Chapter 4

Textile Forms' Computer Simulation Techniques

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Additional information is available at the end of the chapter

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Abstract

Computer simulation techniques of textile forms already represent an important tool for textile and garment designers, since they offer numerous advantages, such as quick and simple introduction of changes while developing a model in comparison with conventional techniques. Therefore, the modeling and simulation of textile forms will always be an important issue and challenge for the researchers, since close-to-reality models are essential for understanding the performance and behavior of textile materials. This chapter deals with computer simulation of different textile forms. In the introductory part, it reviews the development of complex modeling and simulation techniques related to different textile forms. The main part of the chapter focuses on study of the fabric and fused panel drape by using the finite element method and on development of some representative textile forms, above all, on functional and protective clothing for persons who are sitting during performing different activities. Computer simulation techniques and scanned 3D body models in a sitting posture are used for this purpose. Engineering approaches to textile forms' design for particular purposes, presented in this chapter, show benefits and limitations of specific 3D body scanning and computer simulation techniques and outline the future research challenges.

Keywords: textile forms, computer simulation techniques, 3D scanning, 3D body models

1. Introduction

The chapter entitled textile forms' computer simulation techniques is intended for raising awareness about the importance of modeling and simulation of different textile forms. Since textile objects are very common and omnipresent all-around us, the appropriate simulation techniques can be stated as a very important part of a wide area of computer simulation.

Textiles can be generally divided into linear (fibers, yarns, threads), two-dimensional (woven, knitted fabrics, nonwovens) and three-dimensional (garments, architectural textiles, some technical textiles) textile forms. Modeling and simulation of these forms can be extremely complex due to their visco-elastic properties and unique behavior when exposed to forces, even though relatively small ones, such as gravitational force.

The topics, referring to computer-based simulation of textile-based objects, have already been investigated by a number of researchers and authors. Many of them have developed or applied different methods and models for describing the structure and behavior of textile forms. However, there is still lack of newer publications, dealing with the intriguing phenomena, related to modeling and simulation of complex textiles, garments, and other textile forms.

The modeling and simulation techniques for woven and knitted fabrics and garments are discussed in view of accurate understanding of the relationship between the construction and behavior of textile forms as a key in engineering of textile forms' design for intended applications. Three approaches for modeling of textile forms are presented, i.e., geometry-based, physically based, and hybrid approach. Computer simulation of textile forms in interaction with the 3D objects and its importance for the development of specific, custom-designed garments are considered from the perspective of virtual prototyping on the 3D scanned body models.

The chapter introduces three case studies, related to recent advances in engineering approach to computer simulation techniques in the field of textile science. The first one deals with modeling and simulation of textile fabrics and fused panels based on finite element method. The second case study refers to simulation of garments using the sitting 3D human body models using one of the commercial 3D CAD packages. Topic of the third case study is connected with application of simulation techniques used for developing of a special form of protective clothing for sport aircraft pilots—the so-called antig suit.

2. Complex modeling and simulation techniques of textile forms

The visual appearances of the textile forms for both the real and the virtual are influenced by:

(a) the shapes of the three-dimensional (3D) textile forms determined by the corresponding two-dimensional (2D) pattern pieces and

(b) used textile materials that which behavior is influenced by their mechanical and physical properties.

The realistic behavior of textile materials in the virtual environment mainly depends on computer-based models of the textile materials. They are used for simulation of different textile forms such as tablecloths, flags, garments, shoes, etc. with the aim to study the behavior of textile materials in the virtual environment or to develop the complex shape of the textile forms, which consist of two or more pattern pieces.

The simulation techniques of textile forms should be stable and fast so that they can be applied in different environments, and interactive performance can be achieved [1].

To simulate textile forms, different modeling approaches are developed to model the structure of textile materials. These are either geometrical, physical, or hybrid models [1–3]. In the virtual environment, interactions between the textile forms and other 3D objects (collision detection and collision response) are of great importance, therefore, should be also computed. When the 3D shape of the textile form is computed, it could be rendered for visualization.

2.1. Geometrical models

The geometrically based approaches are used when the final shape of the textile form is needed without considering the dynamic process. They are simple and have low cost of computation [1].

In the computer graphics, the fabric simulations were first performed by using the geometrical models. These models represent simple geometrical formulations of the fabric without its physical and mechanical properties on local surfaces. Therefore, they are unsuitable for complex reproducible fabric simulation. They focused on appearance of the geometrical shape, particularly folds and wrinkles, which are presented by geometrical equations [1, 2].

The first attempt to the fabric simulation by using a geometrical model was presented by Weil in 1986 [2, 4]. He suggested a method for simulation of the hanging fabric as a mesh of points. The simulation of its shape was carried out by fitting of the catenary curves between the hanging or constraint points.

The research studies regarding the garments simulation by using the geometrical modeling can be found in 1990. A method for modeling of the sleeve on a bending arm was based on a hollow cylinder that consists of a series of circular rings and with a displacement of circular rings along the axial direction, the folds are formed [1, 2]. A method for designing of the 3D garment directly on a 3D digitized shape of the human body was presented by Hinds and McCartney [5]. They represented the garment as a collection of 3D surfaces (pattern pieces) of complex shape around the static 3D body, whose fit around panel edges with respect to body form may vary over the surface. A geometrical approach for modeling of the fabric folds on the sleeve was proposed by Ng and Grimsdale [6], where a set of rules was developed for automatic generation of the fold lines.

In general, the geometrically based simulation techniques are used for modeling of the fabric and garment drape. Therefore, they are effective in computing the shape of fabrics or garments. However, the geometrically based techniques usually do not take into account the dynamic interaction between the fabric/garment and the object, because they are difficult to be geometrically modeled [1].

Stumpp et al. [7] proposed a geometric deformation model for the efficient and robust simulation of garments. With this model a high stretching, shearing, and low bending resistance could be modeled, and the deformed region can be restored back to its original shape. Therefore, it can be used for modeling of the interaction between the fabric and other objects of different shapes. Researchers had represented the physically plausible dynamics of their approach with a comparison to a traditional physically based deformation model, **Figure 1**. The results show that the similar fabric properties can be reproduced with both models.

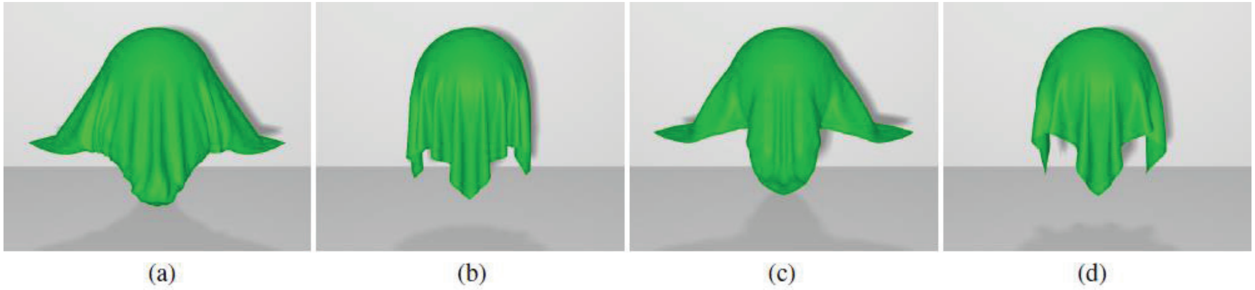

Figure 1. Computer simulation of a fabric piece onto a sphere: (a, b) fabric draping by using the physically-based approach, (a, b) (c, d) fabric draping by using the geometrically-based approach [7].

2.2. Physical models

The physically based approaches are widely used for computing the mechanical behavior of textile forms. In addition, in physical-based methods, deformation is based on the structures and properties of textile materials. The structures and properties of textile forms have been investigated as highly flexible mechanical materials from the 1970s. Mechanical simulation intends to reproduce the virtual fabric surface with given parameters, which are expressed as strain-stress relationships and described by curves due to different degrees of simplification and approximation. Simple linear models can approximate these curves, whilst the nonlinear analytic functions (polynomials on interval-defined functions) are used for accurate models. In addition, the fabric mass per surface unit should be considered [3].

The physically based models are independent of geometrical representation. Therefore, with them it is possible to solve complex numerical problems by integrating various constraints. The special attention was been paid to simulation of large deformations of textile forms [1]. The behavior of textile material can be described by a complex system of mathematical equations (mechanical laws), which are usually partial differential equations or other types of differential systems. Analytical solutions, which are provided only for a limited class of simple equations and solve only simple situations, are not suitable for complex fabric simulations. Therefore, the numerical methods are implemented into a fabric simulation, which requires discretization, explicit computation of the physical values at precise points in space and time. Space discretization can be achieved through numerical solution techniques (models derived from continuum mechanics), or through the mechanical model itself, as in particle system models [3].

The first approach to simulation of the fabric and deformable surfaces introduces Terzopoulos et al. [1, 3, 7–9]. He obtained the motion of the object's points using the Lagrange's equations of motion that had been first discretized by a finite-element method. Therefore, there was a need to solve a large system of ordinary differential equations.

