, 12, 22]. High-speed scouring and milling create a fibrous surface and, at the same time, it changes the other properties of the fabric, particularly the shear rigidity and volume. The heat treatment may cause crimping the fibers, leading to the increase in fabric bulkiness. Meanwhile, the 'peach skin' effect on the surface of fabric can be obtained by an enzymatic treatment. As a result, the fabric becomes soft and pleasant in touch [6].

Processes such as cropping and singeing lead to the removal of fibrous protrusions from the surface of fabric and thus the surface of fabric becomes smooth [6].

Research conducted by Mamalis et al. [23] showed that the flame-retardant finishing of knitted fabrics affected their mechanical properties. As a result of finishing processes, the bending and shear rigidities increased significantly, what adversely affected the knitted fabrics handle.

Kawamura et al. [24] studied the handle of jean fabrics from different countries and manufacturers. Their research showed that the jeans fabrics produced in the United States were rough and hard, but the Japanese fabrics were soft and smooth. Moreover, they confirmed that the hand of fabrics including jean fabrics have a direct relationship with their physical properties.

The above examples show that the fabric handle depends on many factors that should be considered according to the assessment of fabric in terms of sensorial comfort.

In this paper, we focus on the study of fabrics parameters having a direct impact on sensorial comfort. Using the instruments included in the KES system, the THV and the primary hand values, that is, koshi, numeri, and fukurami were determined. The aim of this study was picking the appropriate fabric for the reference clothing. The selection was performed based on the results of parameters influencing the physiological and sensorial comfort.

2. Experimental

2.1 Materials

For research, seven fabrics of different raw material content and different structure were chosen. The fabrics were designated by letters from A to G (Table 1). In six cases, these are cotton/polyester fabrics, wherein three of them, that is, fabrics D, E, and G were characterized by the identical weave and the content of constituent fibers (35% cotton/65% PES), while the remaining structure parameters, that is, the warp and weft density, warp and weft linear density, mass per square meter, and thickness, were different. A viscose/polyester fabric with a preponderance of polyester fibers was also tested.

The selection criterion was the low mass per square meter and appropriate raw materials, that is, the contents of both the hydrophilic fiber (cotton or viscose) and hydrophobic fiber (polyester). The participation of both kinds of fiber can provide satisfactory biophysical and biomechanical properties.

2.2 Methods

KES-system developed in JapanKawabata [25] was used for research. This system includes four instruments for measuring mechanical properties of fabrics at low stresses (tensile, shear, bending, compression) and the surface properties (friction and roughness) (Table 2). These properties determine the fabric handle [26].

The characteristic values calculated by the KES system on the basis of curves obtained on particular instruments were given in Table 1.

Tensile and shear properties were measured on the same instrument (KES-1) for both warp and weft directions. Bending properties were determined on the instrument KES-2, also in both directions, whereas compression properties were measured in any direction on the instrument KES-3. In turn, the measurements of surface properties of fabrics, such as coefficient of friction and surface roughness, were performed on the same instrument (KES-4) but using different detectors.

Measuring principles of the KES system were illustrated in Figure 1.

Table 1. Fabric characteristics

Symbol	Raw materials	Linear density (tex)		Weave	Number of threads per 1 dm (dm ⁻¹)		Mass per square meter (g/m ²)	Thickness (mm)
		Warp	Weft		Warp	Weft		
A	Tencel 30% PES 70%	32.0 ± 0.56	29.2 ± 0.63	Twill 2/1 S	389 ± 1.30	241 ± 0.84	196.9 ± 1.51	0.29 ± 0.005
B	Cotton 65% PES 35%	28.3 ± 0.72	27.4 ± 0.77	Twill 2/1 S	370 ± 1.67	238 ± 0.71	190.0 ± 1.24	0.38 ± 0.007
C	Cotton 50% PES 50%	20.8 ± 0.66	19.5 ± 0.59	Satin 4/1(2)	545 ± 1.64	325 ± 1.34	184.9 ± 0.93	0.36 ± 0.005
D	Cotton 35% PES 65%	31.1 ± 0.65	32.1 ± 0.65	Twill 2/1 S	382 ± 1.73	244 ± 1.48	212.7 ± 0.56	0.37 ± 0.000
E	Cotton 35% PES 65%	29.8 ± 0.52	30.0 ± 0.67	Twill 2/1 S	401 ± 1.10	237 ± 1.67	207.4 ± 0.72	0.40 ± 0.0005
F	Cotton 85% PES 15%	19.6 ± 0.61	18.6 ± 0.65	Reinforced twill 2/2 S	572 ± 2.05	320 ± 1.48	196.6 ± 1.69	0.38 ± 0.003
G	Cotton 35% PES 65%	18.4 ± 0.45	24.1 ± 0.58	Twill 2/1 S	521 ± 1.41	238 ± 1.87	176.4 ± 0.54	0.35 ± 0.000

