Sajjadi *et al. Fashion and Textiles (2023) 10:9*
https://doi.org/10.1186/s40691-023-00330-2

Fashion and Textiles

RESEARCH

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An experimental and numerical investigation of energy absorption of sportswear in seam area

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Abstract

This study aims to investigate the energy absorption of seam areas in sportswear. Weft knitted fabrics with two structures of plain and rib were fabricated by polyester/Lycra and viscose/ Lycra yarns. Fabrics were stitched in two stitch classes. Moreover, two types of seams were considered. A pull-out test was carried out on all samples to determine the energy absorption values. Furthermore, a finite element model was applied to predict the energy absorption of each structure. The unit cell of each sample was created in ABAQUS software and the tensile load was applied to the stitch yarn. The unit cells of the fabric and the stitched section were modeled in the meso-scale and then elastic and viscoelastic properties of the yarns were assigned to the model. The energy absorption of the sample with rib pattern, lapped seam, and 607 stitch class was more than other samples. Also, the numerical and experimental results showed a high correlation with each other in samples with 304 stitch class and flat seam type.

Keywords: Knitted fabric, Sportswear, Energy absorption, Pull-out test, Finite element model

Introduction

Sportswear plays an important role in determining the athletes' performance. Flexibility, air permeability and mechanical properties are some factors affecting the efficiency of the sportswear used (Das et al., 2007; Marolleau et al., 2020; Sang et al., 2015). In this regard, knitted structures is appropriate for these applications. In this structure, knit loops have enough porosity to improve air permeability, and the geometry of the knit loops shows good flexibility in the knitted fabrics (Liu et al., 2017). So, some studies have been conducted to investigate the geometry of knitted fabrics and their air permeability (Dehkordi et al., 2017; Leaf, 1960; Peirce, 1947). Some models for the geometry of the weft-knitted loop have been proposed (Buet-Gautier & Boisse, 2001; De Jong & Postle, 1977). The model developed by Vassiliadis (Vassiliadis, 2007) is a suitable one for the three-dimensional geometry of the weft-knitted loop. Moreover, some studies have been focused on the computational modeling of the knitted structures based on Vassiliadis' equations (Vassiliadis, 2007). In these studies, a unit cell of the knitted structures was created and the mechanical behavior of the preform was analyzed.

It should be noted that the seam area in sportswear is a critical part on which the efficiency of the sportswear is extremely dependent. This area is under various stresses during athlete activities. So, the mechanical behavior of this area under dynamic loads should be considered. In this regard, Sajjadi et al. (2020) investigated the mechanical behavior of the stitch area of sportswear under dynamic load by applying both experimental and numerical methods. Moreover, the pulling-out of the stitch yarn from the sportswear during the athlete's activity is another phenomenon that should be considered due to its effect on the mechanical performance in the seam rejoins. The energy absorption of the seam area is one of the parameters showing the quality of stitching and the efficiency of the sportswear. In fact, the high energy absorption of the seam area shows that more force should be applied to the stitch yarn to be pulled out from the fabric structures. Therefore, this can serve as a good criterion for the durability of the seam area in the sportswear. In this vein, some studies have been conducted to investigate the energy absorption of the seam section in various pre-forms by the pulling-out of the stitch yarn. Hosseini and Toriumi (Ravandi & Toriumi, 1996), for example, studied the effect of changing the structure of the woven fabric during the pulling-out of the stitch yarn. They used the Fast Fourier Transform function for this purpose. In another study, Kirkwood et al. (2004) proposed an experimental model for pulling-out the energy of the Kevlar yarn from the fabric structure. An analytical model was also proposed by Asayesh et al. (2012) to predict the energy absorption of the knitted fabric by pulling-out the knit loop's yarn from the fabric. On the other hand, Valizadeh et al. (2010) predicted the energy absorption of the woven fabric by finite element modeling, using the pull-out test. They modeled a 3D yarn geometry in the finite element software.

As can be observed, the absorption energy of the fabric is an important factor showing that the amount of fabric resistance to the pulling-out of yarn. Therefore, this can be considered for the seam area of sportswear. However, less studies have been focused on the energy absorption of the seam area of sportswear considering various factors such as seam type, stitch class and fabric structure.

