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Functional Design of Supportive Men's Underwear with a Microbial Barrier

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Abstract
A functional modelling of supportive clothing is proposed in this paper. Body forms and measures were analysed. The digitisation of the human body was performed by 3D scanning, and based on point clouds measurements were taken. and the forms of body parts for which the pattern of clothing was developed, were defined. Pattern parts of the male supportive underwear model proposed were translated into numeric form, and a program was developed in the C++ programming language through which the pattern parts are adjusted to individual measurements and to the material used for the compression of parts of the body. Since clothing can be used post-operatively as well, an analysis of the biodegradable Tencel® materials proposed to be used for these applications was conducted. Material samples were subjected to steam sterilisation at 134 °C, after which tests of microbial barrier permeability were performed using the new method. Aerobic bacterial endospores were used. Based on the samples tested and their properties, the construction of supportive medical clothing which, by their design, enhance the functionality and possibility of preventing infections of a body part subjected to surgery was carried out.

Key words: *microbial barrier, functional design, 3D scanning, Tencel, clothing construction.*

Introduction

Under the term compression clothing, male, female and sports socks are implied; as well as support for the arms, legs and in the abdominal area. The purpose of this kind of clothing is to provide support which is important for people with health problems related to poor circulation, and for those who spend a lot of time in a standing position, as well as athletes, who are subject to heavy loads in the areas of the extremities. Also compressive clothing is used after surgery such as liposuction or when treating scars after burns. Such forms of compression aids and clothing can come in various degrees of compression. For higher levels of compression, medical supervision is required. Compression aids on the feet can prevent venous thrombosis and reduce swelling, especially during various exertions. Such compression clothing is used by athletes during exercise to provide them with certain support, such as to prevent the occurrence of shearing and rash, relieve muscle stiffness after exercise, and to accelerate the time of recovery [1, 2]. Compression clothing improves the athlete's recovery after a period of continuous exercise and helps regulate body temperature. It has been proven that external pressure which is attained by compression clothing can reduce the intramuscular space (which is needed for swelling), ensure the stability of muscle fibres, prevent muscle oscillation, and reduce inflammation and muscle pain [3-6]. The utilisation of compression or supportive clothing is increasingly widespread in sports and medicine. Compression clothing must provide friction reduction, injury prevention, and the support required for injuries caused. Researches in the period from 1975 to 1995 were based on compression aids in medicine, oriented at increased venous blood flow due to compression, resulting in a positive effect on the prevention of venous thrombosis in the lower extremities of postoperative patients [7-10]. With compressive therapy, external pressure with a compressive clothing item and aids is achieved on a specific body part, with the intention of increasing venous or lymphatic flow and reducing tissue edema. Compression requirements are changed depending on the patient's position (standing or lying), and due to their mobility (either mobile or immobile). The pressure on the vein system is much higher in the standing position (pressure 80-100 mm Hg), and is equal to the weight of the blood column from the right atrium chamber to the foot. In patients with normal venous circulation during walking, the pressure rapidly drops to about 10-20 mm Hg. In the lying position, the pressure on the vein system is much lower, especially if the legs are raised. Considering the above-mentioned facts in the compressive therapy of immobile patients, lower pressure should be applied (10-30 mm Hg), while in the standing position and in mobile patients, a higher external pressure is required (40-50 mm Hg). Compressive therapy mechanisms are as follows: venous flow acceleration, the redistribution of blood volume into central parts of the body, the reduction of the reverse blood flow and swelling of the leg, improvement of the action of the muscular pump, acceleration of lymph flow and microcirculation, coagulation and fibrinolysis [11-15]. It is also proven that the use of compression clothing and aids accelerate wound healing and prevent relapse in patients. The results of recent studies have shown that relapse in a patient occurs within one year of irregular use of compression clothing [16]. Compressive therapy is a key element of healing a venous lower leg wound, based on solid scientific evidence. The application of compression clothing and aids in the early stages of treatment prevents disease progression and complications, shortens the time to complete healing, and reduces symptoms of the disease as well as chances of relapses, thus positively affecting the overall quality of life of the patient [17]. Different textile materials provide differ-