Table 2. Mechanical and surface parameters of fabric [25]

Test	Symbol	Description	Unit
Tensile	LT	Linearity of load/extension curve	–
	WT	Tensile energy	(g·cm)/cm ²
	RT	Tensile resilience	%
	EM	Extensibility	%
Shearing	G	Shear stiffness	g/(cm·deg)
	2HG	Hysteresis of shear force at 0.5° shear angle	g/cm
	2HG5	Hysteresis of shear force at 5° shear angle	g/cm
Bending	B	Bending rigidity	(g·cm ²)/cm
	2HB	Hysteresis of bending moment	(g·cm)/cm
Compression	LC	Linearity of compression/thickness curve	–
	WC	Compressional energy	(g·cm)/cm ²
	RC	Compressional resilience	%
Surface characteristics	MIU	Coefficient of friction	–
	MMD	Mean deviation of MIU	–
	SMD	Geometrical roughness	µm
Thickness	T	Fabric thickness	mm
Mass per square meter	W	Fabric mass per square meter	mg/cm ²

Figure 1. Measuring principles of the KES system

The measurements were conducted at the Faculty of Material Technologies and Textile Design in the Lodz University of Technology.

The values listed in Table 1 are used by the KES system to calculate the primary hand values and the THV of fabrics. Table 3 contains the definitions of the primary hand values determined for fabrics selected for research.

3. Results and discussion

3.1 Tensile properties

The low-stress tensile properties of fabrics are presented in Table 4. The fabrics were analyzed by paying special attention to the linearity of load extension curve (LT), tensile energy (WT), tensile resilience (RT), and extensibility (EM).

The LT parameter informs us about the linearity of the load–elongation curve and fabric extensibility at the initial strain range [22]. Low value of LT indicates the high elasticity of material, thus ensuring the high level of clothing utility comfort [22]. Research shows that the fabric F is characterized by the lowest mean value of LT. This fabric has a reinforced twill weave in contrast to other fabrics. The similar low linearity of

load–extension curve in both directions is exhibited also by the twill fabric B.

Tensile energy (WT) is interpreted as the area under the load–elongation curve [25]. The high value of this parameter indicates the high strength of fabric but, at the same time, affects the lower hand value. The results show that the fabric G has the lowest tensile energy, which is probably due to the smallest mass per square meter of this fabric. In the case of fabric G, the WT value in the weft direction is only 3.38 (g·cm)/cm² and it is more than four time slower than the WT value of fabric D with the highest mass per square meter. In the case of fabric D, there occurs a big difference between the WT value in the weft direction (WT = 15.57 (g·cm)/cm²) and in the warp direction (WT = 4.48 (g·cm)/cm²). These differences are also visible in the force–elongation graph (Figure 2).

Tensile resilience (RT) means a recovery from the tensile deformation. Fabrics with the higher value of RT have the better handle [22]. Among the tested fabrics, the fabric G exhibits the highest tensile resilience, especially in the weft direction where RT is nearly 83%. In the case of other fabrics, values of this parameter do not exceed 70%.

The high value of extensibility (EM) means the greater utility comfort. In terms of the handle, it is more advantageous when

Table 3. Definition of primary hand values [25]

Hand		Definition
Japanese	English	
Koshi	Stiffness	A feeling related mainly to the bending rigidity. A springy property intensifies this feeling. The fabrics having a compact structure and made of elastic yarn usually gives the high value of this feeling.
Numeri	Smoothness	It is a combination of soft, supple and smooth feelings. The fabric made of cashmere fiber have a high value of this feeling.
Fukurami	Fullness and softness	The mixed feeling coming from a combination of bulky, rich and well-formed impressions. This feeling is closely related to the springy property in compression and fabric thickness.

