Research on the virtual simulation of the drape of cotton-linen blended fabrics of high bending rigidity

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ABSTRACT – REZUMAT

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A major challenge in virtual 3D garment prototyping is still the lack of precise and reliable simulation of the drape of textile materials. Accurate simulation of the fabric drape depends on the CAD 3D programme used, the physical and low-stress mechanical properties of the fabrics and the possibility of varying the simulation parameters, like the density of the 3D fabric polygon mesh, which is particularly important for high-bending-rigidity fabrics. Hence, in this study, the effect of the polygon mesh density on the virtual drape of heavy cotton-linen fabrics with high rigidity, suitable for spring outwear garment, was investigated. Four fabrics were developed with identical yarns and fabric count and differentiated by fabric weave. The virtual drape simulations of the fabrics were performed using the OptiTex software with variable polygon mesh density (0.3–0.9) and were compared with the real fabric drape assessed by the Cusick Drape Tester. In addition, the draping of two virtual 3D garments was analysed to identify differences due to variable polygon mesh density. Largely different physical and low-stress mechanical properties of the fabrics, depending on weave, resulted in different drape behaviour, with plain and satin fabrics displaying the highest (0.91) and lowest (0.86) drape coefficient, respectively. Analysis of the drape coefficients of both real and virtually simulated fabrics suggests that more reliable and realistic simulations of high rigidity fabrics can be achieved with low polygon mesh density (0.7 and 0.9). The density of the 3D fabric polygon mesh slightly influences garment drape simulation and appearance. Specifically, for the skirt, orthogonal projections reveal fold displacement and variations in fold shape and depth correlated with polygon mesh density. These results can help garment developers to carry out realistic simulations of high-rigidity fabrics.

Keywords: *cotton-linen blended fabrics, fabric weave, fabric real drape, virtual drape simulation, polygon mesh density*

Cercetare privind simularea virtuală a drapajului țesăturilor din amestec de bumbac și in cu rigiditate ridicată la îndoire

O provocare majoră în prototiparea virtuală 3D a articolelor de îmbrăcăminte rămâne în continuare lipsa unei simulări precise și fiabile a drapajului materialelor textile. Simularea precisă a drapajului țesăturii depinde de programul CAD 3D utilizat, de proprietățile fizice și mecanice ale țesăturilor cu solicitare redusă și de posibilitatea de a varia parametrii de simulare, cum ar fi densitatea rețelei poligonale 3D a țesăturii, care este deosebit de importantă pentru țesăturile cu rigiditate ridicată la îndoire. Prin urmare, în acest studiu a fost investigat efectul densității rețelei poligonale asupra drapajului virtual al țesăturilor din bumbac-in cu masă mare și rigiditate ridicată, potrivite pentru îmbrăcămintea de primăvară. Au fost dezvoltate patru țesături cu fire și densitate identice, care se diferențiază prin legătura țesăturii. Simulările drapajului virtual al țesăturilor au fost efectuate utilizând software-ul OptiTex cu densitate variabilă a rețelei poligonale (0,3–0,9) și au fost comparate cu drapajul real al țesăturii evaluat cu Cusick Drape Tester. În plus, a fost analizat drapajul a două articole de îmbrăcăminte virtuale 3D pentru a identifica diferențele datorate densității variabile a rețelei poligonale. Proprietățile fizice și mecanice foarte diferite ale țesăturilor, care depind de legătura țesăturii, au dus la un comportament diferit al drapajului, țesăturile cu legătură pânză și cele cu legătură atlaz prezentând coeficientul de drapaj cel mai ridicat (0,91) și, respectiv, cel mai scăzut (0,86). Analiza coeficienților de drapaj ai țesăturilor reale și simulate virtual sugerează că se pot obține simulări mai fiabile și mai realiste ale țesăturilor cu rigiditate ridicată cu o densitate redusă a rețelei poligonale (0,7 și 0,9). Densitatea rețelei poligonale 3D a țesăturii influențează ușor simularea drapajului și aspectul articolului vestimentar. Mai precis, în cazul fustei, proiecțiile ortogonale relevă deplasarea pliurilor și variațiile formei și adâncimii pliurilor corelate cu densitatea rețelei poligonale. Aceste rezultate pot ajuta dezvoltatorii de articole vestimentare să realizeze simulări realiste ale țesăturilor cu rigiditate ridicată.

Cuvinte-cheie*: țesături din amestec de bumbac și in, legătură pânză, drapaj real al țesăturii, simulare virtuală a drapajului, densitatea rețelei poligonale*

INTRODUCTION

In the current context of the textile sector, innovative and sustainable textiles are expected to enter the market, and their digitalisation is necessary for the purpose of garment development, pursuing minimal resource use by means of simulations as an alternative to the production of multiple prototypes.

With around 26 million tonnes, cotton is the second most important fibre in terms of production volume and had a market share of around 24 percent of global fibre production in 2020, while other plant-based fibres, including linen and hemp, had a market share of around 6 percent [1]. As the most up-and-coming natural fibres, linen and hemp have a growing potential for use in various products [2]. The global market for linen fabrics is expected to reach USD 3,125.4 million by 2030, and the compound annual growth rate is expected to exceed 6.2% [3]. Linen is an excellent, environmentally friendly fibre obtained from the inside of the woody stem of the flax plant. The fibre is spun on a long-fibre spinning system [4,5]. It is very absorbent, and linen garments are valued for their exceptional coolness and freshness in hot weather. Linen has several advantages over cotton: it is stronger and conducts heat better than cotton, it is less elastic and stiffer than cotton and creases easily [5]. Linen fabrics are available in various qualities, from ultra-light fabrics to heavy linen canvases. They are used for a wide range of products, from men's and women's clothing to towels, napkins, bed linen, etc. Compared to synthetic fabrics, they do not cause an increase in reactive oxygen species and oxidative stress in the human organism [6] and have a positive effect on the human body in terms of their comfort properties [7, 8, 9]. By blending linen with other compatible natural and man-made fibres, different structural and functional properties can be achieved. Fabrics made of 100% linen and their blends with cotton and viscose have been studied for their physical, mechanical and comfort properties [4]. Okur [1] found that blending linen and hemp with cotton increases the air permeability, water absorption and drying speed.

Based on the blending potential of natural fibres such as linen and hemp, research has increasingly focused on how fabric construction, particularly weave structure, affects the physical and mechanical properties of these textiles. Begum and Milašius [10] have provided an overview of the effects of weave structure on fabric properties, including drapability. Todihi et al. [11] analysed the influence of weave structure on the properties of bending rigidity of fabrics. Matusiak [12] investigated the drapability of twelve cotton fabrics with different structures. Among the examined fabrics, the twill weaves 3/1 S and 2/2 S had the highest drape coefficient, while the rep weave 2/2 (2) had the lowest. Süle [13] noticed an increase in the drape coefficient with increasing weft density and weft yarn thickness, and no influence of warp tension on the drape coefficient.

The shape and aesthetic appearance of garments are influenced by the specific properties of textile materials, especially the bending and shear rigidity and drapability of textiles [14–17]. Numerous studies investigated the relationship between various physical or mechanical properties of the fabric and its ability to drape and highlighted the most important ones in predicting the drape coefficient [18–25], among which fabric stiffness, showing that very stiff fabrics have a high drape coefficient.