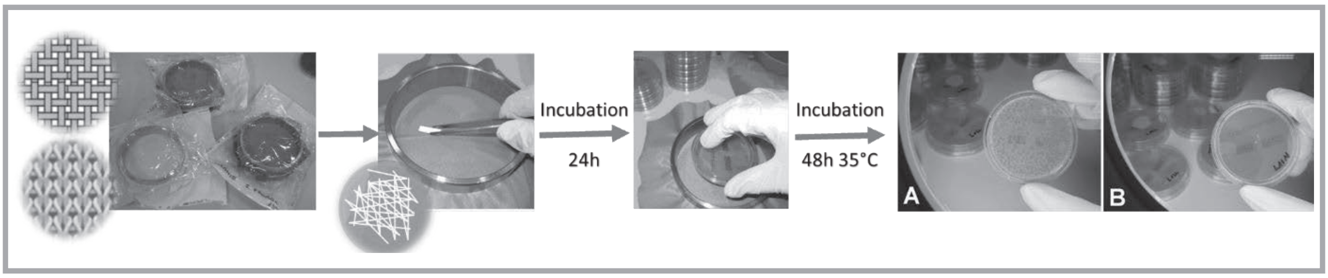


Figure 1. Schematic of microbial barrier permeability testing.

ent degrees of compression. In medicine, compression in clothing is measured in pressure units, mmHg. It is divided into four classes, where class I comprises clothing with the smallest compression, and in class IV the largest. The most optimal compression for athletes is about 20 mmHg, which is class I, while compressive pants and socks can also be in the 2nd class. How compression works depends on the fit of the compression clothing to the body [18].

Underwear is a garment that directly covers the body, and because of the knitted fabric structure from which it is made, it is highly adaptable to the shape of the body. It is very important after injuries or surgery that it provide adequate protection from infections and irritations, which can greatly affect the time of a patient's recovery. Underwear is exposed to microorganisms from the environment and directly from the carrier itself, thus it is necessary to properly select materials with an appropriate microbial barrier. It is also important to design compression clothing that will follow the shape of the body and have the support and functional design required.

To achieve the best functionality of clothing, clothing production is individualised. For this purpose, 3D body scanners are used to determine body mass, body shape and posture. In this way, the indicators can be determined while the person is in a specific position. Based on the 3D scanning, it is possible to collect all relevant information from the anthropometric, biomechanical and ergonomic viewpoints essential to the development and modelling of functional clothing. Except for fashion purposes, an individualised approach to clothing design is applied to clothes for people with disabilities and those outside the standard body measure. It can also be applied to protective clothing that has a specific purpose. In this group, apart from clothing intended for medical purposes, clothes that need to have a specific compression on specific body parts are taken into account. Such clothes are made for pilots [19-23].

Such compression underwear with their shape will minimise negative impact on the patient's recovery by avoiding or greatly reducing irritation on the part of the body having been subjected to an operational procedure and by providing the necessary support. In order to ensure the comfort and functionality of compression or supportive underwear, it is necessary to design a model that enables individual adjustment to body measurements and to the compression required on different parts of the body by applying materials that, in addition to the necessary compression, will also provide a microbial barrier.

Experimental

The support or compression required can be achieved by functional design, construction and a combination of Tencel® knitted fabric and Tencel® woven fabric. To ensure the best protection against infection, it is essential that the material has a microbial barrier and comfort without causing irritation. It is also important to choose an appropriate type of supportive medical underwear or aids depending on the type of injury.

Materials

Three single jersey knitted fabrics (samples II-IV) were tested as well as one twill woven fabric (sample I) made of 100% lyocell with and without chitosan for use in supportive underwear. Sample III was post-treated with a chitosan solution (0.8%), while in the case of sample IV, chitosan was incorporated in the last phase of fibre production (0.3%).

According to standard methods for testing samples of knitted fabric and woven fabric, the thickness, surface area, yarn count and density were measured [24, 25]. Characteristics of the materials used are shown in ***Table 1*** [26].

Tencel® is a man-made cellulosic fibre of the generic fibre type – lyocell. The specialty of this textile material is in the ability of the fibres to absorb water and moisture into their nanostructure, thereby having a reduced tendency for the development of microorganisms, and the high absorption capacity provides the necessary comfort. In medicine, Tencel® has a growing advantage because it does not create textile dust [27]. Thomas L. Diepgen's study showed a positive effect of Tencel® on people with sensitive skin, and even on patients with atopic dermatitis and psoriasis [28].

Permeability of microorganisms in dry conditions of extreme contamination

Testing the permeability of a microbial barrier of dry textile material was conducted according to a newly developed method [29, 30]. The samples are fixed into a ring device which is packed in a transparent sterilisation package. After that, the samples are sterilised at 134 °C

Table 1. Properties of the textiles used.