2.2.1. Particle-based approach

A particle-based system divides the object (fabric) into small particles on triangular or rectangular mesh. The points are defined as finite masses at the mesh intersections [2]. The number of points is defined according to the used problems and techniques. For example, a piece of fabric could be modeled as a two-dimensional arrangement of particles, which conceptually representing the intersection points of the warp and weft yarns within a fabric weave, thus can be plain, twill, satin weave, etc. [10].

The first particle systems for fabric simulation are based on a form of the mesh [11, 12]. By using this simulation approach, the fabric drape as a dynamic phenomenon was simulated very realistic on the table, on the sphere, etc. These types of simulations have already been reflected by the nonlinear behavior similar to continuum mechanics models. Their accuracy was limited for simulation of large deformations and required longer computation times. Furthermore, faster models based on spring-mass meshes were developed, and for computation were used to fast implicit numerical integration methods [3, 13]. In this modeling technique, an object is represented as a collection of mass points (circle particle) that are interconnected by structural, bend, and shear springs through a mesh structure. The mass points are interconnected by linear springs within the position and velocity at a certain time and mass [1, 10, 14]. The way the springs are connecting the particles (the topology of the object) and the differences in strength of each spring influence the behavior of the object as a whole. The different type of mesh topologies has been presented with respect to the connection between the mass and springs [15]. These are rectangular mesh that was first proposed in 1995 by Provot [16], **Figure 2(a)**, responsive mesh was described by Choi and Ko [17], **Figure 2(b)**, triangular mesh was presented by Selle et al. [18], **Figure 2(c)**, and the simplified mesh Hu et al. [19], **Figure 2(d)**.

2.2.2. Finite-element approach

The finite elements method (FEM) is widely used for mechanical simulation and numerical analysis. It is based on the usage of matrix algebra. The finite-element method was been developed in a particular scientific disciplines with a wide possibility of solving various problems in mathematics, physics, continuum mechanics, etc.

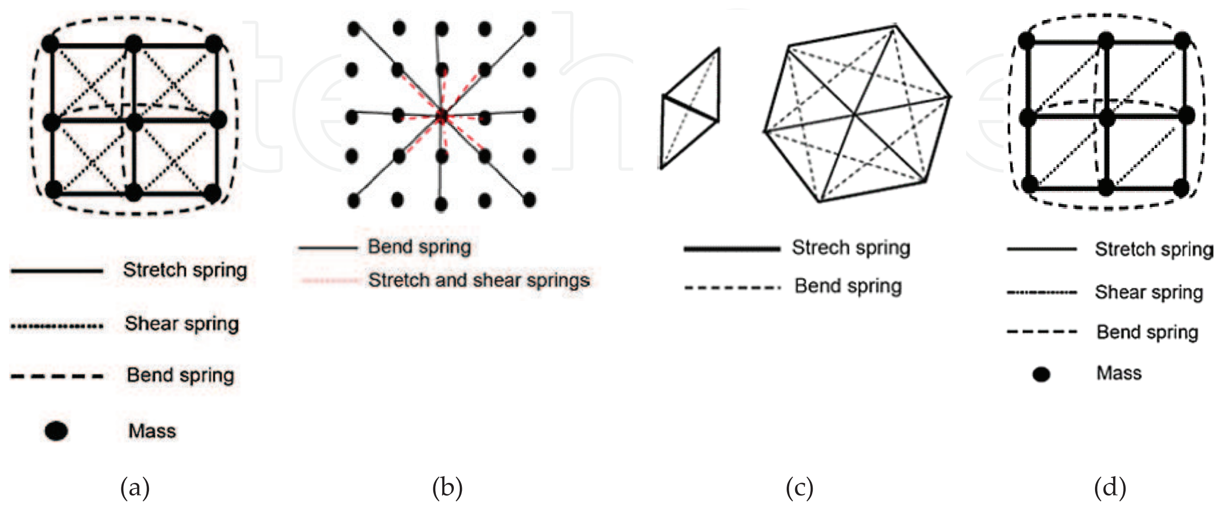

Figure 2. Mesh topologies of the mass spring model [15].

FEM is mainly used for application of elastic solid or shell modeling for mechanical engineering purposes, where linear elasticity and small deformations appears. Therefore, it is not so well adapted for fabrics, which is very deformable object. Early attempts to fabric modeling by using FEM showed high computation times [3, 20]. However, it was discovered that by using appropriate simplification and efficient algorithms the FEM is also usable in interactive graphics applications on the field of textile engineering [3]. The research studies regarding the finite element analysis applied to fabrics are well described in source [21].

For solving problems with FEM, it could use different computer programs such as ANSYS, ABAQUS.

Solving of the mechanical problems with finite element method proceeds in several steps [22]:

- discretization of the continuum,
- element equation,
- integration,
- boundary conditions,
- numerical analysis,
- interpretation of results.

For the analysis of problems using the finite element method, it is first necessary to create the so-called geometric model of the real problem. This step is followed by the discretization of a problem on one-, two- or three-dimensional elements, depending of the structure [22]. When building the finite elements mesh, we have to assure that the mesh fits the structure of the geometric body. The elements should be selected in a way that their shape suites the form of the body. Depending on their form, the elements are divided in liner, shell and volume elements, beam elements, membrane elements, spring, and damper elements and infinite elements, **Figure 3**.

Each finite element has a certain number of nodes, which determine the geometry and position of each individual element, **Figure 4**. The elements are interconnected via nodes and form a finite element mesh.

If we observe the displacement u in the element, we can see that, taking into account a generally designed and loaded model, it changes depending on the coordinates. This scenario is unknown in advance and is given in the form [24]:

$$\{u\} = \begin{Bmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{w} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f(x, y, z)} \\ \mathbf{g(x, y, z)} \\ \mathbf{h(x, y, z)} \end{Bmatrix} \tag{1}$$

For any chosen finite element, Eq. (1) can be written in the matrix form [24]:

$$\{\mathbf{u}\} = [\mathbf{a}]\{\mathbf{c}\} \tag{2}$$

where $\{\mathbf{u}\}$ is the displacement vector in the element, $[\mathbf{a}]$ the matrix, $\{\mathbf{c}\}$ is the vector of constants.

The basic equation of the finite element specifies a link between the node forces, respectively, the vector of external loads {F} and nodal displacements {U} and is given as follows [24]:

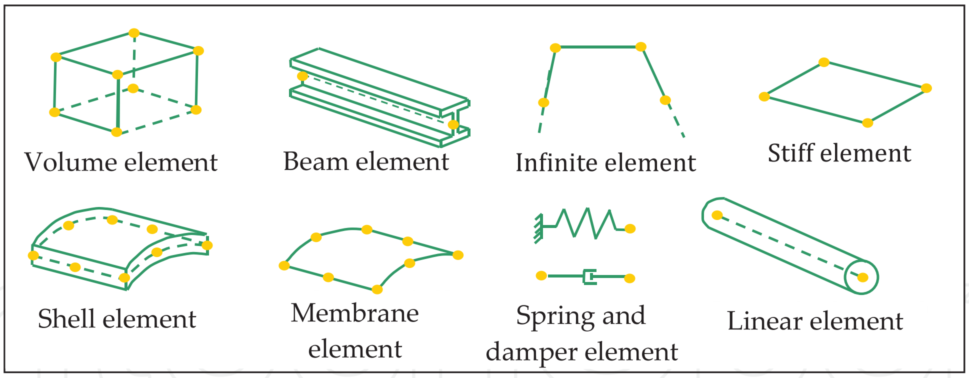

Figure 3. Types of finite elements [23].

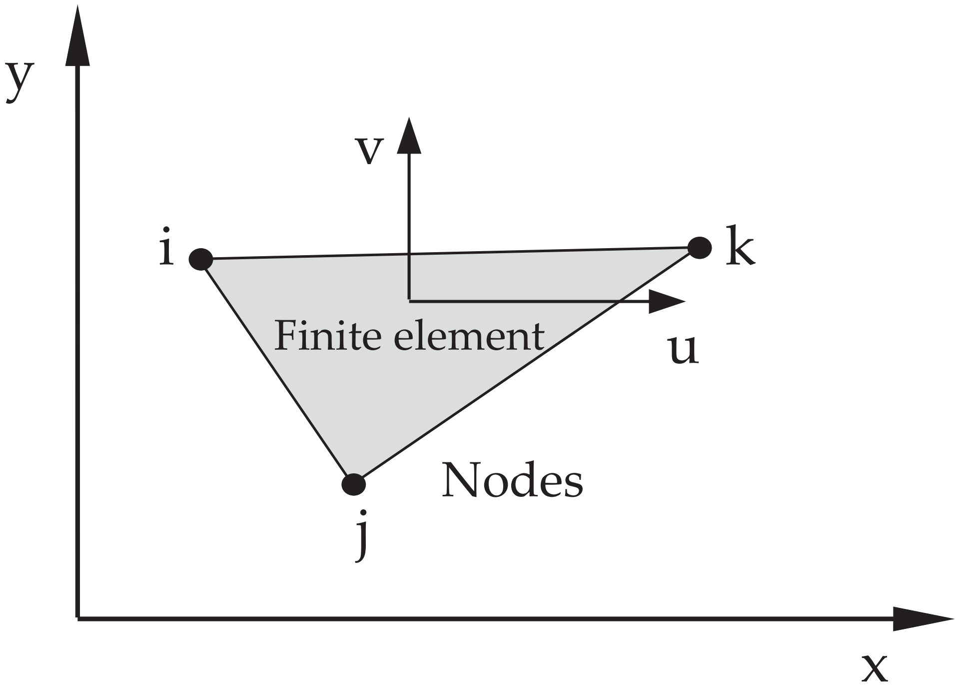

Figure 4. General description of the element.

$$\{\mathbf{F}\} = [\mathbf{K}]\{\mathbf{U}\} + \{\mathbf{F}^T\} \tag{3}$$

where [**K**] is the stiffness matrix of the finite element, which depends on the shape functions of the used elements and on rheological parameters (Young's modulus, shear modulus, Poisson's number), and $\{\mathbf{F}^T\}$ is the load vector, which takes into account the temperature of the load.