Table 4. Tensile properties

Parameter A		Fabric symbol						
		B	C	D	E	F	G	
LT (–)	o	1.304	1.335	1.414	1.435	1.456	1.262	1.355
	w	1.377	1.331	1.385	1.260	1.376	1.337	1.444
	m	1.341	1.333	1.400	1.347	1.416	1.299	1.400
WT ((g·cm)/cm ²)	o	4.00	6.15	5.35	4.48	5.53	8.60	6.08
	w	6.40	8.85	6.50	15.57	9.03	13.97	3.38
	m	5.20	7.50	5.93	10.02	7.28	11.28	4.73
RT (%)	o	66.65	62.89	60.44	66.17	57.83	52.90	62.19
	w	65.39	65.92	66.16	57.71	62.56	55.26	82.81
	m	66.02	64.40	63.30	61.94	60.20	54.08	72.50
EM (%)	o	1.23	1.84	1.51	1.25	1.52	2.74	1.80
	w	1.86	2.66	1.88	4.94	2.63	4.18	0.94
	m	1.54	2.25	1.69	3.10	2.07	3.46	1.37

Abbreviations: o, warp; w, weft; m, mean

the value of EM is higher [26]. Research showed that the fabric G, which received the highest value of RT in the ranking, was characterized unfortunately by the lowest mean of EM. In turn, the fabrics D and F have the highest values of EM, particularly in the weft direction, where EM exceeds 4%. It is further noted that in most cases (except the fabric G), the EM is higher in the weft direction than that in the warp direction.

Figure 2. The load–elongation curves for fabric D. Black represents warp direction and red weft direction

3.2 Shear properties

Shear properties of fabrics are described by parameters such as the shear rigidity (G), hysteresis of shear force at 0.5° shear angle (HG) and hysteresis of shear force at 5° shear angle (2HG). The results of these parameters are given in Table 5.

Shear rigidity (G) is defined as the fabric resistance to the movement of warp and weft threads at the cross-over points when the fabric is subjected to shear deformations. In terms of the handle, the lower value of this parameter is more preferred [27]. Research shows that the fabrics C and F are characterized by the lowest shear rigidity. That results mainly from the structure of these fabrics, because the fabric C has a satin weave and the fabric F has reinforced twill weave. Other fabrics are twill weave fabrics. Thus, weaves of fabrics C and F are characterized by the smaller number of warp and weft interlacements than the twill weave, what affects the handle improvement. Moreover, it was noted that in all cases, the value of G was lower in the weft direction than that in the warp direction, which was probably due to the lower density of weft threads. In turn, the highest shear stiffness have fabrics D and E, which are characterized by the highest mass per square meter in comparison to other fabrics.

The values of 2HG and 2HG5 mean the hysteresis of shear force at 0.5° and 5° . The existence of shear hysteresis loop means that the deformed fabric cannot resume its original geometrical state [6]. Therefore, it is more advantageous that the value of 2HG and 2HG5 are lower. Among the tested fabrics, fabrics C and F have the lowest values of these parameters, which are also characterized by the lowest shear stiffness (G). In the contrast, fabrics D and E have the highest value of 2HG and 2HG5. In Figures 3 and 4, the shear stress–strain curves for fabrics F and E were shown.

Figure 3. The shear stress–strain curves for fabric F

Figure 4. The shear stress–strain curves for fabric E

Table 5. Shear properties

Parameter		Fabric symbol						
		A	B	C	D	E	F	G
G (g/(cm·deg))	o	4.94	3.70	3.13	5.40	5.30	3.32	4.28
	w	4.11	3.48	3.10	4.25	4.62	2.70	3.57
	m	4.53	3.59	3.12	4.82	4.96	3.01	3.93
2HG (g/cm)	o	6.22	5.79	4.31	8.53	9.87	4.82	9.51
	w	4.50	5.34	4.50	8.63	8.27	2.77	3.02
	m	5.36	5.57	4.40	8.58	9.07	3.80	6.27
2HG5 (g/cm)	o	13.97	9.64	6.99	16.81	18.16	8.44	15.37
	w	11.51	8.77	6.79	13.93	15.51	5.33	9.55
	m	12.74	9.20	6.89	15.37	16.83	6.88	12.46

Abbreviations: o, warp; w, weft; m, mean

3.3 Bending properties

The bending rigidity (B) and the hysteresis of bending moment (2HB) are the characteristic parameters determined by the bending test. The values of these parameters are given in Table 6.