For this reason, studies looking at the relationship between mechanical properties and drapeability and garments' shape and appearance in real and virtual environments were conducted for decades. Targeting improved accuracy of virtual drape simulations, the effect of low-stress mechanical properties measured with KES or the FAST measurement system on the drape of the fabric has been investigated in many studies [26–29]. A realistic 3D clothing simulation requires dedicated software programmes, but proprietary algorithms hinder the analysis. In the study by Schiller et al. [30], the VStitcher software was used to evaluate the fabric parameters using drape tests and drape coefficient (DC) calculations. The analysed fabrics had DC values between 0.1 and 0.7. The bending rigidity had the greatest influence on the DC, while the thickness, elongation and shear rigidity had only a minor influence on the DC. In the study by Ashmawi et al. [31], three different fabrics, cotton, polyester and cotton-polyester, were used for virtual 3D simulations of garments using CLO3D software and found that this software is not suitable for simulating garments with optimal simulation of fabric draping. Miguel et al. [32] examined how fabric type, weave and thickness affect the drape behaviour of clothing by comparing single-layer and double-layer fabrics of the same weight in a jacket prototype. Their experimental tests and virtual simulations using Marvellous Designer 8 revealed notable differences in drape and aesthetics, with the double-layer fabric showing less fall but a more harmonious drape than the single-layer fabric. Also, Rudolf et al. [33] studied the effects of fabric properties (such as extension, bending, shear rigidity, and thickness) and simulation parameters (including resolution, solver settings, and soft bending) on fabric draping and the shape and fit of the virtual garments. They recommended using different simulation parameters for soft and flexible fabrics as opposed to rigid fabrics to achieve more realistic drape simulations. The optimal simulation parameters using the OptiTex 3D software, depending on the measured low-stress mechanical properties using the measuring systems FAST and KES, were also investigated by Petrak et al. [34] for nine fabrics (polyester, wool, polyester and wool blends with cotton, viscose, and elastane). They found an optimal polygon size of 0.4 cm for fabrics with a drape coefficient ranging between 0.20 and 0.35, a size of 0.6 cm for fabrics with a drape coefficient between 0.35 and 0.50 and a size of 0.8 cm in the case of a drape coefficient above 0.5. The recent developments of systems for the digitalisation of textiles, based on artificial intelligence, are now opening new possibilities for the virtual 3D prototyping of garments [35–37].

Today, the fashion and clothing industry is increasingly striving to use sustainable and renewable textile materials and to digitise the entire production process. In this context, virtual 3D simulation of garments will continue to play an important role, significantly supporting the development, presentation and sale of garments on the market. Therefore, there is a need for knowledge about the integration of a large range of textiles in a virtual environment with the aim of simulating the draping of virtual 3D garments as realistically as possible.

Hence, this study aims to complement existing research and examine heavy cotton-linen blend fabrics with high bending rigidity, barely considered in other studies. The focus is on the influence of the fabric weave and the size of the triangles of the 3D fabric polygon mesh on the virtual fabric drape and garment simulations using OptiTex 3D software. It hypothesises that for high-bending-rigidity fabrics, more reliable and realistic simulations can be achieved with a lower polygon mesh density.

EXPERIMENTAL

Materials

For this study, four fabrics (FB1 – FB4) were developed on a Dornier industrial rapier weaving loom 1.6 m width differentiated by four distinctive weaves and having identical fabric count and yarn composition, i.e. 150 tex linen yarns and 40 tex cotton yarns in weft and warp direction, respectively. The types of weaves (i.e. plain 1/1, twill 3/1, reinforced twill 1/1 2/2, satin 4/1) were chosen targeting large differences in fabric properties, bending stiffness in particular.

The physical properties of the four fabrics were measured as described in section 2.2.1 and are listed in table 1. The thickness of the fabrics varied roughly between 1.1 mm (plain fabric FB1) and 1.4 mm (satin fabric FB4), and their weight between 339 g·m^{-2} (FB4) and 355 g·m^{-2} (FB1), respectively.

Methodology

The fabrics were conditioned for at least 24 hours according to the standard ISO 139:2005 [38] prior to their physical, low-stress mechanical properties and drapeability being assessed, and the simulations of the garment and fabrics' drape were executed.

Physical properties

The fabric count in warp and weft direction was determined according to the standard ISO 7211/2:1984 [39]. The fabric thickness was measured with a thickness gauge according to the standard ISO 5084: 1996 [40] and the fabric weight according to ISO 3801:1977 [41].

Low-stress mechanical properties

The low-stress mechanical properties of the fabrics, including extensibility (E5, E20, E100), shearing rigidity (G), bending rigidity (B) and surface thickness (ST) were measured using a FAST measuring system [42]. The measured mechanical properties of the fabrics were subsequently converted into the units of the OptiTex 3D V11 software [43] and used for the simulation of fabrics and garments' drape.

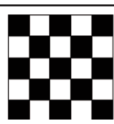
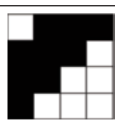
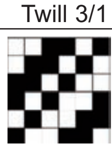
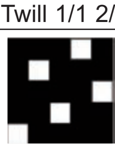
Fabric drape

A Cusick Drape Tester (CDT) (James H. Heal & Co. Ltd., Halifax, England) was used to determine the real drape coefficients of the fabrics using the Drape Analyser software. The pedestal of the Cusick Drape Tester, with a diameter of 18 cm, and the fabric sample with a diameter of 30 cm were used. The orthogonal projections of fabric drapes were taken with a digital camera, and the drape coefficients (DC) were calculated.

To determine virtual fabric drape, a 3D pedestal model with a diameter of 18 cm was imported into the

Table 1

THE PHYSICAL PROPERTIES OF THE FABRICS (FB1-FB4), DEVELOPED WITH IDENTICAL YARNS AND FABRIC COUNT AND DIFFERENTIATED BY FABRIC WEAVE

Fabric code	Weave type	Yarn linear density (tex)		Fabric count (thread/cm)		Fabric thickness (mm)	Fabric weight (g·m^{-2})
		warp	weft	warp	weft		
FB1	 Plain 1/1	150	40	18	10	1.11 ± 0.01	354.92 ± 2.80
FB2	 Twill 3/1	150	40	18	10	1.42 ± 0.01	340.31 ± 2.62
FB3	 Reinforced Twill 1/1 2/2	150	40	18	10	1.39 ± 0.02	348.77 ± 3.22
FB4	 Satin 4/1	150	40	18	10	1.44 ± 0.01	339.96 ± 1.70