If the temperature by observing the construction load is neglected, the basic equation for the finite element is given as [24]:

$$\{\mathbf{F}\} = [\mathbf{K}]\{\mathbf{U}\} \tag{4}$$

The finite elements of a certain space occupy their local coordinate system, and therefore they must be transformed into a so-called common global coordinate system. This transformation of the equations of individual elements from the local coordinate system (x, y, z) in the global system (X, Y, Z) is effected by transformation matrices. The equation, which defines the rule of the transformation of the equation of a finite element from the local to the global coordinate system, is given in the following form [24]:

$$\{\overline{F}\} = [\overline{K}]\{\overline{U}\} \tag{5}$$

where $\{\overline{F}\}$ is the nodal forces given in the global coordinate system, $\{\overline{U}\}$ is the nodal displacements given in the global coordinate system.

The system, which is discretized into finite elements, has *e* elements and *n* nodes, **Figure 5**. The equation of the system is obtained by aggregating all the equation of the expression Eq. (5) for all the elements *e* in the total equation, symbolically given as [24]:

$$\mathbf{F} = \mathbf{K} \cdot \mathbf{U} \tag{6}$$

Aggregation takes place in a way to combine all the elements of the matrices belonging to the common node.

Vectors of nodal forces **F** and nodal displacements **U** are further written in the following form [24]:

$$F = \begin{matrix} \{\overline{\mathbf{F}}_1\} \\ \{\overline{\mathbf{F}}_2\} \\ \{\overline{\mathbf{F}}_3\} \\ \vdots \\ \{\overline{\mathbf{F}}_\mathbf{n}\} \end{matrix}, \quad U = \begin{matrix} \{\overline{U}_1\} \\ \{\overline{U}_2\} \\ \{\overline{U}_3\} \\ \vdots \\ \{\overline{U}_\mathbf{n}\} \end{matrix} \tag{7}$$

where the submatrices $\{\overline{F}_i\}$ and $\{\overline{U}_i\}$ have such number of components as the degrees of freedom of a certain node.

K is the stiffness matrix consisting of n × n submatrices $[\overline{K}_{rs}]$ and is determined based on the stiffness matrix of individual elements, when they are divided into submatrices that belong to

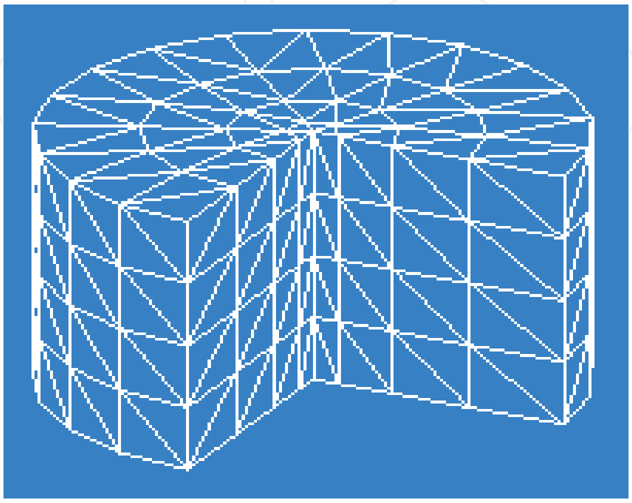

Figure 5. Discretization of the geometrical model.

each node. Thus, for example, the structural equation for a linear element, which always has two nodes, is given in the form [24]:

$$\begin{Bmatrix} \{\overline{\mathbf{F}}_i\} \\ \{\overline{\mathbf{F}}_j\} \end{Bmatrix} = \begin{bmatrix} [\overline{\mathbf{K}}_{ii}] & [\overline{\mathbf{K}}_{ij}] \\ [\overline{\mathbf{K}}_{ji}] & [\overline{\mathbf{K}}_{jj}] \end{bmatrix} \begin{Bmatrix} \overline{\mathbf{U}}_i \\ \overline{\mathbf{U}}_j \end{Bmatrix} \tag{8}$$

Each structure must be stable supported. Therefore, a part of the nodal displacements and rotations is known. They represent boundary conditions. In the finite-element method, the forces, which act on a structure, are always given in the global coordinate system and are introduced into the equation of the structure through the elements' nodes [24]. Numerical analysis represents the way of solving of equilibrium equations, or so-called structure equation [25]. Numerical analysis becomes very complex when it comes to solving nonlinear problems, because in solving equilibrium equations we have to take into account also the change in the geometry of the body in order to obtain the correct solution. Nonlinear models can only contain a few or an extremely large number of variables. Thus, instead of one solution, which is obtained from the linear problems, nonlinear problems are solved iteratively, since during computing the stiffness matrix and the shape of the deformation of the body are changing. The most frequently used iterative method for finding the roots in multidimensional spaces is a *Newton-Raphson method*. The convergence of this method is very effective for well-selected initial values.

2.3. Hybrid models

Hybrid models combine geometrically based and physically based techniques. In this method, the rough shape of the textile form is computed based on the geometrical model and physically based methods are then employed to refine the final shape of the textile form, which is computationally efficient [1].

The work by Rudomin [26] proposes to shorten the computation time needed in traditional physical techniques by using the geometrical approximation as a starting condition. Kunii and Gotoda [27] proposed a hybrid method for simulation of the fabric wrinkling. The fabric physical model in this method consists of spring connecting points, metric energy, and curvature energy. During the fabric simulation, the shape of the fabric was obtained by using a gradient descent method to find the energy minima. After that, singularity theory was used to characterize the resulting wrinkles. In the next approach proposed by Taillefer [2, 28], the hanging fabric's folds between two hanging points were characterized horizontal and vertical. The horizontal folds were modeled by using catenaries, whilst vertical fold were modeled by using the relaxation process, similar as suggested in the work by Wail [4]. In addition, also other hybrid models for simulation of fabric folds were proposed in works described in Ref. [2].

3. Textile forms' computer simulation

3.1. Case study 1: computer simulation of fabric and fused panel drape by using FEM

A number of modeling and simulation techniques have been used for representation of textile woven and knitted fabrics. Each of them has certain advantages, but also restrictions and limitations. Although finite element method is mainly applicable in mechanical, civil, and electrical engineering, it has been successfully used also in textile engineering for modeling of textile fabrics and complex multilayered textile forms.

3.1.1. Modeling of fabric and fused panel

Finite element method was used for modeling and simulating of a fabric and fused panel drape [29]. When modeling textile fabrics, we proceeded from the assumption that the fabric is a continuum with homogeneous orthotropic properties. Its structure is defined by the following rheological parameters: the modulus of elasticity in the warp and weft direction, the shear modulus in the warp and weft direction and the Poisson's number. The model of a fused panel is based on theoretical principles of laminate materials [30]. The fused panel is treated as a two-layer laminate; one lamina was the fabric and the other lamina was the fusible interlining. Fabrics and adhesive interlinings are characterized by local inhomogeneities and anisotropic properties. Therefore, we set up the assumption that interlining is a continuum with average homogeneous and orthotropic properties. Its structural features are described with the same rheological parameters as in the case of fabric.

Simulations of the fabric and fused panels drapes were carried out according to a measuring process using KES methodology for fabric and fused panel. The joint, which connects the fabric and the adhesive interlining, is formed by using the thermoplastic material, and thus forming a matrix of connections of the fused panel. The resulting joint typically is not uniform over the entire surface due to the thermoplastic layer in the form of points [31]. However, we have assumed that the joint was uniformly distributed across the entire surface of the model of the fused panel.

3.1.2. Geometrical model for simulation and numerical analysis of fabric and fused panel drape

The geometric model for numerical analysis related to draping of a fabrics and laminate was designed in the shape and size of the testing specimen using the measuring device Cusik Drape Tester. The test specimen with a diameter of 300 mm is centrally placed on a horizontal table/pedestal having a diameter of 180 mm. Thus, 60 mm of a specimen falls freely over the edge of a horizontal base due to its own weight. As a result, the folds in textile specimen are formed.

The geometric model is discretized with 240 finite elements. For this purpose, we have used thin 3D shell elements, type S9R5 [23], **Figure 6**. The part of the sample, which falls freely over the edge of the pedestal, is described by 120 shell elements. The remaining 120 shell elements describe the specimen positioned on the base. The pedestal for testing of the specimen is also modeled at the very edge of the base (for modeling the tangential rotational degree of freedom), **Figure 6**.

The specimen model was observed under the load of its own weight. Newton-Raphson's iterative method was used for solving the equations of a designed model.