The bending rigidity (B) is a measure of easeness with which the fabric bends. The low value of this parameter indicates the better fabric handle [28]. Research shows that the bending rigidity of fabrics is not the same in both directions. The fabrics folded in the warp direction exhibit the higher value of this parameter. It can be explained by the fact that the warp threads are generally more twisted, because it has to resist the stresses to which they are subjected during the weaving process. However, the high twist of yarn results in the high rigidity of fabric; thereby, it is impairing its handle. Research exhibits that the fabric G is the less rigid, despite the fact that its bending rigidity in the weft direction is slightly higher than that in the case of fabrics B–F. The low value of fabric B is mainly due to the low mass per square meter, which is directly related with the low linear density of warp. In turn, the mean bending rigidity of the fabric E is more than twice higher than that of the fabric B. This is due to the fact that this fabric has the largest thickness and the relatively high mass per square meter in comparison to other fabrics.

Pavlinić and Geršak defined [29] the hysteresis of bending moment as a measure of fabric's ability to recover. The lower value of 2HB is more advantageous, because it means the higher fabric elasticity [22]. According to Table 6, the fabric F gives the smallest hysteresis of bending moment in both warp and weft directions, but in the weft direction, this value is more than twice lower. Meanwhile, the largest value of this parameter was obtained for the fabric E, especially in the warp direction. The examples of bending hysteresis are shown in Figure 5.

Figure 5. The bending hysteresis for fabric F

3.4 Compressional properties

Kawabata and Niwa developing the KES system proposed three parameters to describe the compressional properties of fabrics. They are the linearity of compression/thickness curve (LC), compressional energy (WC), and compressional resilience (RC). The values of these parameters for the selected fabrics are shown in Table 7.

These parameters are closely related to the primary hand value (fukurami) of fabric. The higher value of WC means the higher compressibility of fabric, which in turn is associated with the feeling of bulkiness [22]. An important parameter affecting the value of WC was found to be the thickness of fabric. Analyzing the results, the significant difference in the value of WC of fabrics with the highest (fabric E) and the smallest thickness (fabric A) can be seen. The value of WC in the case of fabric E is 0.193 (g·cm)/cm², and in the case of fabric A, this value is only 0.149 (g·cm)/cm².

Table 6. Bending properties

Parameter		Fabric symbol						
		A	B	C	D	E	F	G
B ((g·cm ²)/cm)	o	0.202	0.133	0.140	0.210	0.357	0.168	0.114
	w	0.104	0.076	0.070	0.088	0.103	0.079	0.093
	m	0.153	0.105	0.105	0.149	0.230	0.123	0.103
2HB ((g·cm)/cm)	o	0.1845	0.1303	0.1452	0.2333	0.3201	0.1204	0.1290
	w	0.1057	0.0676	0.0632	0.0798	0.1013	0.0579	0.1296
	m	0.1451	0.0989	0.1042	0.1566	0.2107	0.0891	0.1293

Abbreviations: o, warp; w, weft; m, mean

Table 7. Compressional properties

Parameter	Fabric symbol						
	A	B	C	D	E	F	G
LC (–)	0.692	0.432	0.508	0.583	0.552	0.428	0.578
WC ((g·cm)/cm ²)	0.149	0.196	0.186	0.178	0.193	0.185	0.156
RC (%)	74.94	64.69	66.80	70.68	68.21	65.65	75.38

Compressional resilience (RC) informs about the spongy properties of fabric, in other words, its ability to return after the compressional deformation [8]. Research shows that in most of the cases, the value of RC does not exceed 75%. The exception is the fabric G. The lowest values of compressional resilience (RC) were noted for fabrics with the highest content of cotton fibers (fabrics B and F). Therefore, it can be concluded that the raw materials also affect the compressional properties of fabrics. An example of the compressional curve is shown in Figure 6.

Figure 6. The compressional curve for fabric F

3.5 Surface properties

The surface properties of fabrics are described by the parameters such as coefficient of friction (MIU), mean deviation of MIU (MMD), and geometrical roughness (SMD). The values of these parameters for the different fabrics are shown in Table 8.

The surface properties of fabrics have a huge impact on their handle. These properties decide on numeri (smoothness) of fabric. Research exhibits that all fabrics are characterized by higher coefficient of friction in the weft direction than that in the warp direction. This relationship also occurs in the case of parameter MMD. This is mainly due to the lower weft density in the structure of fabrics. Owing to the fact that the fabric G exhibit the lowest mean value of MIU in both directions and the relatively low value of MMD, it can be assumed that this fabric is also characterized by high smoothness. In turn, the highest value of MIU was recorded for the satin weave fabric C tested in the weft direction.