Samples	Textiles	Weave	Surface weight, g/m²	Thickness, mm	Yarn count, tex		Density, threads/cm	
					Warp	Weft	Warp	Weft
I	Tencel® (100% Lyocell)	bluette 2/1	194	0.32	22.8	31.3	50	27
II		single knits	244	0.42	24		35	22
III		single knits	280	0.43	22		37	23
IV		single knits	195	0.34	25		30	22

for 5 minutes. Spores are rubbed down onto the sterilised samples in aseptic conditions. Incubation follows for 24 hours, after which prints are taken with CT3P agar plates, first from the back and then from the front side (***Figure 1***). The agar plates are incubated for 72 hours at 35 °C, after which follows the counting of bacterial colonies (CFU) [29, 30].

Supportive garment

A functional model of two-layer male supportive underwear is shown in ***Figure 2***. It is made of a material which has an appropriate microbial barrier from a combination of Tencel® knitted fabric and Tencel® woven fabric. The inner layer of the underwear is marked with a dashed line, which includes the torso area, where compression is most often required. This can be worn after any abdominal surgery, such as laparotomy, nephrectomy and bariatric surgical procedures. Compression around the affected area increases blood circulation, and reduces swelling and discomfort at the surgical location. It is secured with a side seam on the upper layer of the underwear, and the rest of the belt is independent of the outer layer. The inner compression layer is buckled to 6 cm from the left side seam with velcro tape, which allows additional compression adjustment. The rest of the model is divided into segments, each of which can be made of a material that will provide compression on predetermined parts of the body. The combination of materials and construction proposed (***Figure 2***) will provide the compression required on defined body positions as well a greater fit [31, 32].

Defining body shapes and taking body measurements

For the purpose of adequate design, 3D scanning of the human body was carried out using a 3D body scanner, whereby the male body was digitised, and the geometric features and numerical data used in defining the shape and construction of the compression or support underwear were determined. For this purpose, the 3D body scanner VITUS (Vitronic, Germany) smart was used, which was installed at the University of Zagreb, at the Faculty of Textile Technology, in the Department of Clothing Technology. The ScanWorx software package was used for this interactive computer-based work when taking measurements and point cloud cross-sections to accurately define body shape.

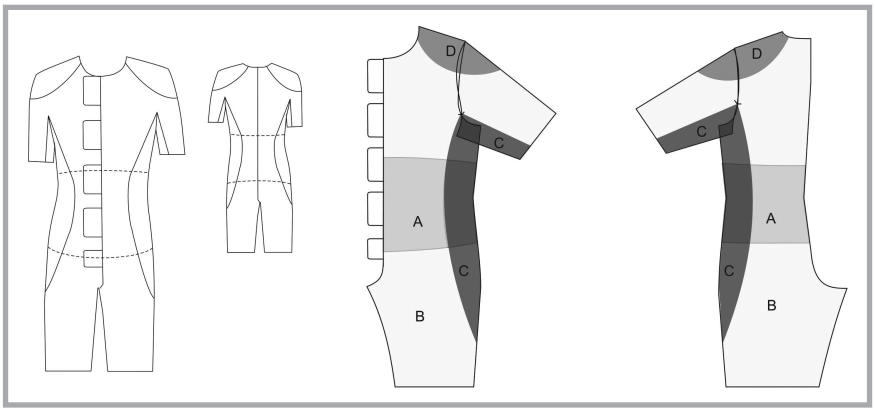


Figure 2. *Sketch of the model and construction of supportive underwear in a standard clothing size with compression areas: A – sample I, B – sample III, C – sample IV, D – sample II.*