Moreover, previous studies have been focused on conducting experimental analyses on the properties of the fabrics and stitch yarns, and no research has been done on the modeling of fabrics and stitches in the garment seam line. Also, the study on pulling the stitch yarn out of the seam line and the modeling of the stitch yarn and fabric are very important from the point of view of energy absorption, but they have not been investigated so far.

So, in this study, the energy absorption of the seam section of sportswear was studied by both numerical and experimental methods. Accordingly, various factors such as seam type, stitch class, fabric material and fabric structure were considered. The pull-out test was carried out on all samples to determine the energy absorption values. Moreover, a finite element model was applied to predict the energy absorption of each sample. This study helps athletes feel good mentally and physically, and have better performance when they have activities with suitable sportwear (McDonald, 2021).

Table 1 Physical and mechanical properties of yarn samples

Yarn	Density (g/cm^3) ± SD	Young modulus (MPa) ± SD	Poisson Ratio ± SD	Nominal Yarn Count (den) ± SD
Polyester/Lycra	1.40 ± 0.03	236 ± 5.9	0.3 ± 0.009	100 ± 3
Viscose/Lycra	1.32 ± 0.02	14.7 ± 0.3	0.3 ± 0.009	50 ± 3
Polyester	1.38 ± 0.03	340 ± 10.5	0.3 ± 0.003	132 ± 3

Table 2 Taguchi levels used for this study

Symbol	Variable name	Level 1	Level 2
A	Fabric material	Polyester/Lycra (94%/6%)	Viscose/Lycra (94%/6%)
B	Fabric structure	Plain	Rib
C	Seam type	Lapped	Flat
D	Stitch class	304	607
E	Stitch density	13	20

Methods

It should be mentioned that the weft knitted structure is a conventional fabric used to produce sportswear. So, in this study, two different weft knitted fabrics, single jersey and double jersey, were produced by polyester/lycra and viscose/lycra yarns. The fabrics were stitched together by polyester yarns. Tensile properties such as the elastic modulus of the yarn samples were measured using a Zwick Universal Testing Machine. The test was replicated for 10 samples of 250 mm clamp distance under standard laboratory conditions (20 °C, 65% relative humidity). Properties of the yarns used in this study are given in Table 1.

Two different stitch classes including 304 and 607, commonly applied for sportswear, were utilized to stitch fabrics together (Sajjadi et al., 2020). In class 304, two knitted fabrics are stitched together by 2 yarns, but in class 607, 6 yarns are applied. Moreover, two different seam types, lapped and flat, were used. In the lapped type, the edges of fabrics lie on each other, whereas, in the flat type, the edges lie tangentially. The stitch was done in both wale and course directions. In order to design the experimental samples, the Taguchi method was applied. The five selected factors, including the fabric material, fabric structure, seam type, stitch class and stitch density (stitch per inch), marked as A, B, C, D and E, respectively, are shown in Table 2 at two levels. Due to the number of factors and levels, by using the Minitab software, the Taguchi matrix could be created in eight rows (samples) and five columns (factors), as given in Table 3.

In a one-dimensional relaxation test, the material was subjected to a sudden strain was kept constant (50%) over the test, from which the stress was measured over time. The aim of this test was to obtain the viscoelastic properties of the yarns. At a constant strain rate up to 50%, with a moveable cross-head speed of 700 mm/min, stress relaxation tests were also conducted in the linear viscoelastic range of the yarns using the same tensile tester. To this end, the test was replicated on ten samples that were allowed to be relaxed for at least 600 s.

Table 3 Taguchi matrix

Sample code	Factor$_{Level}$				
T1	A1	B1	C1	D1	E1
T2	A1	B1	C1	D2	E2
T3	A1	B2	C2	D1	E1
T4	A1	B2	C2	D2	E2
T5	A2	B1	C2	D1	E2
T6	A2	B1	C2	D2	E1
T7	A2	B2	C1	D1	E2
T8	A2	B2	C1	D2	E1