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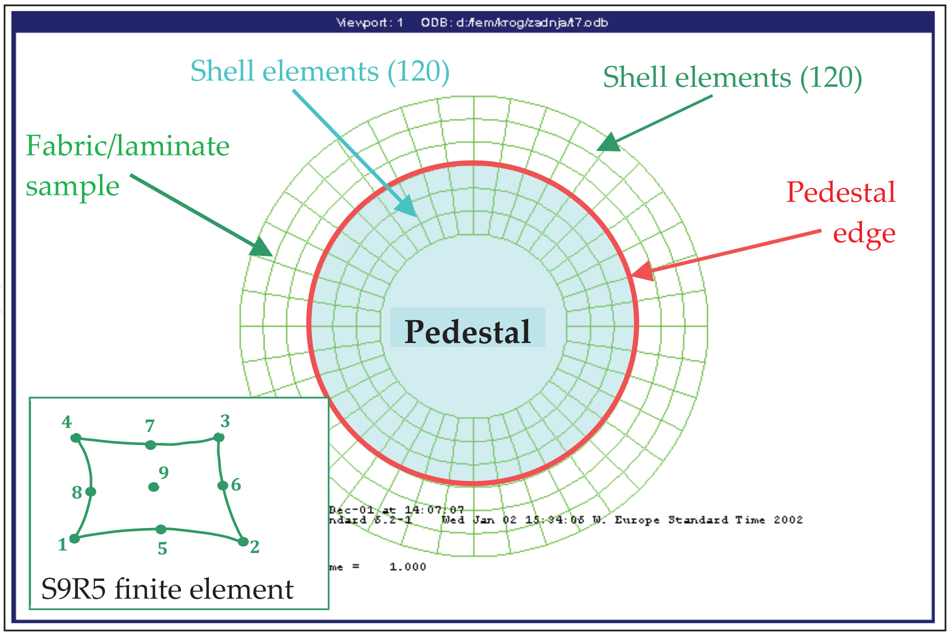

Figure 6. Discretized model for testing the draping of a fabric and fused panel.

3.1.3. Results and discussion of modeling and numerical simulations of fabric and fused panel drapes

Figure 7 represents the model for performing simulations of fabric and fused panel draping. The following parameters were analyzed: maximum and minimum amplitude of folds, maximum and minimum deflection, and the depth and number of folds.

The results of draping tests using a measuring device Cusik Drape Tester (five tests) and numerical simulations of a fabric (F-1), are shown in **Figure 8**. The results of draping tests for two fused panels consisting of the same fabric and two different fusible interlinings (F-1_L1 and F-1_L2) are shown in **Figures 9** and **10**.

The numerical analysis of draping of fabrics and fused panels was aimed at studying the impact of material properties of woven fabric and fused panel, as components of garments clothing, on their real behavior. Related approaches for modeling of material properties have been used in order to assure the comparability of all analyses. Here, the specimens were exposed to the gravitational force, which caused relatively large displacements.

Numerical computation of a problem related to draping of fabrics and fused panels was carried out using static analysis. Static analysis is more favorable than dynamic analysis in terms of computation time, while there were no significant differences between the obtained draping results.

The results of the experimentally obtained forms of draping of woven fabrics show the similarity when comparing with the draping results using numerical simulation with ABAQUS software, **Figure 8**. The figures indicate that the form of the draped fabric in experimental testing is never exactly the same (five tests). Therefore, it is also unrealistic to expect that the form of computer-simulated draped fabrics would be identical as in the real

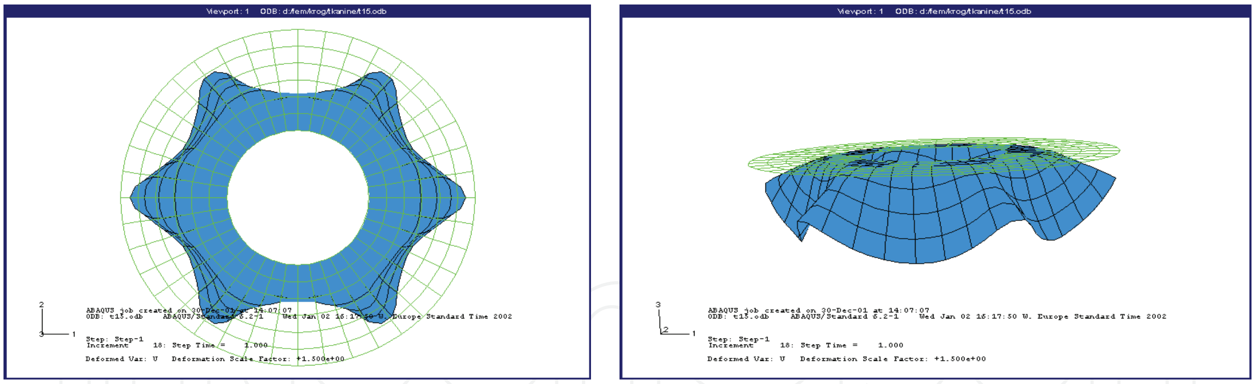

Figure 7. Model for simulation of a woven fabric and fused panel.

experiment. The form of a simulated fabric is symmetric due to the fact that the fabric is observed as an orthotropic material, **Figure 8a**. This cannot be expected by experimentally obtained forms of draped fabrics. Asymmetry in folds of tested fabrics is due to locally inhomogeneous structure of woven fabrics. The results of fabric draping show a good correlation between the experimental and calculated numerical values regarding the maximum and minimum deflection of folds, **Figure 8**.

The results of experimental testing and numerical simulation of draping of fused panels (F-1_L-1 and F-1_L-2) show particularly good match for the number and depth of folds, and the maximum amplitude, **Figures 9** and **10**. Comparison between the experimental and numerical results of draping of fused panels showed that the behavior of the simulated fused panels was more rigid (smaller number of folds, lower maximum and minimum deflection and maximum and minimum amplitudes, greater depth of folds), **Figures 9** and **10**. From detailed analysis, it was stated that the cause of such behavior lies in the approach of modeling the joint between the fabric and fused interlining. From the studies of bending it is apparent [32], that, if we have *n*-laminae, between which there is no connection, their bending stiffness is significantly lower than in the case, if we have *n*-laminae, fused by joints. The problem can be illustrated using a rectangular beam. Deflection of a beam *f* is inversely proportional to the moment of inertia of a cross-section of the beam. In the case of a rectangular beam, composed of *n*-laminae, the proportionality can be expressed in the following form:

$$f \infty \left(\frac{1}{n^{\infty}}\right) \tag{9}$$

where n is the number of laminae, α is the joint quality parameter, limited as follows: $1 \le \alpha \le 3$.

In case α equals 1, the laminae are not joined. If α equals 3, laminae are joined. The values of α are closer to 1 in fused panels with pointed deposit of glue. In fusible interlinings having a thermoplastic material applied in paste form, α is closer to 3. This was taken into account when modeling the joints of fused panels corresponding to the difference, which occurred in the observation and comparison of experimental and numerical results.

It can be concluded that draping represents a spatial problem. Therefore, for realistic modeling of draping of fused panels, it is necessary to carry out preliminary modeling of the joints with