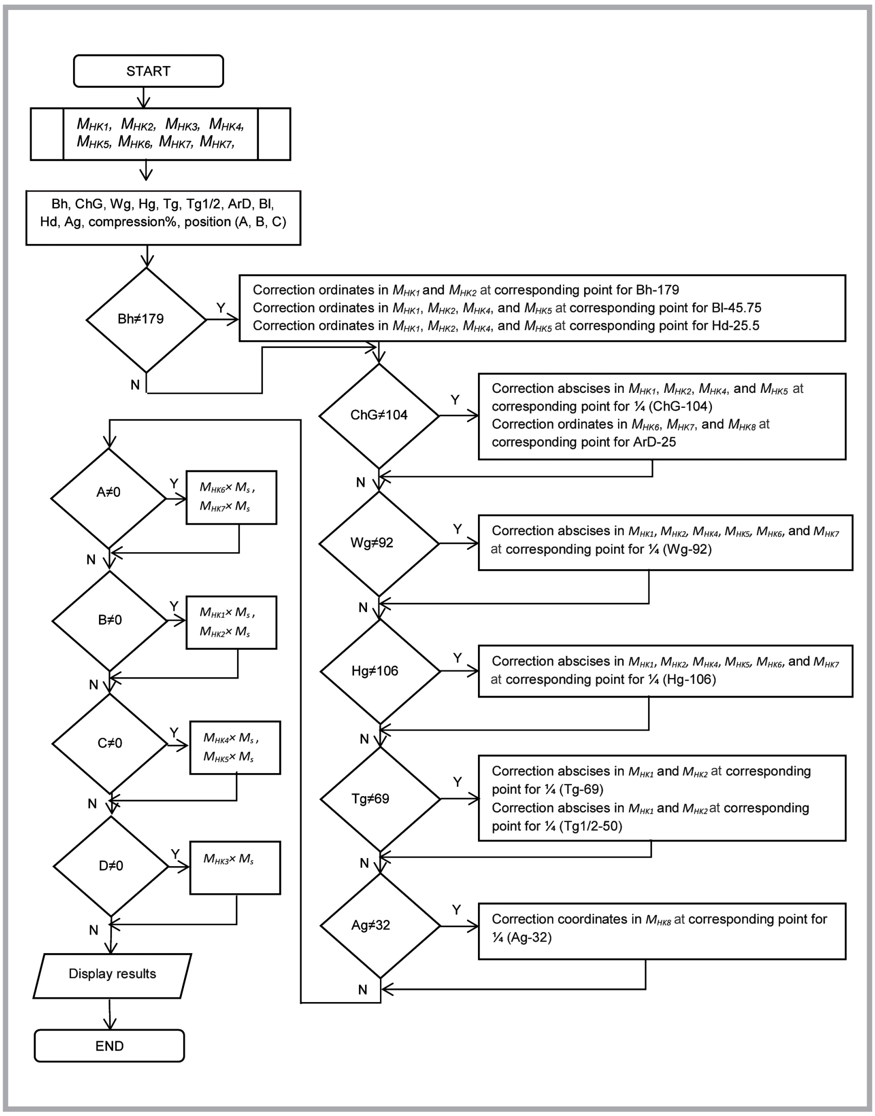


Figure 3. *Flowchart of a computer program for adjusting the cutting parts of supportive men's underwear.*

Numerical modelling and adjustment of a pattern

For numerical adjustment and shaping of pattern parts, the positions of pattern part points that exactly describe each pattern part are defined. The coordinates of the points of each pattern part are used to form matrixes of homogeneous coordinate points (1) of the following shape [33, 34]:

$$M_{HK}=\begin{bmatrix}x_1 & y_1 & 1\\ x_2 & y_2 & 1\\ x_3 & y_3 & 1\\ \vdots & \vdots & \vdots\\ x_n & y_n & 1\end{bmatrix} \quad (1)$$

In this way, a base of pattern parts of male supportive underwear in a standard clothing size is created in numerical form. Reference points are defined within the homogeneous coordinate pattern part matrix. Their values change depending on the individual measurements obtained based on 3D scanning. The change of position of the points is achieved by the translating of points on the modelling pattern parts. The next step is the forming of pattern parts to achieve compression. In this way, pattern parts which cover specific parts of the body are reduced to an exact amount depending on the properties of the material and the compression required. Pattern parts in a numeric form (homogeneous coordinate matrix) are multiplied with a scaling matrix in which there are integrated parameters that provide adequate compression. The scaling matrix (2) is in the following form [34]:

$$M_S=\begin{bmatrix}a_x & 0 & 0\\ 0 & a_y & 0\\ 0 & 0 & 1\end{bmatrix} \quad (2)$$

Where a_x i a_y are scaling parameters of the pattern parts depending on the required compression and material.

By multiplying the M_{HK} matrix with M_S, the numerical values of the pattern parts are obtained.