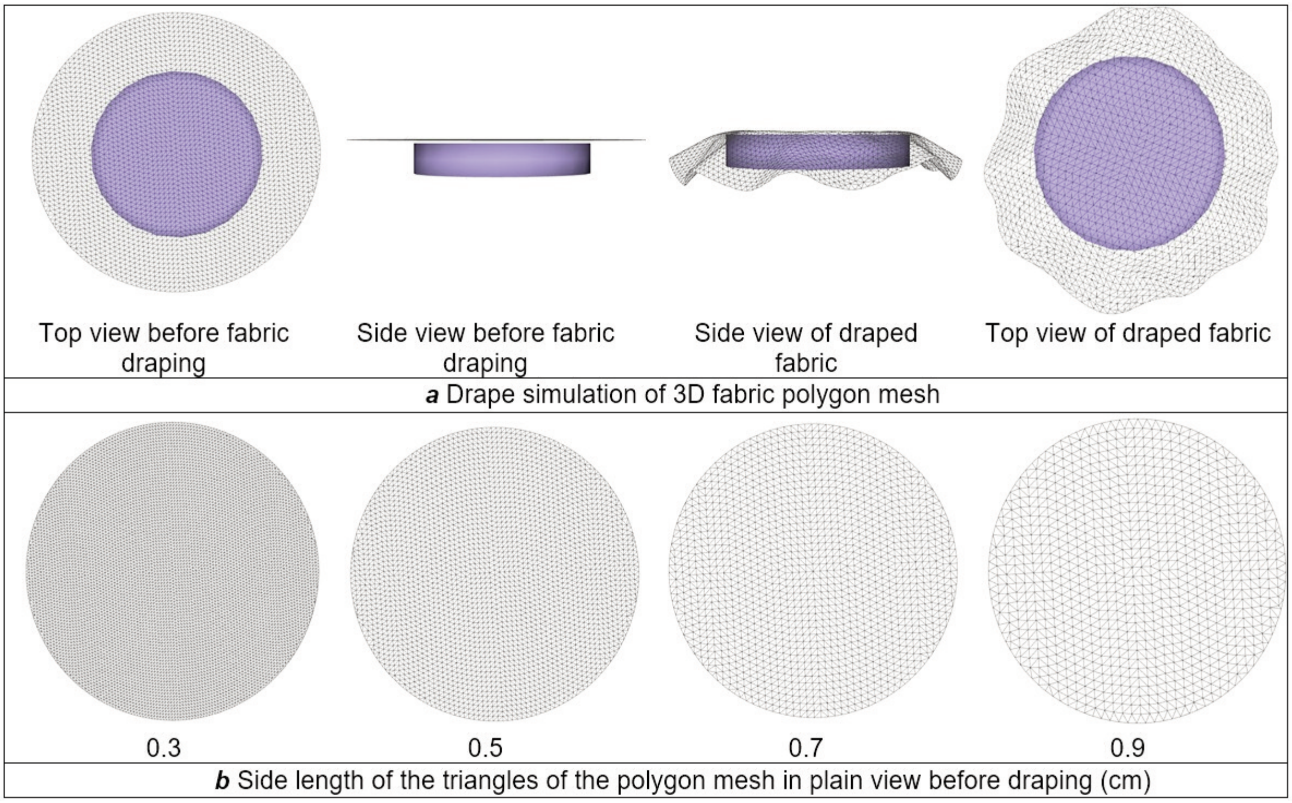


Fig. 1. Fabric drape simulation showing: *a* – fabric top and side view before and after draping; *b* – visualisation of various side lengths (0.3–0.9) of the triangles of the polygon mesh, in the OptiTex 3D software

OptiTex 3D software. Drape simulations of the 30 cm diameter 3D fabric pattern piece were performed using the default simulation parameters (i.e. world, time and stitch parameters) and by varying the density of the 3D fabric polygon mesh.

For the virtual draping, the measured low-stress mechanical properties of the real fabrics were used, i.e. extensibility (E100), bending rigidity (B), shear rigidity (G), surface thickness (ST) and weight (W) were used. The fabric simulations were performed with different densities of the 3D fabric polygon mesh (0.3, 0.5, 0.7, 0.9), corresponding to a side length of the triangles of 0.3 cm, 0.5 cm, 0.7 cm and 0.9 cm, respectively, as shown in figure 1. The position of the virtual 3D fabric pattern piece was kept the same in all simulations.

After simulating each fabric drape, its orthogonal projection was recorded, figure 2, *a*, to compare it with the orthogonal projection of the CDT and to compare the drape coefficients between real fabrics and simulated fabrics.

The orthogonal projections of the draped fabrics were extracted using a CorelDraw software programme [44], and they were imported into the ArchiCAD programme [45], where the surface areas (mm^2) were measured using the Fill/ Dimension tool,

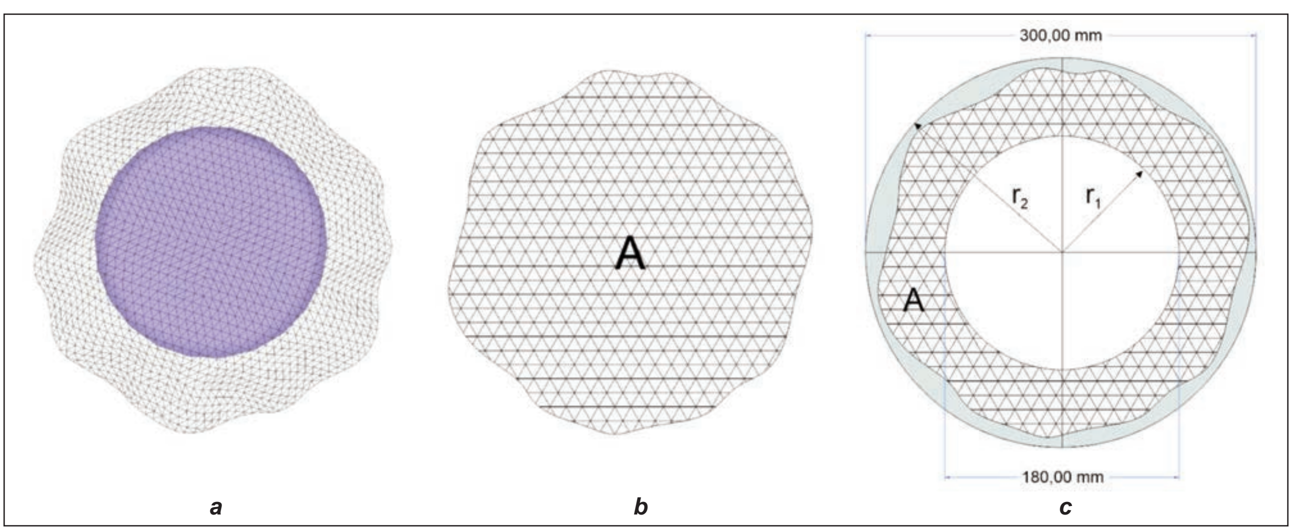


Fig. 2. Procedure for calculating the drape coefficients for virtually draped fabrics: *a* – fabric drape simulation; *b* – surface area of the draped fabric; *c* – parameters for the calculation of the drape coefficient

figure 2, *b*. The drape coefficients (DC) were calculated using equation 1 [46]:

$$DC = \frac{A - \pi r_1^2}{\pi(r_2^2 - r_1^2)} \qquad (1)$$

where A (mm^2) is the surface area of the orthogonal projection of the draped fabric, r_1 (mm) – the radius of the pedestal, and r_2 (mm) – the radius of the undeformed fabric sample before draping, figure 2, *c*. The higher the value of DC, the lower the drapability of the fabric [12].

Garments drape

A standard 3D woman's body model available in the library of the OptiTex 3D V11 software was used to carry out the drape simulations of the clothing set consisting of a jacket and an A-line skirt in accordance with the fabrics developed. Drape simulations were performed using the default simulation parameters by varying the density of the 3D fabric polygon mesh (0.3, 0.5, 0.7, 0.9), corresponding to a side length of the triangles of 0.3 cm, 0.5 cm, 0.7 cm and 0.9 cm, respectively.

Measured low-stress mechanical properties of the real fabrics, i.e. extensibility (E100), bending rigidity (B), shear rigidity (G), surface thickness (ST), and weight (W) were used to obtain the garments' drape simulations (figure 3). In the drape simulations, the position of the virtual 3D pattern pieces of garments around the 3D body model was the same in all simulations.