Table 8. Surface properties

Parameter		Fabric symbol						
		A	B	C	D	E	F	G
MIU (-)	o	0.143	0.148	0.146	0.147	0.153	0.144	0.130
	w	0.155	0.154	0.163	0.157	0.160	0.148	0.140
	m	0.149	0.151	0.154	0.152	0.156	0.146	0.135
MMD (-)	o	0.0073	0.0079	0.0071	0.0082	0.0091	0.0091	0.0075
	w	0.0255	0.0259	0.0124	0.0244	0.0212	0.0102	0.0173
	m	0.0164	0.0169	0.0097	0.0163	0.0151	0.0096	0.0124
SMD (μm)	o	1.19	1.53	1.11	1.55	1.75	2.12	1.57
	w	2.07	3.04	2.08	2.84	2.76	1.79	1.67
	m	1.63	2.29	1.60	2.20	2.26	1.95	1.62

Abbreviations: o, warp; w, weft; m, mean

Among all of the fabrics tested in terms of surface properties, the fabric C gives the lowest surface roughness, especially in the warp direction. The relatively low values of SMD at a level not exceeding 1.7% was also obtained for fabrics characterized by the smallest thickness (fabric A and G). In contrast, the highest geometrical roughness exceeding 3 μm was noted in the case of fabrics B tested in the weft direction. The surface properties of fabrics G and B are compared, and the results were illustrated on the graphs shown in Figures 7 and 8).

Figure 7. Surface behavior at low deformation (fabric B). Black represents warp direction and red the weft direction

Figure 8. Surface behavior at low deformation (fabric G). Black represents warp direction and red the weft direction

3.6 Hand value of fabrics

For the assessment of sensorial comfort of fabrics, the primary hand values, that is, koshi, numeri, and fukurami, and the THV have to be determined. The primary hand values were calculated from the empirical equations [25] using the mechanical parameters obtained on the instruments of KES system. THV was calculated by the KES-system from the following regression equation [25]:

$$THV = -1,2293 + 0,5904Y_1 - 0,0441Y_1^2 - 0,1210Y_2 + 0,0517Y_2^2 + 0,6317Y_3 - 0,0506Y_3^2 \quad (1)$$

where

Y_1 is the koshi (English: stiffness),

Y_2 is the numeri (English: smoothness),

Y_3 is the fukurami (English: fullness).

The results of primary hand values and THVs of fabrics are given in Table 9 and Figure 9.

Research exhibited that the fabric F is characterized by the highest THV (3.89), as can be seen in Figure 9. This is due to the low value of koshi (stiffness) and the high values of numeri (smoothness) and fukurami (fullness).

Figure 9. Total hand value of fabrics

In the case of tested fabrics, one of the primary hand values—koshi (stiffness)—is particularly important. Clothing made of fabric characterized by high stiffness makes that the movement of worker is impeded; and thereby, it reduces the efficiency and productivity of carried out work. The stiffness of fabric (koshi) is closely related to its thickness, mass per square meter, and mechanical parameters determined in bending, tensile, and

shear tests that reflect the real conditions of clothing use. The fabrics that reached the lowest value of koshi have the satin weave (fabric C) and reinforced twill weave (fabric F). These weaves (in particular the satin weave) are characterized by much smaller number of yarn interlacements than the twill weave used in five other fabrics. In turn, the small number of warp and weft interlacements translates into the lower value of koshi (stiffness) of fabric, which is confirmed by the results of the shear rigidity (G). An important parameter influencing the value of koshi is the bending rigidity (B). The fabric E is characterized by the highest value of this parameter, which coincides with the highest value of koshi. In turn, the lowest value of bending rigidity (B) in the weft direction has the fabric C, but the fabric G is characterized by the lowest mean value of this parameter.

The selected fabrics were also analyzed in terms of numeri (smoothness), which is the combined feeling coming from the characteristics, such as smoothness, softness, and crimp. The numeri depends on both the surface properties of fabric and the parameters designated in the bending test and compression test. Although the fabric G is characterized by the lowest mean of coefficient of friction (MIU) and the relatively low value of geometrical roughness (SMD), this fabric didn't reach the highest value of numeri. Owing to this reason, the fabrics F and C, which are characterized by the lowest value of MMD, were found to be the best. This is mainly due to the structure of fabrics, because these fabrics have the largest density of the warp and weft threads in comparison to other fabrics. In addition, these fabrics were made of yarn of the low linear density (no exceeding 21 tex). This fabric structure gives a high uniformity of surface and, therefore, a high feeling of smoothness.