Computer program for modelling and adjustment of basic underwear pattern

To customise supportive men's underwear with individual measurements, a computer program was created in the C++ programming language. The program is designed in such a way that a database of numerically defined pattern parts is created in a standard clothing size in a matrix form. As input parameters of the program, the individual measurements and areas of the compression required according to the sketch of the model proposed are defined (***Figure 2***). Based on the data, above the coordinate points of the pattern parts are calculated, which can be used to make supportive underwear with the compression required in the areas specified.

Figure 3 shows a flowchart of a computer program that in the first step adjusts the cutting parts of a standard garment size (***Table 4***) by individual measures.

Cutting parts are defined by the M_{HK1}, M_{HK2}, ..., M_{HK7} matrices i.e. the M_{HK1} front defining matrix, the M_{HK2} rear part, the M_{HK3} shoulder part, the M_{HK4} front side, the M_{HK5} rear section, the M_{HK6} inner front section, the M_{HK7} inner rear section and the M_{HK8} lower sleeve. The elements of each matrix are the coordinates of the points of a single cutting part that uniquely define it. Adjusting the individual measures of cutting parts is performed by correcting the values of abscises or ordinates in the exact point of the homogeneous coordinate matrix. In the second step, the cutting parts are scaled to the selected cutting parts or segments of the garment item according to the predetermined parameters of the material from ***Tables 1*** and ***2*** or the compression desired, which means that the corrected matrices of the homogeneous coordinates of the selected parts are multiplied by the scaling matrix. In the scaling matrix, the values of a_x and a_y obtain values of the selected compression rate in a predetermined range.

Table 2. *Results of breaking force and extension at break testing of the samples.* ***Note:*** $\bar{x}$ *– mean; SD – standard deviation, N; CV – coefficient of variation, %.*

Samples fabrics		Breaking force, N		Extension at break, %	
		longitudinally	transversely	longitudinally	transversely
Sample I	$\bar{x}$	909.00	608.00	16.66	15.78
	SD	11.07	40.0	0.57	1.83
	CV	1.22	6.61	3.41	11.61
Sample II	$\bar{x}$	256.67	222.05	97.41	160.75
	SD	10.93	4.58	2.11	2.59
	CV	4.26	2.06	2.17	1.61
Sample III	$\bar{x}$	202.80	180.60	107.60	152.27
	SD	24.40	8.71	5.32	0.61
	CV	12.03	4.82	4.94	0.40
Sample IV	$\bar{x}$	255.67	212.31	64.88	95.65
	SD	29.76	8.87	4.80	0.98
	CV	11.64	4.18	7.40	1.02

Table 3. *Test results of microbial barrier permeability of the samples tested after extreme contamination with bacterial spores Geobacillus stearothermophilus and Bacillus atrophaeus.* ***Note:*** *CFU – colony forming unit.*

Sample fabrics	Number of isolates	Front – back ration CFU
Sample I	6	1:60
Sample II	6	1:3
Sample III	6	1:10
Sample IV	6	1:10

Table 4. *Individual measurements of scanned person relevant to the adjustment of supportive underwear.*

Body dimension	Abbr.	Body measures, cm	
		Standard	Individual
Body height	BH	179.0	178.5
Chest girth	ChG	104.0	103.8
Waist girth	Wg	92.0	82.8
Hips girth	Hg	106.0	103.7
Thight girth	Tg	69.0	65.0
Middle tight girth	Tg 1/2	50.0	50.0
Armscye depth	ArD	25.0	24.9
Back length	Bl	45.75	45.6
Hips depth	Hd	25.5	25.0
Arm girth	AG	32.0	28.9

Results and discussion

A tensile strength tester, Statimat M, tt. Textechno, was applied for evaluation of the mechanical properties of the samples i.e. breaking strength and breaking elongation, according to Standard EN ISO 13934-1, shown in ***Table 2*** [35].

Test results of medical cellulosic textiles for the permeability of microorganisms after extreme conditions of contamination with bacterial spores are shown in ***Table 3*** and ***Figure 4***.

The results of microbial barrier permeability testing after extreme contamination with bacterial spores *Geobacillus stearothermophilus* and *Bacillus atrophaeus* showed that Tencel® woven fabric has the best microbial barrier (1:60), which can be explained by the structure of the textile material itself. Tencel® knitted fabirc with chitosan has a better microbial barrier (1:10) than Tencel® knitted fabric without chitosan (1:3).