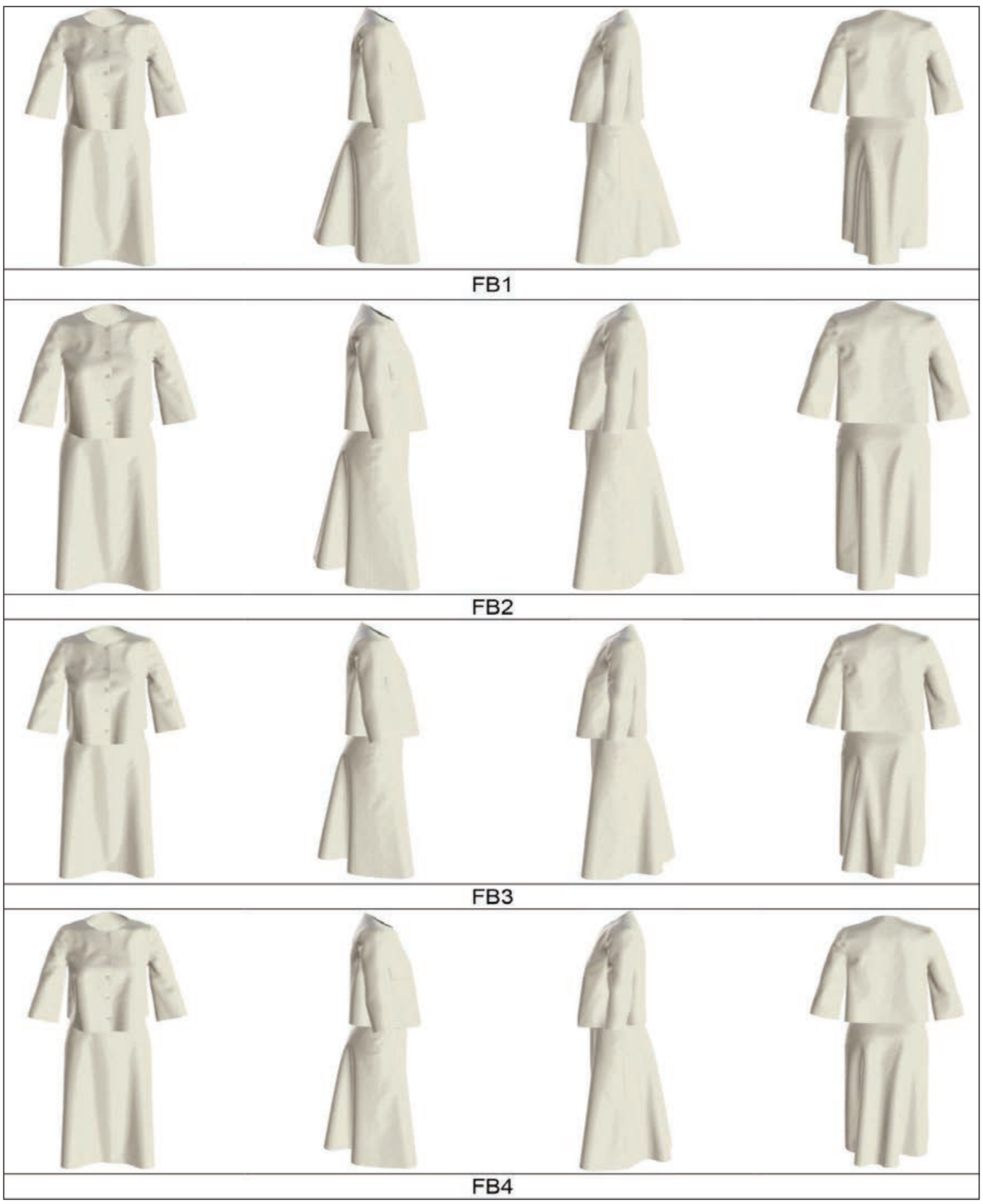


Fig. 3. Simulations of a virtually draped garment, for fabrics FB1–FB4 and a polygon mesh density of 0.9

The simulation of a woman's dress with a 3D fabric polygon mesh density of 0.3 could not be performed; the simulation failed. Therefore, only simulations with densities of 0.5–0.9 were carried out.

After the simulation, the bottom views of both the jacket and skirt were separately recorded (figure 4, *a*) to compare the areas between the 3D fabric polygon mesh densities. The bottom views of the draped jacket without sleeves and skirt were extracted using the CorelDraw programme (figure 4, *b*). They were imported into the ArchiCAD programme, and their surface areas (m^2) were measured using the Fill/ Dimension tool (figure 4, *c*).

Comparison of the real and simulated fabrics' drape coefficients and surface areas of draped garments

Comparisons between the orthogonal projections of the real and virtual fabrics' drapes based on the Cusick method and between the surface areas of 3D virtually draped garments were performed to investigate the effect of the 3D fabric polygon mesh densities on the drape simulations of the developed fabrics. For this purpose, the absolute (Δ) and relative (%) differences between the drape coefficients of fabric FB1 and the other three fabrics (FBX) were calculated, as well as the drape coefficient of the real (DCCDT) and virtually simulated fabrics for various polygon mesh densities (DC0.3, DC0.5, DC0.7, DC0.9). The surface areas of the orthogonal projections of the jacket without sleeves and the skirt were compared between 3D fabric polygon mesh densities.

RESULTS AND DISCUSSION

In this section, the low-stress mechanical properties of the four cotton-linen blended fabrics measured with the measuring system FAST are first analysed, and their correlations with the measured drape coefficients are discussed. Subsequently, the real and the virtually simulated draped fabrics are compared, whereby the importance of the polygon mesh density becomes clear. The virtually simulated draped garments are compared depending on the polygon mesh density to determine their effect on the draping of garments.

Analysis of the low-stress mechanical properties and drape coefficients

The measured low-stress mechanical properties of the fabrics using the FAST measuring system are displayed in table 2. The extensibility E5, E20, E100 (%) corresponds to a fabric load of 4.91 $N{\cdot}m^{-1}$, 19.62 $N{\cdot}m^{-1}$ and 98.07 $N{\cdot}m^{-1}$ respectively. They were assessed in warp (i.e. E100-1) and weft (E100-2) directions, similar to bending rigidity (B-1) and (B-2), respectively.

Among the four fabrics tested, plain fabric FB1 had the highest bending rigidity (B-1 = 201.42 $\mu N{\cdot}m$, B-2 = 285.55 $\mu N{\cdot}m$), shear rigidity (G = 738.00 $N{\cdot}m^{-1}$) and weight (354.92 $g{\cdot}m^{-2}$) and the lowest extensibility (E100-1 = 0.87%, E100-2 = 0.20%) and surface thickness (ST=0.189 mm). It is followed by the reinforced twill fabric FB3 with a lower bending rigidity