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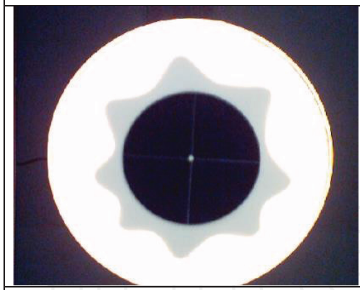
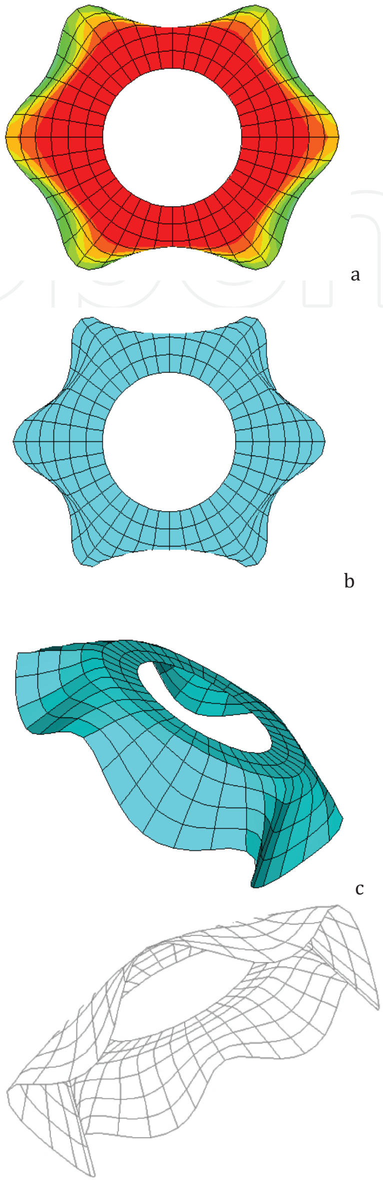
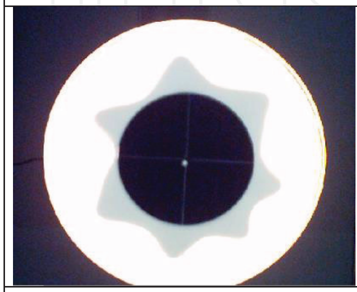
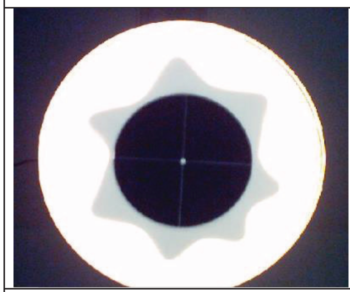
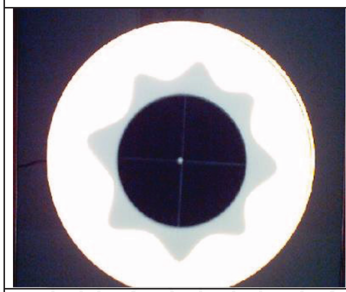
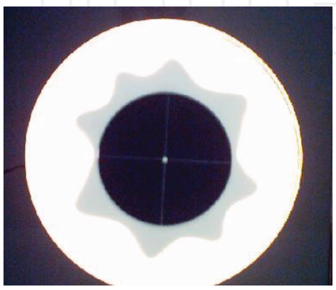
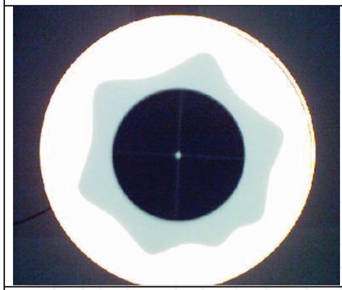
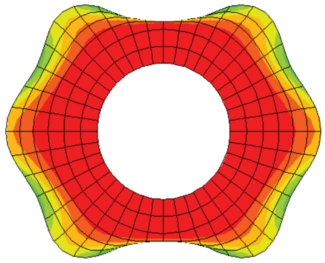
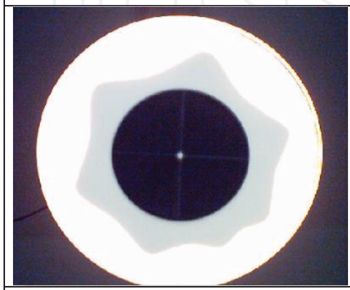
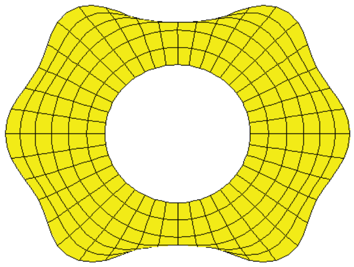
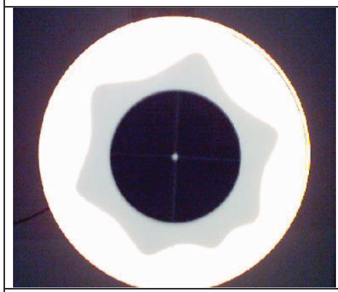
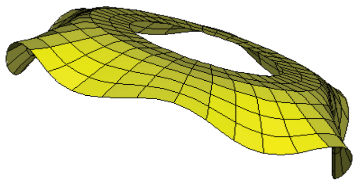
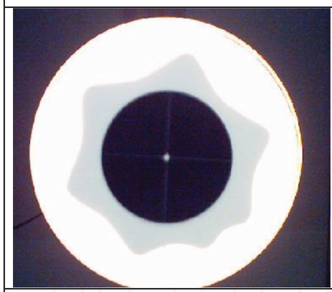
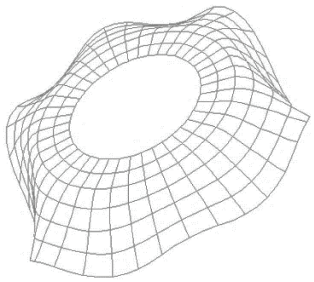
Experimental draping test			Draping simulation
Fabric code: F-1	Measured / calculated parameters		Different views
	Measurement No.	1	
	Number of folds	8	
	Max. deflection / mm	59,24	
	Min . deflection / mm	36,13	
	Fold depth /mm	38,40	
	Max. amplitude / mm	137,9	
	Min. amplitude / mm	99,5	
	Measurement No.	2	
	Number of folds	7	
	Max. deflection / mm	59,85	
	Min . deflection / mm	35,73	
	Fold depth /mm	44,00	
	Max. amplitude / mm	138,2	
	Min. amplitude / mm	94,2	
	Measurement No.	3	
	Number of folds	7	
	Max. deflection / mm	59,70	
	Min . deflection / mm	33,90	
	Fold depth /mm	43,60	
	Max. amplitude / mm	139,5	
	Min. amplitude / mm	95,9	
	Measurement No.	4	
	Number of folds	8	
	Max. deflection / mm	59,70	
	Min . deflection / mm	37,79	
	Fold depth /mm	40,70	
	Max. amplitude / mm	136,6	
	Min. amplitude / mm	95,9	
	Measurement No.	5	
	Number of folds	8	
	Max. deflection / mm	59,70	
	Min . deflection / mm	38,04	
	Fold depth /mm	40,50	
	Max. amplitude / mm	136,4	
	Min. amplitude / mm	95,9	

Calculated parameters	Exper.	Simul.	Diff. (%)
Number of folds	7,6	6	1,6
Max. deflection / mm	59,64	59,7	0,06
Min . deflection / mm	36,32	36,4	0,08
Fold depth /mm	41,44	36,32	5,12
Max. amplitude / mm	137,72	149,25	11,53
Min. amplitude / mm	96,28	112,93	16,65

Figure 8. Results of experimental testing and numerical simulations of a fabric F-1.

Experimental draping test			Draping simulation
Fabric code: F-1_L-1	**Measured / calculated parameters**		**Different views**
	Measurement No.	1	 a
	Number of folds	7	
	Max. deflection / mm	56,31	
	Min . deflection / mm	27,93	
	Fold depth /mm	32,40	
	Max. amplitude / mm	143,1	
	Min. amplitude / mm	110,7	
	Measurement No.	2	 b
	Number of folds	7	
	Max. deflection / mm	56,60	
	Min . deflection / mm	29,40	
	Fold depth /mm	32,40	
	Max. amplitude / mm	142,3	
	Min. amplitude / mm	109,9	
	Measurement No.	3	 c
	Number of folds	7	
	Max. deflection / mm	57,76	
	Min . deflection / mm	28,86	
	Fold depth /mm	34,70	
	Max. amplitude / mm	142,6	
	Min. amplitude / mm	107,9	
	Measurement No.	4	 d
	Number of folds	7	
	Max. deflection / mm	57,45	
	Min . deflection / mm	29,22	
	Fold depth /mm	35,10	
	Max. amplitude / mm	142,4	
	Min. amplitude / mm	107,3	

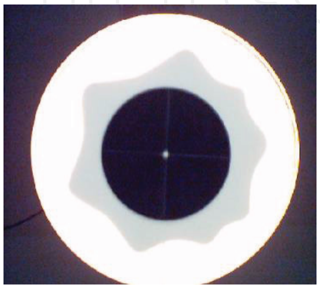
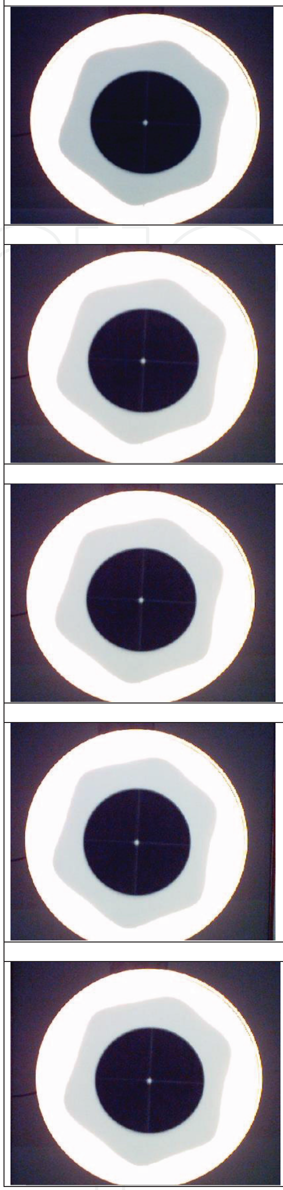
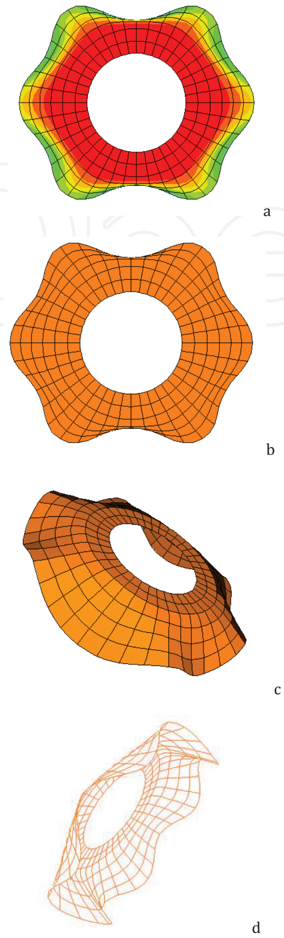
			Calculated parameters			
	Measurement No.	5		Exper.	Simul.	Diff. (%)
	Number of folds	8	Number of folds	7,2	6	16,67
	Max. deflection / mm	56,77	Max. deflection / mm	56,98	45,33	20,45
	Min . deflection / mm	31,60	Min . deflection / mm	29,40	23,63	19,63
	Fold depth /mm	30,60	Fold depth /mm	33,04	37,40	13,20
	Max. amplitude / mm	141,0	Max. amplitude / mm	142,28	139,5	1,95
	Min. amplitude / mm	109,4	Min. amplitude /	109,04	102,1	6,36

Figure 9. Results of experimental testing and numerical simulations of a fused panel F-1_L-1.