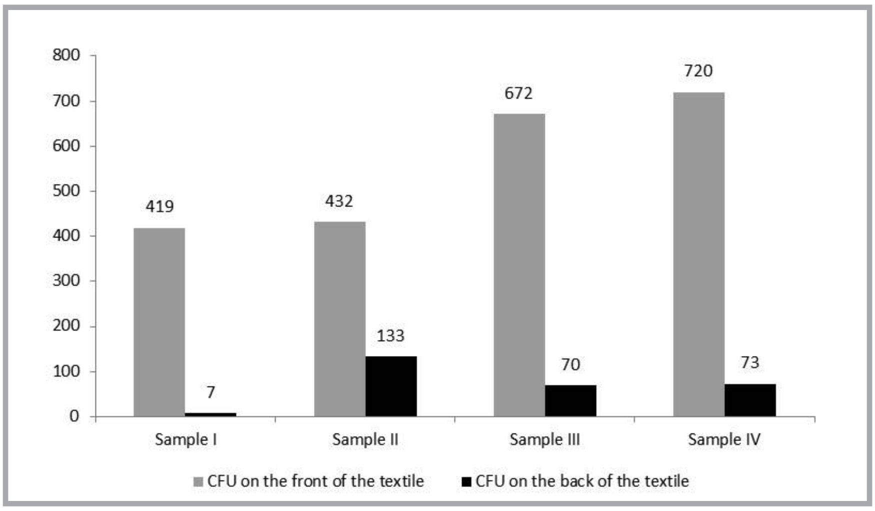


Figure 4*. Results of microbial barrier permeability: The average number of bacterial colonies on the front and back side (CFU).*

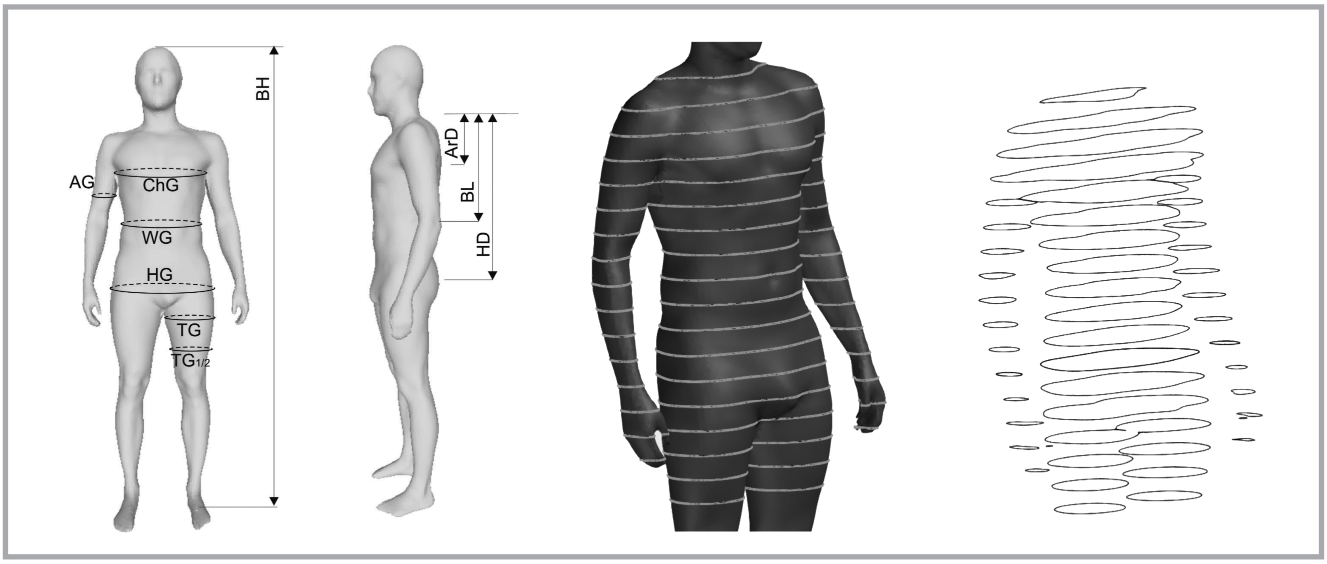
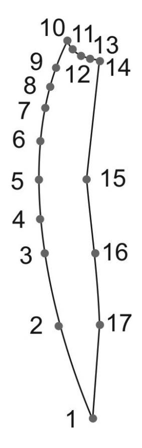


Figure 5. *Measurements and shapes obtained by 3D scanning.*

Table 5. *Numerical data of the front side part of men's underwear before and after adjusting to individual measurements and after scaling.*