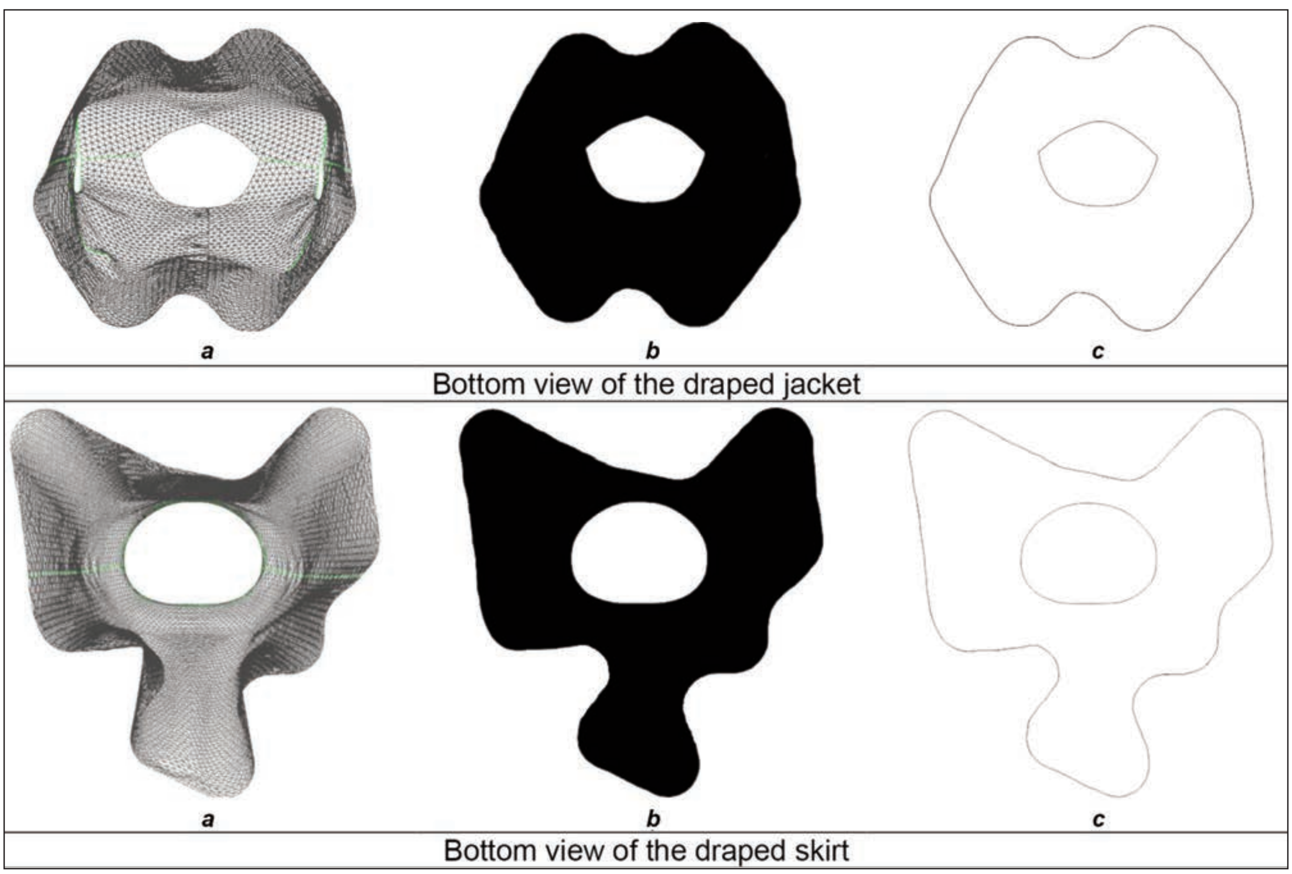


Fig. 4. Procedure for calculating the surface area of the garments (fabric FB4, polygon mesh density 0.9): *a* – OptiTex bottom view; *b* – CorelDraw extracted orthogonal projection; *c* – ArchiCAD surface area

(B-1 = 154.37 μN·m, B-2 = 153.30 μN·m), shear rigidity (G = 295.20 N·m^{-1}) and weight (348.77 g·m^{-2}), a higher extensibility (E100-1 = 1.53%, E100-2 = 0.33%) and the highest surface thickness (ST = 0.278 mm). Among the two twill fabrics FB2 and FB3 investigated, fabric FB2 had the lowest bending rigidity (B-1 = 141.96 μN·m, B-2 = 173.36 μN·m), shear rigidity (G = 157.02 N·m^{-1}), weight (340.31 g·m^{-2}), extensibility (E100-1 = 1.47%, E100-2 = 0.27%) and surface thickness (ST = 0.217 mm). Satin fabric FB4 has the lowest bending rigidity (B-1 = 111.29 μN·m, B-2 = 134.16 μN·m), shear rigidity (G = 60.49 N·m^{-1}) and weight (339.96 g·m^{-2}), and the highest extensibility (E100-1 = 1.60%, E100-2 = 0.73%) among the examined fabrics and its surface thickness (ST = 0.250 mm) is slightly lower than that of the thickest fabric FB3.

As expected, plain weave (FB1) had the highest bending rigidity and satin weave (FB4) the lowest, which is also consistent with the findings of Tohidi et al. [11]. They investigated woven polyester fabrics differentiated by five weaves (i.e. plain, 1/2 twill, 1/3 twill, 1/4 twill and 1/5 twill), and concluded that the increase in float yarns resulted in a strong decrease in bending rigidity regardless of the fabric direction.

The extensibility parameters E5 and E20 were used to calculate the shear rigidity and calculated fabric formability F, but the latter is not needed to simulate draping of textiles with OptiTex 3D software. For all four fabrics, the extensions at loads of 4.91 N·m^{-1} (E5) and 19.62 N·m^{-1} (E20) are extremely low, which is reflected in the high shear rigidity and drape coefficients of all examined fabrics. The extensibility of all fabrics was higher in the warp direction, regardless of the load.

Considering the similar fabric count and yarns used, the results suggest a significant influence of the weave on the physical and low-stress mechanical properties of the four cotton-linen blend fabrics investigated. In particular, a pronounced linear trend of the dependence of the weave on the weight (R^2 = 0.90), the bending rigidity in the warp direction (R^2 = 0.95) and the shear rigidity (R^2 = 0.87) was found, as illustrated in figure 5. On the contrary, this linear dependence is less pronounced in the case of thickness, extensibility and bending rigidity in the weft direction.

The results of the drape coefficients of the fabrics (table 2) indicate the plain fabric FB1 as having the highest drape coefficient (0.92), followed closely by FB3 (0.90), FB2 (0.88) and FB4 (0.87).

The results of the drape coefficients of the fabrics (table 2) indicate the plain fabric FB1 as having the highest drape coefficient (0.92), followed closely by FB3 (0.90), FB2 (0.88) and FB4 (0.87). In figure 5, we also see a clear linear dependence between the drape coefficient (R^2 = 0.99) and the weave type, the highest for plain weave 1/1 (FB1), followed by twill weave 1/1 2/2 (FB3), twill 3/1 (FB2) and satin 4/1 (FB4). The comparison between the drape coefficient and the weight, thickness, extensibility, bending rigidity and shear rigidity shows a clear trend: the higher the weight, bending rigidity and shear rigidity, and the lower the thickness and extensibility, the higher the drape coefficient of the examined fabrics (figure 5, *a*–*e*). Given the identical yarn and fabric count of the four fabrics, this can only be attributed to the differences in weave, and these differences are especially visible for bending and shear rigidity. These findings are aligned with previous studies [10, 12, 47–49], which investigated the relationship between the fabric weave, mechanical properties and drapability of the fabric. Among the fabrics they examined, Matusiak [12] found that the twill weaves 3/1 S and 2/2 S had the highest drape coefficient and the rep weave 2/2 the lowest for cotton fabrics with the same linear warp density and two different weft densities. Lightweight fabrics usually have lower DC compared to heavy fabrics [47]. In these studies, the weight and

Table 2

LOW-STRESS MECHANICAL PROPERTIES OF FABRICS FB1-FB4, MEASURED BY THE FAST SYSTEM AND DRAPE COEFFICIENTS (DC) MEASURED BY THE CUSICK DRAPE TESTER (CDT)

Fabric code		Mechanical parameters						Drape coefficient (DC_{CDT})
		Extensibility (%)			Bending rigidity B (μN·m)	Shear rigidity G (N·m^{-1})	Surface thickness ST* (mm)	
		E5	E20	E100				
FB1	Warp	0.03	0.13	0.87	201.42	738.00	0.189	0.92
	Weft	0.00	0.03	0.20	285.55			
FB2	Warp	0.20	0.43	1.47	141.96	157.02	0.217	0.88
	Weft	0.00	0.00	0.27	173.36			
FB3	Warp	0.17	0.40	1.53	154.37	295.20	0.278	0.90
	Weft	0.00	0.04	0.33	153.30			
FB4	Warp	0.13	0.40	1.60	111.29	60.49	0.250	0.87
	Weft	0.03	0.30	0.73	134.16			

Note: *Surface thickness ST is calculated as the difference between the fabric thickness at a load of 0.196 kN·m^{-2} and the fabric thickness at a load of 9.807 kN·m^{-2}. Fabric thickness is assessed according to ISO 5084:1996, which explains the differences noticeable in table 2 and table 1.