Experimental draping test			Draping simulation
Fabric code: F-1_L-2	Measured / calculated parameters		Different views



Measurement No.	1
Number of folds	6
Max. deflection / mm	51,72
Min . deflection / mm	26,15
Fold depth /mm	23,60
Max. amplitude / mm	144,0
Min. amplitude / mm	120,4
Measurement No.	2
Number of folds	6
Max. deflection / mm	51,60
Min . deflection / mm	27,55
Fold depth /mm	23,22
Max. amplitude / mm	143,3
Min. amplitude / mm	120,1
Measurement No.	3
Number of folds	6
Max. deflection / mm	51,90
Min . deflection / mm	26,96
Fold depth /mm	23,50
Max. amplitude / mm	143,6
Min. amplitude / mm	120,1
Measurement No.	4
Number of folds	6
Max. deflection / mm	52,01
Min . deflection / mm	26,76
Fold depth /mm	23,80
Max. amplitude / mm	143,7
Min. amplitude / mm	119,9
Measurement No.	5
Number of folds	5
Max. deflection / mm	51,78
Min . deflection / mm	26,76
Fold depth /mm	19,50
Max. amplitude / mm	143,7
Min. amplitude / mm	124,2



Calculated parameters	Exper.	Simul.	Diff. (%)
Number of folds	5,8	6	3,45
Max. deflection / mm	51,8	48,82	5,75
Min . deflection / mm	26,74	22,94	14,21
Fold depth /mm	22,72	24,3	6,95
Max. amplitude / mm	143,66	140,1	2,48
Min. amplitude / mm	120,94	115,8	4,25

Figure 10. Results of experimental testing and numerical simulations of a fused panel F-1_L-2.

respect to the function of friction. In our case, the friction depends on the normal force in the joint, as well as on relative displacement between the two layers. From experimental studies [31], it can be concluded that the rheological model functionally depends on the deformation state.

3.2. Case study 2: computer simulation of functional clothes for wheelchair users

3D scanning and computer simulation techniques were studied for development of individualized functional garments for wheelchair users from perspective of ergonomic comfort in a sitting posture, functional, and aesthetic requirements and needs regarding their health protection.

Some recent studies have shown that clothes for disabled users should not only be based on various design, fashion and comfort concepts, but should also consider particular medical problems [33–37]. The interviewing conducted in Slovenia among 58 adult respondents revealed that paraplegic wheelchair users are faced also with accompanying health problems because of their primary disease [35]. They are mostly faced with incontinence (66.7%), infection and inflammation of the urinary tract (50.0%), frequent colds (33.0%), while some of them also have pressure sores (14.6%), skin irritations and inflammations (12.5%). The hand pains (50.0%) and leg cramps (41.7%) are common health problems of paraplegics. It is well known that they are faced also with limited mobility of hands, atrophy of the leg muscles, poor blood circulation, and regulation of body temperature of lower extremities [34, 38, 39]. With the respect to the above facts, the paraplegic wheelchair users have difficulties in wearing regular garments due to their insufficient functionality and protection.

3.2.1. 3D scanning

Producers of 3D human body scanners usually offer software for visualization of the scanned (standing) 3D body model and automatic extraction of the anthropometrical dimensions based on standard ISO 8559 [43]. However, this software cannot represent scanned sitting body and extract anthropometrical body dimensions automatically. The research on a sitting posture's 3D body model, obtained by scanning with Vitus Smart XXL human body scanner and two general-purpose optical scanners (GOM Atos II 400 and the Artec™ Eva 3D hand scanner), showed that more appropriate digitized mesh can be achieved using the general purpose optical scanners [34, 40, 41], **Figure 11**. Digitizing was carried out on a rotation chair. The accurate sitting 3D body models were achieved after modeling and reconstruction procedures that are deeply described in a source [34]. In this research, the fully mobile persons were involved to avoid unnecessary burdening of paraplegics at this stage of the research.

The experiences gained from this study enabled us to include the immobile persons within the research. With respect to the poor body balance due to spine injury and modeling/reconstruction procedure of the scanned 3D body models, there was a need to develop a special chair for scanning, adjustable to the individuals’ body dimensions, **Figure 12(a)**. Scanning of the paraplegic wheelchair users was performed by using the optical hand scanner Artec Eva 3D. The 3D body models were achieved after modeling and reconstruction procedures described in a source [34]. In addition, a comparative analysis of the scanned 3D bodies’ virtual measurements and manual measurements was performed for fully mobile and immobile persons to find if the poor body balance of the immobile persons affects the accuracy of the 3D body models. During manual measurements, using a measuring tape, locations of the body dimensions, anthropometrical landmarks and standard procedure for the human body measuring were taken into account according to the standard ISO 8559 [42]. All dimensions of the limbs were measured on the left limbs. The virtual measurements of the scanned 3D body models were performed at the same locations as described for the manual measurements using the measuring tools of the OptiTex 3D system, **Figure 12(c)**. The statistical analysis of the virtual

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(a) GOM ATOS II 400 optical scanner (b) Artec Eva 3D hand scanner

Figure 11. Scanning of fully mobile persons in a sitting posture.

(a) Chair for scanning of IMP	(b) Scanned and reconstructed 3D body model of IMP	(c) Virtual measuring of 3D body dimensions

Figure 12. Scanning of the IMP by using a scanning chair and optical hand scanner Artec Eva 3D, and virtual measuring of the 3D body dimension [36].

and manual measurements indicated that the mobility of a person does not affect the accuracy of the virtual measurements and sitting posture 3D body models, respectively [36].

3.2.2. Development of functional garments for wheelchair user by using the computer simulation

In this part of the research, study regarding the virtual prototyping of functional garments was carried out on a sitting 3D body models by using the Optitex 3D program. Construction of the garments' pattern designs was based on the virtually measured 3D body models' dimensions.

In the study regarding the pants and blouse pattern designs for a sitting posture a reconstruction procedure of the basic patterns was performed in order to obtain well-fitted garments, which also meet demands of the wheelchair users due to additional health problems (pressure sores, obstruction of the blood flow, inflammation of the urinary tract, etc.) and aesthetic appearance [34]. In this research, a comparison between the real garments and virtual prototypes showed that development of functional garments for a sitting posture is extremely suitable when using scanned 3D body models and computer simulation techniques. In addition, experiments have proven a synergistic effect of the computer simulation techniques during the development process of the ergonomic garments and their great potential for use and radical changes in the production of custom-made garments for wheelchair users [36].

The 3D scanning and computer simulation approach was studied for design of functional garments for health protection of the wheelchair users [35, 37]. It was based on 58 in-depth interviews conducted with adult wheelchair users at the national level, as described at the beginning of this chapter. The study focused on development of functional pants, adapted to individuals who suffered from pressure sores, incontinence or sweating in the crotch area, between the thighs and under the buttocks. On the other hand, we concentrated on development of special protective garments, such as sitting bag and cape, in terms of human protection from external influences, i.e., cold, wind, humidity, which could cause to immobile persons problems with the temperature of lower extremities, the chronic urinary infections and frequent colds. The chronical moistening of the skin was found to be a major problem for potential skin irritations and inflammations or even wounds due to the incontinence or sweating. Therefore, by using the antimicrobial and antioxidative textile materials (AATM) [43] in specific parts in the pants (crotch area, between the thighs, contacts of the body with a wheelchair), the prevention against potential health problems can be achieved.

The development of well-fitted functional pants on the scanned 3D body model enabled us: (a) to simulate person's morphological shape and extract main features of the body shape and (b) to simulate and validate pants pattern design with integrated AATM in exact parts of the pants on the 3D human body, **Figure 13(a)**. The pants will act as a protection regarding the chronically skin moistening. In addition, the functional pants pattern design was developed for a wheelchair user with a pressure sore on the hips. The AATM was integrated in the exact part of the pants with help of 3D scanning of this person due to exact location of the wound and virtual simulation and validation of the pants pattern design on this 3D body model, **Figure 13(b)**. The pants will act in a curative manner regarding the pressure sore on hips. This study showed new steps toward the efficient approach to responsible development of functional garments not only for wheelchair users, but also for elderly and persons who are forced to a sitting posture during the day, and could not find appropriate clothes in regular stores. In addition, 3D scanning of the immobile persons with incontinence pads, diapers, or briefs is also challenging for development of well-fitting pants pattern designs for individuals by using the 3D virtual prototyping.