Cutting part	Number of points	Homogeneous coordinates of the cutting part					
		Homogeneous coordinate of the original cutting part		Coordinates after adjusting to individual measurements		Coordinates after scaling	
		x	*y*	x_{1T}	y_{1T}	x_{2T}	y_{2T}
	1	1.043	-41.881	1.043	-41.881	1.01171	-40.6246
	2	-4.539	-25.548	-4.539	-25.548	-4.40283	-24.7816
	3	-6.851	-15.086	-6.851	-15.086	-6.64547	-14.6334
	4	-7.949	-7.11	-7.949	-7.11	-7.71053	-6.8967
	5	-8.18	0.0	-8.18	0.0	-7.9346	0.0
	6	-8.18	3.583	-8.18	3.583	-7.9346	3.47551
	7	-7.371	11.155	-7.371	11.155	-7.14987	10.82035
	8	-6.099	17.051	-6.099	17.051	-5.91603	16.53947
	9	-4.77	20.75	-4.77	20.75	-4.6269	20.1275
	10	-3.337	24.077	-3.337	24.077	-3.23689	23.35469
	11	-2.169	22.426	-2.169	22.426	-2.10393	21.75322
	12	-0.782	21.443	-0.782	21.443	-0.75854	20.79971
	13	0.605	20.923	0.605	20.923	0.58685	20.29531
	14	2.221	20.75	2.221	20.75	2.15437	20.1275
	15	0.0	0.0	-1.15	0.0	-1.1155	0.0
	16	1.588	-15.086	1.013	-15.086	0.98261	-14.6334
	17	2.244	-25.548	2.244	-25.548	2.17668	-24.7816

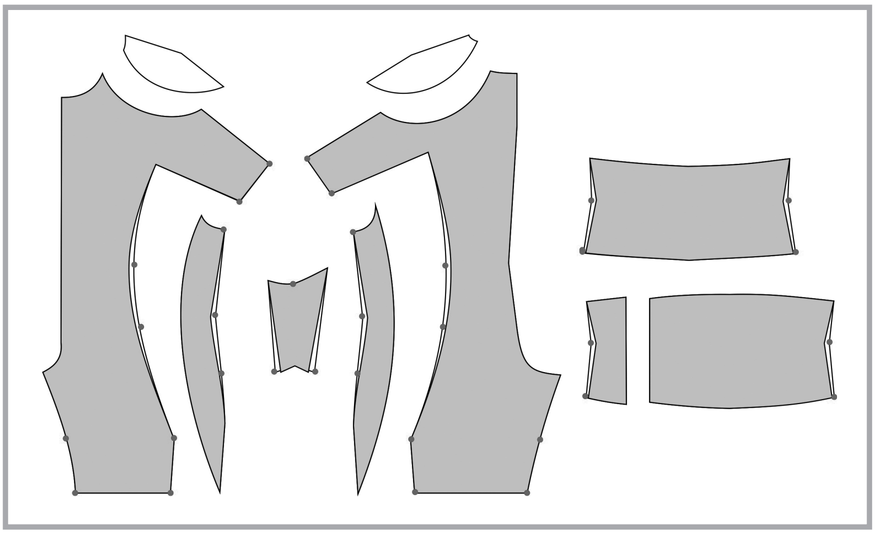


Figure 6. *Adjustment of men's underwear based on individual measurements at corresponding points.*