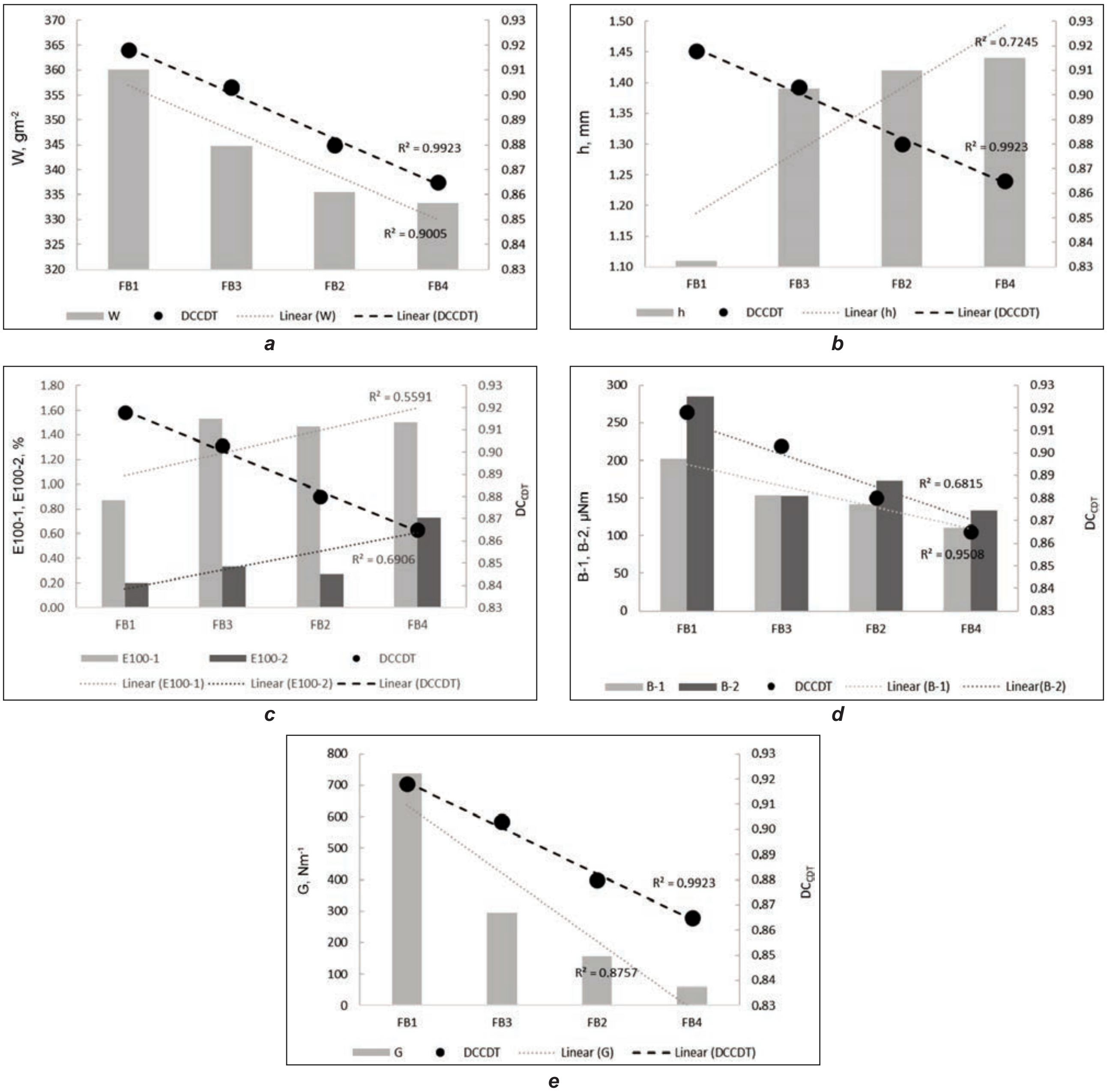


Fig. 5. Relationship between the measured drape coefficient (DC_{CDT}) and: *a* – the weight; *b* – thickness; *c* – extensibility in warp (E100-1) and weft direction (E100-2); *d* – bending rigidity in warp (B-1) and weft direction (B-2); *e* – the shear rigidity of the fabrics

thickness of the fabrics were lower than those of the fabrics FB1–FB4; thus, drapability results cannot be directly compared. However, we can observe a similar trend, indicating that fabrics with greater weight and thickness have higher bending and shear rigidity, which translates into lower drapability in both real and virtual environments [33, 34, 48].

The Pearson correlation coefficient (table 3) also shows a very high positive correlation (0.92–0.96) between the drape coefficient of the fabric and its bending rigidity, shear rigidity and weight, meaning the higher the weight, bending and shear rigidity of the fabric, the higher the drape coefficient. On the contrary, we observe a high negative correlation between the drape coefficient and the extensibility of the fabric (–0.78 and –0.79); the lower the extensibility of the fabric, the higher the drape coefficient. A very high correlation (0.90–0.99) was also found between weight, bending and shear rigidity.

These results indicate a strong dependency between the drape coefficient of the fabric and its physical and mechanical properties, weight, bending and shear rigidity in particular, which all reflect the contribution of the weave.

Analysis of real and virtually simulated draped fabrics

Drape simulations of the 3D virtual fabrics were performed using Optitex 3D software by varying the side length of the triangles of the polygon mesh (0.3 cm, 0.5 cm, 0.7 cm, 0.9 cm). The low-stress mechanical properties measured for four fabrics were used for the simulations of the drape. The orthogonal projections of the real and simulated fabrics are shown in

Table 3

CORRELATION BETWEEN THE DRAPE COEFFICIENTS AND PHYSICAL AND LOW-STRESS MECHANICAL PROPERTIES									
		DC_{CDT}	**E100-1**	**E100-2**	**B-1**	**B-2**	**G**	**ST**	**W**
Real drape coefficient	DC_{CDT}	1.00							
Extensibility (at 98.07 $N \cdot m^{-1}$), in warp direction	E100-1	–0.78	1.00						
Extensibility (at 98.07 $N \cdot m^{-1}$), in the weft direction	E100-2	–0.79	0.63	1.00					
Bending rigidity in warp direction	B-1	0.96	–0.92	–0.83	1.00				
Bending rigidity in the weft direction	B-2	0.79	–1.00	–0.68	0.93	1.00			
Shear rigidity	G	0.92	–0.96	–0.68	0.98	0.95	1.00		
Fabric surface thickness	ST	–0.33	0.81	0.49	–0.60	–0.83	–0.61	1.00	
Fabric weight	W	0.95	–0.91	–0.65	0.96	0.90	0.99	–0.51	1.00

table 4, where the shapes of the orthogonal projections of all real draped fabrics show an indistinct number of shallow folds. However, differences can be observed between the drapes of fabrics depending on the weaves, in accordance with their drape coefficients from table 2.

The same applies to orthogonal projections of virtually simulated fabrics, which differ from real fabrics, especially in the case of simulated drapes with a polygon mesh density of 0.3 and 0.5. The folds are more pronounced, and their number appears to be slightly higher. On the contrary, less pronounced and