The garment's protective function can be achieved with the body heat balance in order to ensure the thermal comfort and physiological sense of safety. This can be obtained by appropriate textile materials properties, clothing design, and the design of the complete clothing system and its components. Virtual prototyping approach was used to develop the sitting bag and the cape pattern designs [35]. The development of the sitting bag was performed on scanned 3D body models of the wheelchair users, whilst for the cape on the scanned 3D body model with a wheelchair. The garments fitting was carried out due to measured mechanical properties of the used fabrics, which enabled us to develop correct form of the pattern pieces. The sitting bag was designed according to the trends of newer forms of the wheelchairs, which have narrower leg supports. Requests of interviewees related to the length of the sitting bag were also considered. Therefore, it covers only the lower extremities. The respondents’ request that the cape should cover the backrest and wheels of a wheelchair has been also taken into account in the cape’s design. The developed virtual prototypes of the special protective clothing are shown in **Figure 14**. In this figure, we can see that for development of

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the cape it was used the complex 3D model. The deformation of the cape occurred in location of the wheelchair handles and error in the fabric's collision with a sharp part of the 3D object, **Figure 14(a)**. We could not avoid it even at higher simulation resolutions. During simulations of the sitting bag, using the gravity of 0 ms^{-2} enabled us to develop a pattern design of suchlike dimensions that fits different body shapes, **Figure 14(b)**.

The study presented in this part of the chapter showed high usability, efficiency and benefits of 3D scanning, and virtual simulation techniques in the development process of custom-made functional garments and ready-made protective garments for wheelchair users. On the other hand, we are still facing with robustness at positioning of the 2D pattern pieces

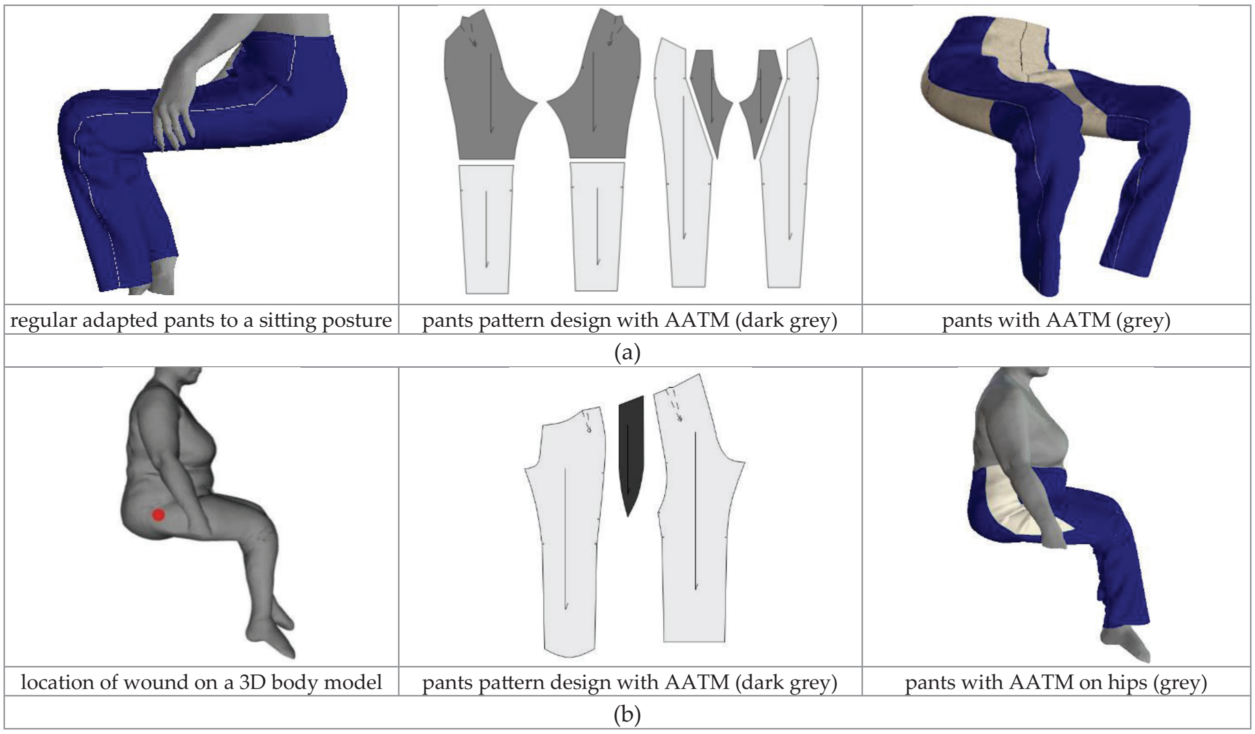

Figure 13. Development of functional pants pattern designs by using 3D scanning and virtual simulation techniques [37].

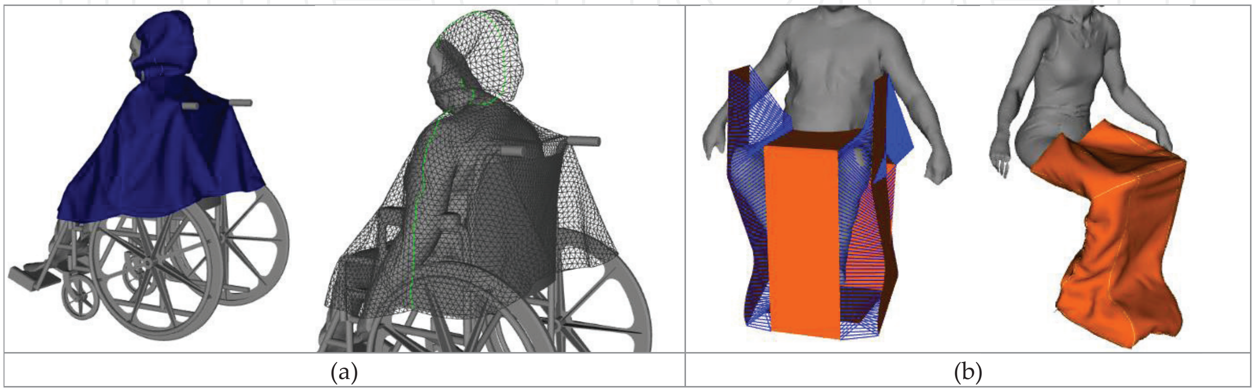

Figure 14. Virtual prototypes of special protective clothing for paraplegic wheelchair users [35].

around the sitting 3D body model due to limited possibilities of pattern pieces folding, which indicates the potential future challenge in the development of commercial 3D CAD programs for garments simulation on sitting body postures.

3.3. Case study 3: computer simulation of protective clothes for sport aircraft pilots

Since the protective equipment is necessary for different areas of human activity, it is essential to take an individual approach to the design of all protective elements (clothes, gloves, shoes, helmets, etc.). During the construction and design the protection and functionality of the protective clothes is of the utmost importance, where the designer and constructor have to have the necessary knowledge about the clothing elements, the usual body movements and additional elements of protection [44].

This study focuses on development of the special protective garment for sport aircraft pilots, or so-called anti-g suit. This is a special form of a flight suit, worn by sport aircraft pilots, who are exposed to high levels of acceleration forces. The pilot sits in a cramped airplane cabin in exact position. Therefore, we suppose that the suit should be developed according to body dimensions in this position. Namely, it is well-known that wearing comfort differs for variety of body shapes and dynamic body postures due to changes in body dimensions [45–48].

The present study is still at an early stage, therefore the importance of 3D body scanning and virtual simulation is shown through the development process of the suit pattern design. 3D body scanning was carried out using three scanning postures (SP), i.e., standard standing posture (SP1_StP), sitting posture (SP2_SiP) and driving-sitting posture (SP3_DSiP), **Figure 15**, by using the 3D human body scanner Vitus Smart XXL at the Textile Technology Faculty, University of Zagreb, Croatia. During scanning, especially for the SP3_DSiP, we were restricted by the volume of the scanning area (1 × 1 m). Therefore, we were not able to scan a person in every proper sitting posture. In addition, the scanned 3D mesh was highly deformed, particularly in areas of crotch, thighs, and calves. Therefore, the modeling and reconstruction of 3D body models was difficult and lengthy process. Based on the experience gained from the study, presented in Chapter 3.2, we can assume that it would be better to use in this research a general-purpose optical scanner, such as hand scanner Artec ™ Eva 3D.

In this study, 24 body dimensions were virtually measured according to the standard ISO 8559 [42] and three additional body dimensions that standard ISO 8559 does not specify (transverse hips girth in a sitting posture, front and back overall length in a standing/sitting posture) by using the software ScanWorks.