Table 4 Geometrical parameters of fabrics used for the modeling

Fabric	$_{c}$a (mm)	Course per centimeter	$_{w}$b (mm)	Wale per centimeter	$_{d}$c (mm)	Thickness (mm)
Plain (Polyester/Lycra)	0.30	33.33	0.53	18.86	0.13	0.25
Plain (Viscose/Lycra)	0.30	33.33	0.53	18.86	0.06	0.65
Rib (Polyester/Lycra)	0.28	35.71	0.56	17.85	0.13	0.73
Rib (Viscose/Lycra)	0.28	35.71	0.56	17.85	0.06	0.94

[a] Distance Between Two Consecutive Courses, [b]Distance Between Two Consecutive Wales, [c]Yarn Diameter

In order to investigate the effect of various parameters such as fabric structure, stitch class and seam type on the energy absorption of the fabrics in the seam area, a pull-out test was carried out on all samples. Samples with the dimensions 10.4 cm × 8 cm were prepared for the test. Two sides of the samples were fixed by the gripers of the machine test. For the samples with class 304, one stitch yarn and for class 607, all 6 stitch yarns were pulled out from the fabric structure. Moreover, 1 cm of the stitch yarn was put outside the fabric structure and kept by the upper gripper in order to pull the yarn. The stitch yarn was pulled out for 4 cm from the fabric structure. The output of the test is the work value for the pull-out test, indicating the energy absorption of the sample.

Finite element model

A finite element model was applied to predict the energy absorption of the stitched fabric while it was pulled out of the stitch yarn. The model was created in the meso scale. A unit cell of each sample including knit loops and stitch yarns was modeled in the ABAQUS software. In this study, Vassiliadis' equations (Vassiliadis, 2007) were used to model the geometry of the knit loop. This model could be used for the Plain (single jersey) fabric and for the Rib (double jersey) fabric formed from two plain knit loops and a linking yarn. Abghari et al.'s model (Abghary et al., 2016) was utilized. All structural parameters of the knitted fabrics, including wale (w) and course distance (c) and yarn diameter (d), were used as the inputs in the python code to design a three-dimensional fabric unit-cell in the Abaqus software. The geometrical inputs used for the modeling are given in Table 4.

Knit loops for two different fabrics (Plain and Rib) were patterned to reach the whole geometry of the unit cell for the stitched fabric. The stitch yarns were created in the CATIA software according to the geometry of the stitch classes. Mechanical properties of the yarns were assigned according to Table 1. The outputs belonging to the relaxation test of the yarns were used to obtain the viscoelastic parameters of the components. In order to introduce the viscoelastic behavior of the yarns, the Prony (Tzikang, 2000) series (Eq. 1) could be used.

$$Y(t) = E_0.\left(1 - \sum_{i=1}^{n} g_i\left(1 - e^{-t/\tau}\right)\right) \tag{1}$$

where Y(t) is the stress relaxation function, E_0 is the initial elastic modulus, *gi* is the Prony constant, t is time, and τ is the relaxation time. This series contains coefficients that should be determined based on the curve resulting from the stress-relaxation experiment. The Prony function was fitted to the stress-time curve in the MATLAB software environment; in this way, the function and the coefficients were obtained.

The coefficients obtained from the fitting process for the Prony series are presented in Table 5. The calculated coefficients for the yarns were introduced to the finite element software, and the yarn structure as a linear viscoelastic material was modeled.

Afterward, the two sides of the unit cell were fixed and a tensile displacement test was applied to the end of the stitch yarn. In order to determine the effect of the interaction between components on energy absorption, all samples were modeled in two unit-cells, and the boundary conditions and tensile loads were applied to them as done for the models with one unit-cell. The penalty method with a friction coefficient of 0.04 (Abdellahi et al., 2017) was also used to define the contact between various parts of the yarns in the model. For meshing the unit cell, hexahedral elements (C3D8R) were used. In this method, an explicit solver was used. Figures 1 and 2 show the process of finite element modeling and all samples unit cells of the stitched fabrics.