Table 4

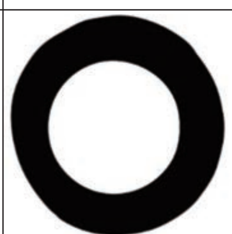
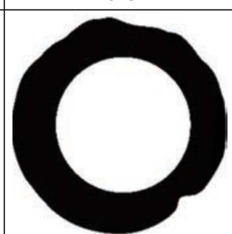
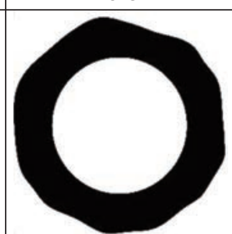
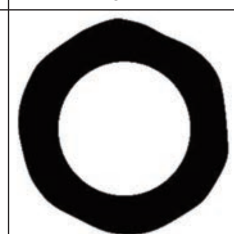
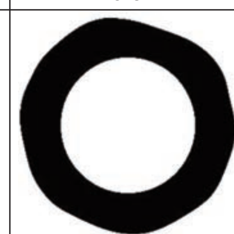
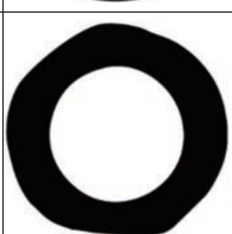
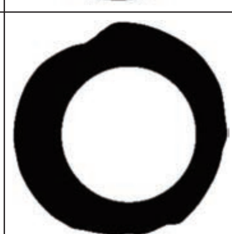
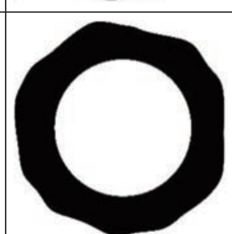
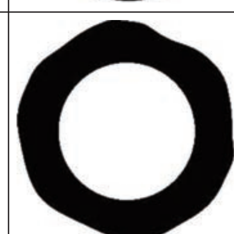
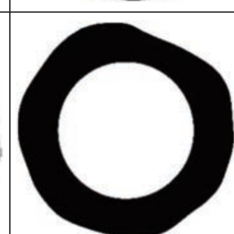
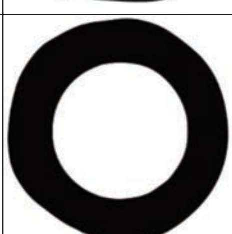
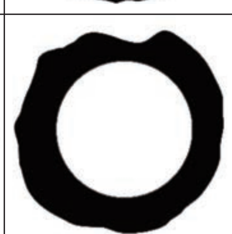
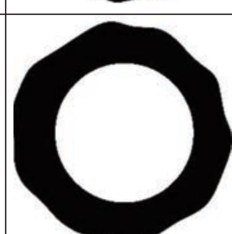
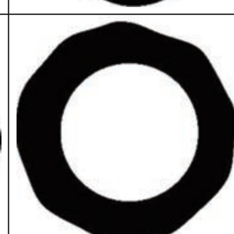
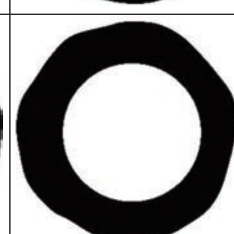
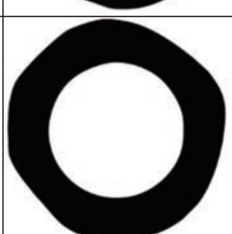
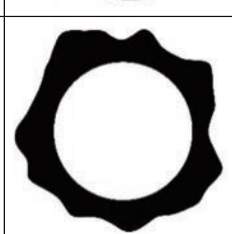
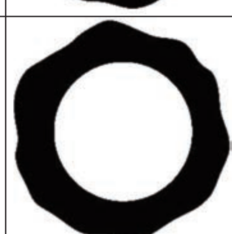
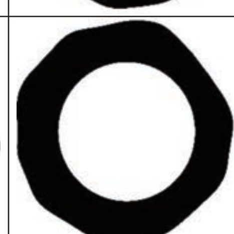
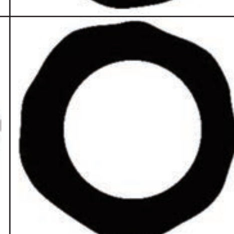
ORTHOGONAL PROJECTIONS OF THE DRAPED FABRICS MEASURED BY CUSICK DRAPE TESTER AND SIMULATED BY OPTITEX 3D, AT FOUR LEVEL DENSITY POLYGON MESH (0.3–0.9)					
Fabric	**Cusick Drape Tester**	**OptiTex 3D / Density of the polygon mesh**			
		0.3	**0.5**	**0.7**	**0.9**
FB1					
FB2					
FB3					
FB4					

Table 5

Fabric	DC_{CDT} Δ $DC_{CDT}(FB1–FB_X)$ Δ $DC_{CDT}(FB1–FB_X)$ (%)	OptiTex / Density of the polygon mesh $DC_{0.3}$ Δ (DC_{CDT}– $DC_{0.3}$) Δ (DC_{CDT}– $DC_{0.3}$) (%)	$DC_{0.5}$ Δ (DC_{CDT}–$DC_{0.5}$) Δ (DC_{CDT}–$DC_{0.5}$) (%)	$DC_{0.7}$ Δ (DC_{CDT}–$DC_{0.7}$) Δ (DC_{CDT}–$DC_{0.7}$) (%)	$DC_{0.9}$ Δ (DC_{CDT}–$DC_{0.9}$) Δ (DC_{CDT}–$DC_{0.9}$) (%)
FB1	0.918	0.834 **0.08** **9.14**	0.827 **0.09** **9.95**	0.860 **0.06** **6.27**	0.860 **0.06** **6.27**
FB3	0.903 **0.02** **1.63**	0.759 **0.14** **15.96**	0.816 **0.09** **9.61**	0.856 **0.05** **5.25**	0.857 **0.05** **5.08**
FB2	0.880 **0.04** **4.14**	0.842 **0.04** **4.33**	0.807 **0.07** **8.32**	0.844 **0.04** **4.08**	0.835 **0.04** **5.10**
FB4	0.865 **0.05** **5.77**	0.603 **0.26** **30.25**	0.784 **0.08** **9.32**	0.840 **0.03** **2.90**	0.836 **0.03** **3.32**

DRAPE COEFFICIENT FOR REAL (DC_{CDT}) AND VIRTUAL DRAPED FABRICS (DC) AT VARIOUS DENSITIES OF POLYGON MESH (0.3–0.5–0.7–0.9)

shallower folds are observed at polygon mesh densities of 0.7 and 0.9 for all virtually simulated fabrics, which approach the appearance of the orthogonal projections of the real draped fabrics.

The results of the drape coefficients of real and virtually simulated fabrics are shown in table 5. The results in this table are ordered FB1-FB3-FB2-FB4, starting with the fabric with the highest drape coefficient and ending with the lowest. The absolute (Δ) and relative (%) differences between the drape coefficients for fabric FB1 and the other three fabrics (FBX) were calculated. Similarly, the differences between the drape coefficient of real fabrics (DCCDT) and the drape coefficients of virtually simulated fabrics at different polygon mesh densities (DC0.3, DC0.5, DC0.7, DC0.9) were also calculated, both as absolute (Δ) and relative (%) differences.

As we have already established, the weave of the fabric affects the drape coefficient. This was highest (0.918) for real plain fabric FB1 and lowest (0.865) for fabric FB4 in satin 4/1 weave, and has decreased by 5.77%. The drape coefficient decreased by 4.14% in the case of fabric FB2 in twill 3/1 weave and by 1.63 % for FB3. Though small, these differences in the drape coefficients are visible for the virtually simulated fabrics (table 4).

For all four fabrics, the percentage difference in drape coefficient between the real and the virtually simulated fabric is greatest at a polygon mesh density of 0.3, ranging from 30.25% (FB4) to 4.33% (FB2). In case of a polygon mesh density 0.5, these were smaller, ranging from 8.32% (FB2) to 9.95% (FB1). By further decreasing the density of the polygon mesh to 0.7 and 0.9, the difference between the drape of the real and virtual fabrics decreases for all fabrics, especially for the fabric FB4, and deviates from the real drape coefficient only by 2.90% (polygon mesh 0.7) and by 3.32% (density of the polygon mesh 0.9).

More realistic clothing simulations are usually achieved with a higher density of the polygon mesh [33, 34] of the 3D fabric model (shorter side length of the triangles of the polygon mesh), but this does not seem to apply to rigid textiles. Based on our results, it can be concluded that with a lower density polygon mesh, i.e. a longer side length of the triangles of the polygon mesh of the 3D fabric model, more reliable and realistic simulations can be obtained for rigid fabrics like those investigated in this study.

Analysis of virtually draped garments

The surface areas of the orthogonal projections of the virtually simulated jacket and skirt for various polygon mesh densities (0.5, 0.7, 0.9) are shown in figure 6.

For all fabrics, a similar trend towards a decreasing surface area of the orthogonal projections of the virtually simulated skirt can be observed, depending on the mesh density of the 3D fabric polygons. Specifically, the smallest surface areas for the skirt projections correspond to a mesh density of 0.9, except for fabric FB1. Conversely, the jacket simulations exhibit the largest surface areas of orthogonal projections at the polygon mesh density (0.9), whereas the smallest orthogonal projection areas occur at a polygon mesh density of 0.7.