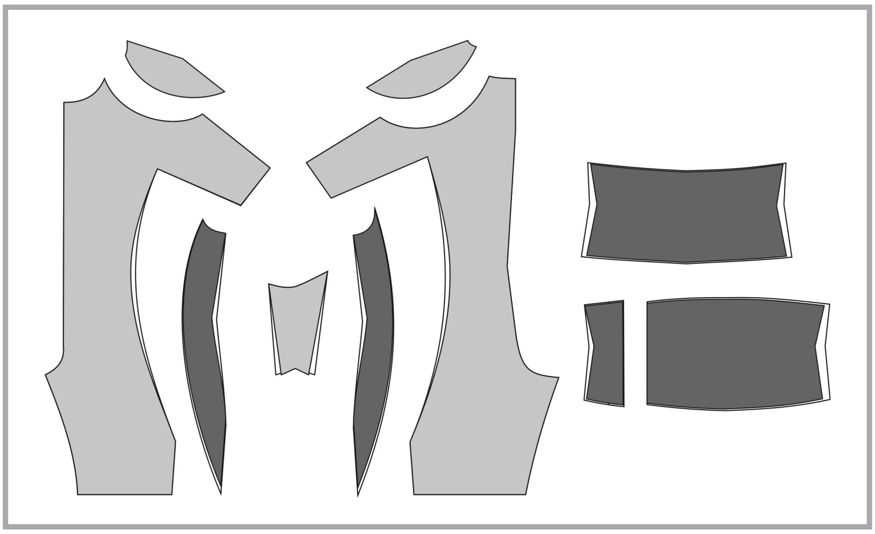


Figure 7. *Pattern parts adjusted to individual measurements and to support required.*

Figure 5 shows clouds of points which are obtained based upon 3D scanning. Measurements are marked that are relevant for the customisation of underwear to individual measurements. Because of individual adjustment of supportive underwear, a 3D scanning of a male person was performed, whose measurements are shown in ***Table 4***. The measurements performed indicate aberrations from standard measurements.

For the purpose of the construction and modelling of supportive clothing, a combination of woven fabric sample I and knitted fabric was used. Sample III was post-treated with a chitosan solution (0.8%), while in the case of sample IV chitosan was incorporated in the last phase of fibre production (0.3%). Since their mechanical properties are largely different from a constructional point of view, which is primarily related to the strength and elasticity of the material, sample I is selected for stabilisation and compression, and knitted fabric samples III and IV for construction of that part of the supportive clothing that must be elastic and has to follow the shape of the body, thereby providing greater comfort, which is especially important when changing body positions. Namely, clothing, especially supportive clothing, must necessarily follow changes in body mass.

Table 5 shows an example of the front side part, showing coordinates that uniquely describe the pattern part. The results which shown in the table are values of the homogeneous coordinate's matrix after the adjustment of the pattern according to the measurements from ***Table 4*** for the person measured.

The translation of the reference points is carried out at points 15 and 16 for the amount obtained based on the difference in sizes in the area of the waist circumference and hip circumference. For point 15 the difference amounts to 1.15 cm, while for point 16-0.575 cm. The difference occurring in the waist area is applied to 8 reference points on different pattern parts, while the difference in the hip area is divided into 4 and defined for the same number of pattern parts or reference points thereon. After that, the homogeneous coordinates matrix is multiplied by the matrix HS, in which the shrinkage parameters were used, where for a_x and a_y a shrinkage of 97% is defined. The values of a_x and a_y are obtained based upon the characteristics of sample I and the anticipated shrinkage of the pattern part that is needed for compression.

The other pattern parts are also adapted in a similar manner. With application of the program created, adjustment of the pattern for each pattern part was carried out. The result of the adjustment of pattern parts by individual measurements using a computer program is shown in ***Figure 6***, where the pattern parts are drawn based on the coordinate points from the homogeneous coordinate matrix, obtained according to the input parameters of the relevant body measurements of the person scanned.

The next input parameter of the program is to define the compression areas. By using the program created, areas of the men's underwear model are selected for body parts where compression is needed. Then follows the multiplication of matrices which belong to individually adjusted body measurements with the scaling matrix. Scale matrix elements can be defined by selecting the degree of compression required. The data obtained are the coordinates of pattern parts, based on which pattern parts are drawn, as shown in ***Figure 7***.

Conclusions

Based upon the results from functional design and construction methods obtained for a combination of Tencel® woven fabrics and knitted fabrics, the support, compression degree, fit and microbial barrier of supportive garments and aids required can be achieved. The translation of pattern parts into a numerical form provides the possibility of computer data processing according to the construction principles. In the program made for the model of clothing item mentioned, where the matrix records of pattern parts and scaling matrix translations required were used, the individual adjustment of a clothing item is possible. It is also possible to define parts of clothing that need to carry out compression on the body. In this way, a large number of individual supportive underwear models can be formed for different use and compression based on the properties of the material and the desired compression using the cutting parts of a standard clothing size.

Hence, for supportive underwear models and aids, a combination of Tencel® woven fabric is recommended, which, due to its strength, can provide the degree of compression or support required, while Tencel® knitted fabric ensures fit adherence to body shape and comfort, respectively. Because Tencel® is biodegradable it meets ecological standards as well. With functional design and construction, new solutions for the appearance of supportive clothing and aids, fit and ease of use are achieved.

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