Fukurami (fullness) is the last primary hand value of fabrics that has been analyzed. This feeling is related to the elasticity of the material undergoing the compression, its thickness, and the feeling of warm handle. As research exhibited, the fabric F has the highest value of this parameter. It is the fabric with the highest content of cotton fibers, which give a warmth feeling at touch. A high value of fukurami of fabric F also results from the large density of warp and weft threads and the relatively high mass per square meter and thickness. However, because of the fact that the selected fabric will be destined to the clothing in which the user will perform the physical exercise, so in terms of physiological comfort, the value of fukurami should not be high. The lowest value of fukurami at the level below 2 was obtained for the polyester/viscose fabric A. However, this fabric is characterized by one of the highest value of koshi, which is

Table 9. Primary hand values of fabrics

Parameter	Fabric symbol						
	A	B	C	D	E	F	G
Koshi	8.27	6.3	6.14	7.65	8.75	6.33	6.67
Numeri	2.65	5.71	5.71	2.96	2.92	6.22	3.80
Fukurami	1.85	4.08	4.08	2.95	3.01	5.07	2.75
THV	1.67	2.55	3.46	2.22	2.09	3.89	2.39

not beneficial. The relatively low value of fukurami and koshi were reached in the case of fabric G.

Figure 10. Primary hand values of fabrics

4. Conclusions

Performing the selection of fabrics to the reference clothing, there was a need to take into account both the parameters of physiological comfort (i.e., the air permeability, heat resistance, water vapor resistance, hygroscopicity) and parameters of sensory comfort (i.e., primary hand values and THV). It is very important because the total utility comfort of clothing, aside from aesthetic and psychological aspects, depends on sensory sensations arising from the contact of skin with the clothing and physiological sensations related to the possibility of discharge of carbon dioxide and sweat from the skin surface.

The fabric G containing 65% PES and 35% cotton in the structure and characterized by the lowest mass per square meter is found to be the best in terms of physiological comfort. In terms of hygroscopicity, this fabric is found in the fourth position, but in terms of the water vapor resistance, this fabric is the best, because it exhibits the lowest value of this parameter. The low values of the water vapor resistance are also exhibited by the fabrics E and D. All these fabrics contain 65% of polyester fibers in the structure. Polyester fibers as the hydrophobic ones practically do not absorb moisture but are able to transmit it by diffusion for hydrophilic fibers, so that the moisture is drained from the skin surface, giving the user the feeling of comfort.

Research also showed that the fabric G was characterized by the highest air permeability, exceeding 200 mm/s. The high value of this parameter results from the lowest mass per square meter and relatively low thickness, which results in the high porosity of this fabric.

An objective assessment of sensorial comfort of fabrics was possible by using the KES system. Research exhibits that the reinforced twill weave fabric F containing 85% cotton and 15% PES in its structure is characterized by the highest THV. The THV of this fabric is 3.89, which results from the relatively low value of koshi and the highest value of numeri and fukurami. In turn, the primary hand values are closely related to the

mechanical parameters determined on particular instruments of KES system.

Research confirmed that the significant effect on the value of koshi have shear and bending rigidities of fabrics, because the lowest value of koshi was obtained for the fabric C, which, at the same time, is characterized by one of the lowest shear rigidity (G) and the lowest bending stiffness (B) in the weft direction. This is mainly due to the using of satin weave characterized by the low number of interlacements of the warp and weft threads. The fabric G with the smallest mass per square meter exhibits the lowest mean value of bending rigidity (B), but the koshi of fabric G is about 0.5 times higher than that of fabric C.

In terms of numeri, the fabric F is found to be the best, which is directly related to the lowest value of MMD. The low value of this parameter results from the high density of warp and weft threads and their low linear densities.

The fabric F is also characterized by the highest value of fukurami. However, in terms of physiological comfort, it is not preferred. It turned out that this fabric has more than twice the lowest value of air permeability than the fabric G, for which the value of fukurami is not more than 3. The fabric F has a slightly greater ability to absorb moisture (higher hygroscopicity), but the fabric G guarantees the lowest value of water vapor resistance, which means a greater ability to take off moisture. Moreover, the fabric G has the lowest value of thermal resistance. Therefore, it was decided that the reference clothing would be made of fabric G, which has slightly lower value of THV than the fabrics B, C, and F but guarantees the high level of physiological comfort.

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