The anticipated influence of polygon mesh density on the orthogonal projection surface area manifests differently between the skirt and jacket simulations. These discrepancies are likely attributable to the distinct draping conditions inherent to each garment. The skirt drapes freely from the waist and over the hips downward, allowing greater fabric displacement, whereas the jacket conforms more closely to the shoulder blades and arms, restricting drape in these regions and permitting freer fabric fall over the chest and shoulders. Additionally, the skirt pattern encompasses a larger surface area and length as compared

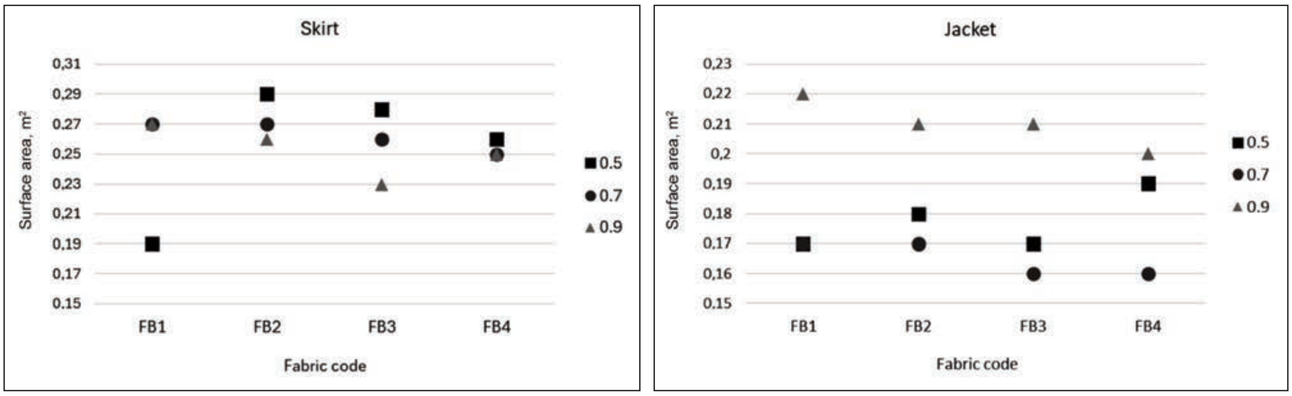


Fig. 6. Surface areas of the orthogonal projections of the virtually simulated jacket and skirt depending on the 3D fabric polygon mesh densities (0.5–0.9)

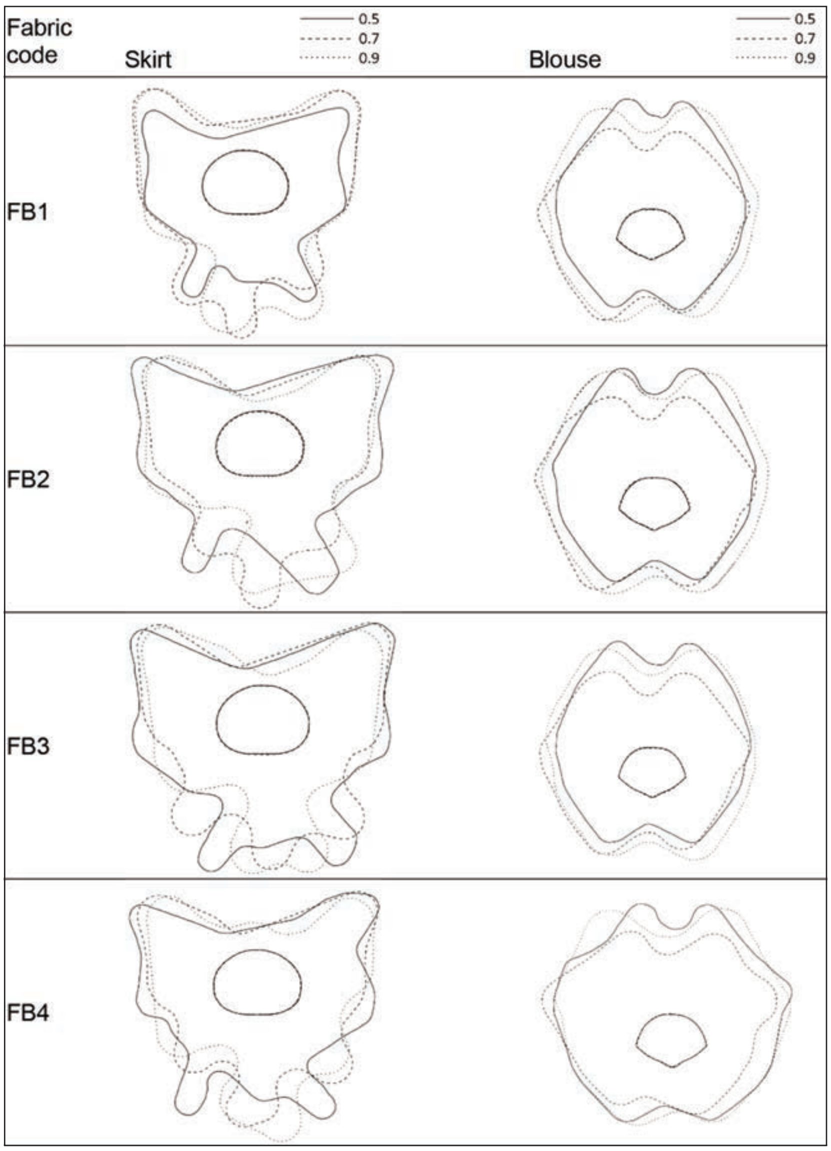


Fig. 7. Comparison between the orthogonal projections of 3D virtually draped garments for researched 3D fabric polygon mesh densities

to the jacket, resulting in greater fabric weight, which may further impact draping behaviour. These observations are further substantiated by figure 7, which shows variations in fabric draping as a function of weave structure and, consequently, the associated physical and mechanical properties, alongside the polygon mesh densities applied in the virtual 3D clothing simulations. In particular, the draping of the skirt shows pronounced changes in fold displacement, shape and depth as a function of polygon mesh density, as shown in the orthogonal projections. In contrast, the draping of the jacket mainly shows variations in fold depth and less pronounced changes in fold geometry.

Based on the results obtained, it can be inferred that the density of the 3D fabric polygon mesh influences the simulation outcomes of garment drape and the resultant visual appearance. Nonetheless, to quantitatively ascertain the precise impact of polygon mesh density on accurate garment drape simulations, further systematic investigations are required. Such studies should encompass a broader range of garment patterns and consider variations in their styles and surface areas to comprehensively validate and extend these preliminary findings.

CONCLUSIONS

For this study, four fabrics were produced from cotton-linen blends, with the same yarns and fabric count but different types of weave. The low-stress mechanical properties of the examined fabrics were measured with the measuring system FAST and imported into the OptiTex 3D V11 software. The virtual simulations of fabric drapes were carried out as a function of the size of the triangles of the polygon mesh of the 3D fabric model. The effect of the fabric weave on the real drape was investigated with the Cusick Drape Tester, and the real drape was compared with the virtual drape simulations. Virtual simulations of the draping of the analysed fabrics were carried out as a function of the polygon mesh densities. The results clearly showed the effect of the fabric weave on the low-stress mechanical properties and drape of the fabrics. The drape coefficient strongly relates to the physical and mechanical properties of the fabrics, weight, bending and shear rigidity in particular.

The fabric with plain weave encountered the highest drape coefficient, and the satin fabric the lowest. The drape coefficients of real and virtually simulated fabrics show that, in the case of rigid fabrics, more reliable and realistic simulations can be achieved with a lower polygon mesh density. This trend is observed based on a limited number of rigid fabrics and needs to be further validated with other similar fabrics, consisting of different yarns and weaves. Future research should also focus on the simulation of garments with different patterns to clarify the discrepancies found between the different polygon mesh densities needed for a realistic simulation of different types and sizes of garments.

The acquired knowledge on the draping of very rigid natural cotton-linen blended fabrics should help developers to realise realistic simulations necessary for the reliable development of virtual garments.

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