The cross sections of 3D body models at three measurement positions of body dimensions, i.e., chest girth, waist girth, and hips girth (sitting postures—transversal hips girth), are presented in **Figure 16**, as well as belonging dimensions in standard and dynamic body postures. In this figure, it can be seen that different cross sections and body dimensions were achieved for different body postures. The main reason for this are activated muscle groups in different body postures that should be considered when constructing the garment pattern

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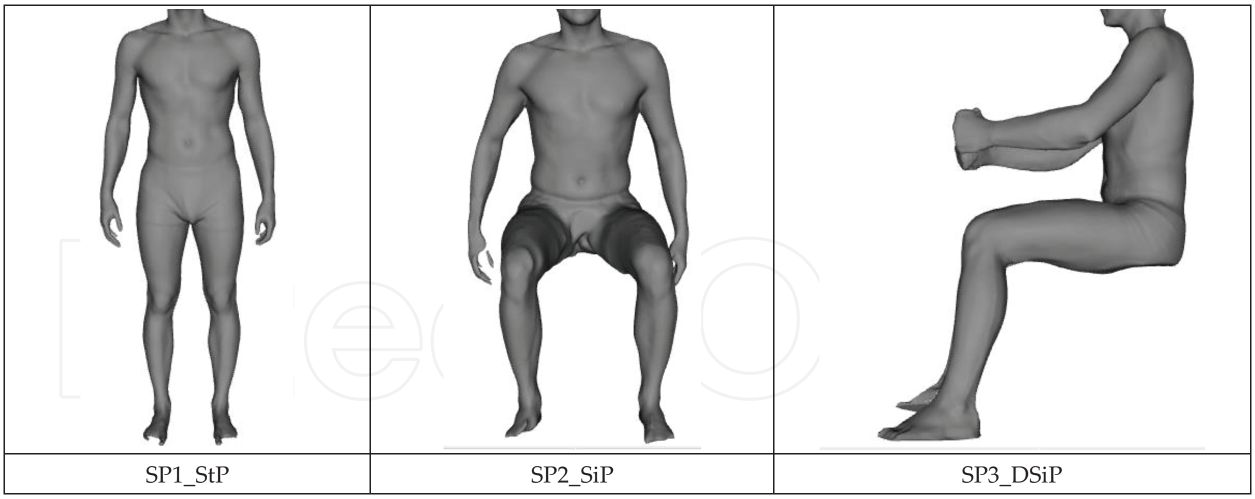

Figure 15. Scanned 3D body models in three different postures.

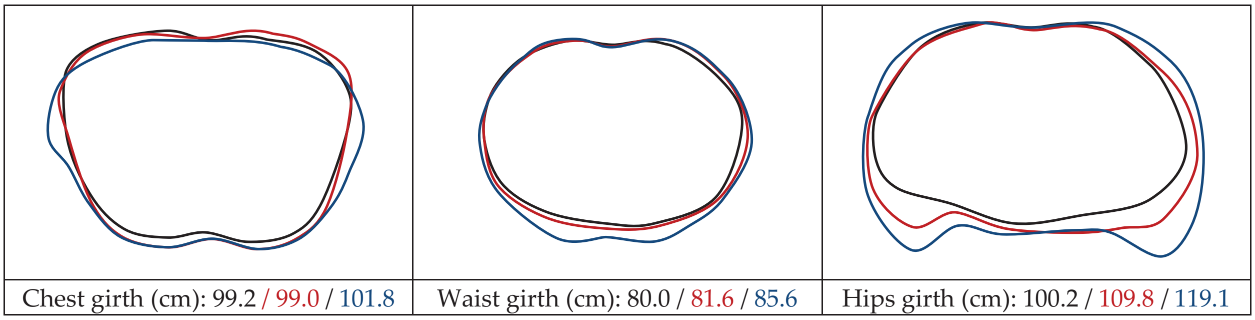

Figure 16. The cross-sections of the 3D body models and body dimensions.

design. The greatest chest, waist, and hips girths were obtained in a body posture SP3_DsiP. The greatest difference in hips girth was achieved between the standing and sitting body model in a driving posture, which was also expected. Therefore, construction of the basic suit pattern design was based on measured dimensions for a posture SP3_DsiP.

The virtual simulations of the suit for all body postures are shown in **Figure 17**. In this figure, a poor suit fit to the standing 3D body model can be seen, especially on the back and in the pants length. This result is understandable in terms of used body dimensions, measured in a sitting posture SP3_DSiP. For this posture, the greatest tension (red) was achieved in the area of armhole seams and over shoulders, which specifies that measure over shoulder should be increased. Even higher tension over shoulders can be seen on both sitting postures SP2_SiP and SP3_DSiP, which confirms the above indication. A more appropriate suit fit to the sitting 3D body model can be seen in a driving posture SP3_DSiP, with the exception of shoulders and hips positions, where the fit must be improved in continuation of the research. In our case, we need to construct the special protective suit, which requires very little freedom of movement.

Based on the above, we will, using the virtual prototyping, confirm the final pattern design of a suit, which will be upgraded with suitable elements into an anti-g suit.

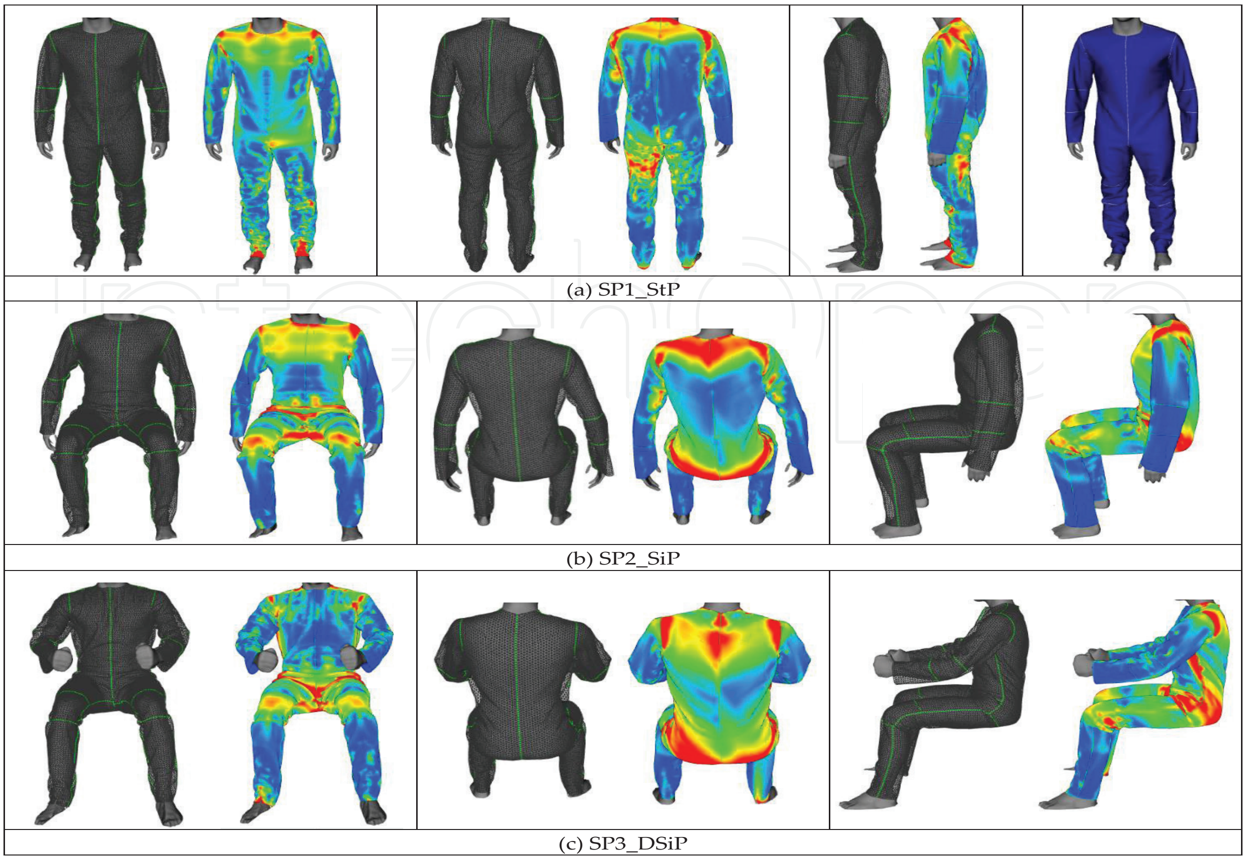

Figure 17. Virtual prototyping of the overall on 3D body model in different postures.

4. Conclusions and future challenges

Engineering approaches to textile forms' design for particular purposes, presented in this chapter, show benefits and limitations of 3D body scanning and computer simulation techniques and outline the future challenges.

The study regarding the fabric and laminate drape by using the FEM in Section 3.1 showed that draping represents a spatial problem. Therefore, for realistic modeling of draping of fused panels, it is necessary to carry out preliminary modeling of the joints with respect to the function of friction. In our case, friction depends on the normal force in the joint, as well as on relative displacement between the two layers. From experimental studies, it can be concluded that the rheological model functionally depends on the deformation state.

The case study in Section 3.2 indicated that 3D scanning and virtual simulation techniques are extremely accurate and appropriate in the development process of custom-made functional garments and ready-made protective clothing. However, there are still limitations in garments virtual simulations on the sitting 3D body models when using the commercial 3D CAD programs. A robust positioning of the 2D pattern pieces around the sitting 3D body model due to limited possibilities of pattern pieces folding and fabric's collision with a sharp parts of 3D objects, as in a case of a wheelchair's handle, is one of weaknesses. Therefore, future challenges in computer simulation techniques are certainly done in the development of commercial 3D CAD software for simulation of garments on a wide variety of nonstandard postures of 3D body models or 3D objects. One of the future challenges would certainly be to build a parametric sitting 3D body model, which would allow the development of garment patterns designs for a sitting population.

The present part of a case study in Section 3.3 showed that we are on the right way to develop the anti-g suit. We found out that in continuation of the study that there should be a general-purpose optical hand scanner, to digitize a person in proper sitting posture, which would enable the modeling of the accurate sitting 3D body model and the development of pattern design of this special protective clothing.

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