Results and Discussion

Figure 3a shows the force-distance curve for the T1 sample through the wale direction. According to Fig. 3, the amplitude of the peak and the area under the graph represent the amount of energy absorption in the seam area of sportswear. In the pull-out test, the first section of the curve showed the opening of the yarn crimp and the change of the curved yarn to the straight one. So, a nonlinear ascending trend could be observed in the first section of the curve (OK). After the peak point of the curve (P), the value of the force was decreased. In fact, the pulled yarn started to slip in the fabric structure and less force was needed to pull it out. However, some oscillations could be seen in the curve that resulted from the interaction between the stitch yarn and loop yarns. For the samples with the 607 stitch class, the trend of the curve was same as that for T1;

Table 5 Coefficients obtained for the Prony series

Yarn	g1[a]	$\tau 1_b$	g2	τ_2	g3	τ_3
Polyester/Lycra	0.2568	13.46	0.01927	0.2785	0.159	406.3
Viscose/Lycra	0.2197	13.94	0.1646	510	–	–
Polyester	0.114	96.13	0.2167	5.621	–	–

[a] gi: Prony Constant [b] τ*i*: Relaxation Time

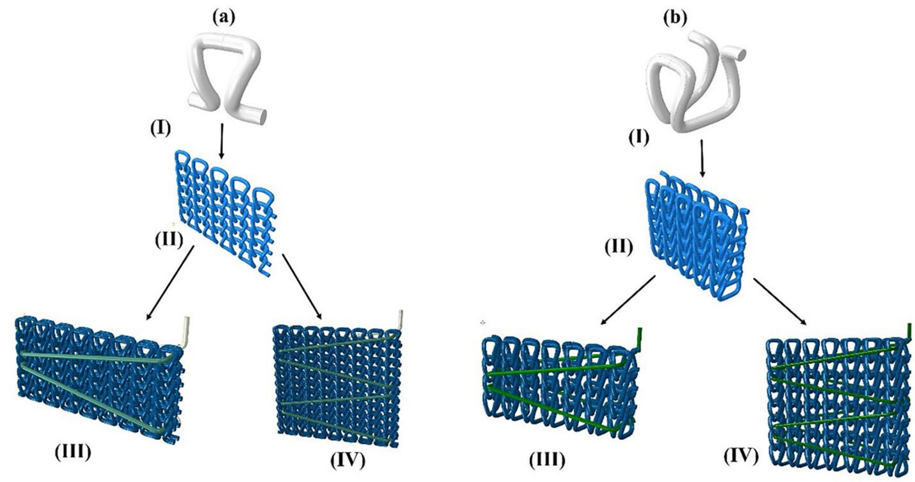

Fig. 1 Procced of the finite element modeling. **a** Plain structure, (I) knit loop, (II) plain fabric, (III) T1 unit-cell, (IV) T1 with two unit-cells. **b** Rib structure, (I) knit loop, (II) rib fabric, (III) T3 unit-cell, (IV) T3 with two unit-cells

however, after the peak, more oscillations could be observed in the curve (Fig. 3b). The reason for this phenomenon could be more interaction between stitch yarns and loop yarns in the samples with the 607 stitch class, whose fluctuations could be seen in the curve during the pulling-out of the stitch yarns.

In the pull-out test, the work value for pulling out the stitch yarn was the output of the test.

Figure 4 shows the work values for all samples.

According to Fig. 4, the maximum work value belonged to T8 in the course direction. Six stitch yarns, Rib structure and the lapped seam type are some factors that could affect the work value in the sample T8. In fact, the mentioned factors could increase the interaction between fabric components, and more load was needed to pull out the stitch yarn from the fabric structure. So, the maximum work value in this sample could be observed. Generally, the samples with class 607 showed more work value than those with class 304. Therefore, it could be concluded that the double jersey structure, class 607 and lapped seam type are some factors increasing the work value and energy absorption in the stitch area of the sportswear.

Figure 5 shows the stress contours of some samples during the pull-out test using FE Modeling.

It could be observed that the stitch yarns were under maximum stress during the pull-out process. The stitch yarn had much friction with loop yarns and other stitch yarns. So, more stress could be seen in this yarn in comparison with others. To predict the energy absorption for the whole fabric, the energy for a unit cell should be multiplied by the number of unit-cells for the whole sample. Moreover, to obtain the effect of the interaction between components by increasing the number of unit-cells, the energy value for a unit-cell was compared with that obtained by the model having two unit-cells. Besides, the energy should not only be multiplied by the number of unit-cells, but also by 1.3. In fact, the number 1.3 is a constant considering the interactions between components by increasing the number of unit-cells. This constant was obtained from a comparison of

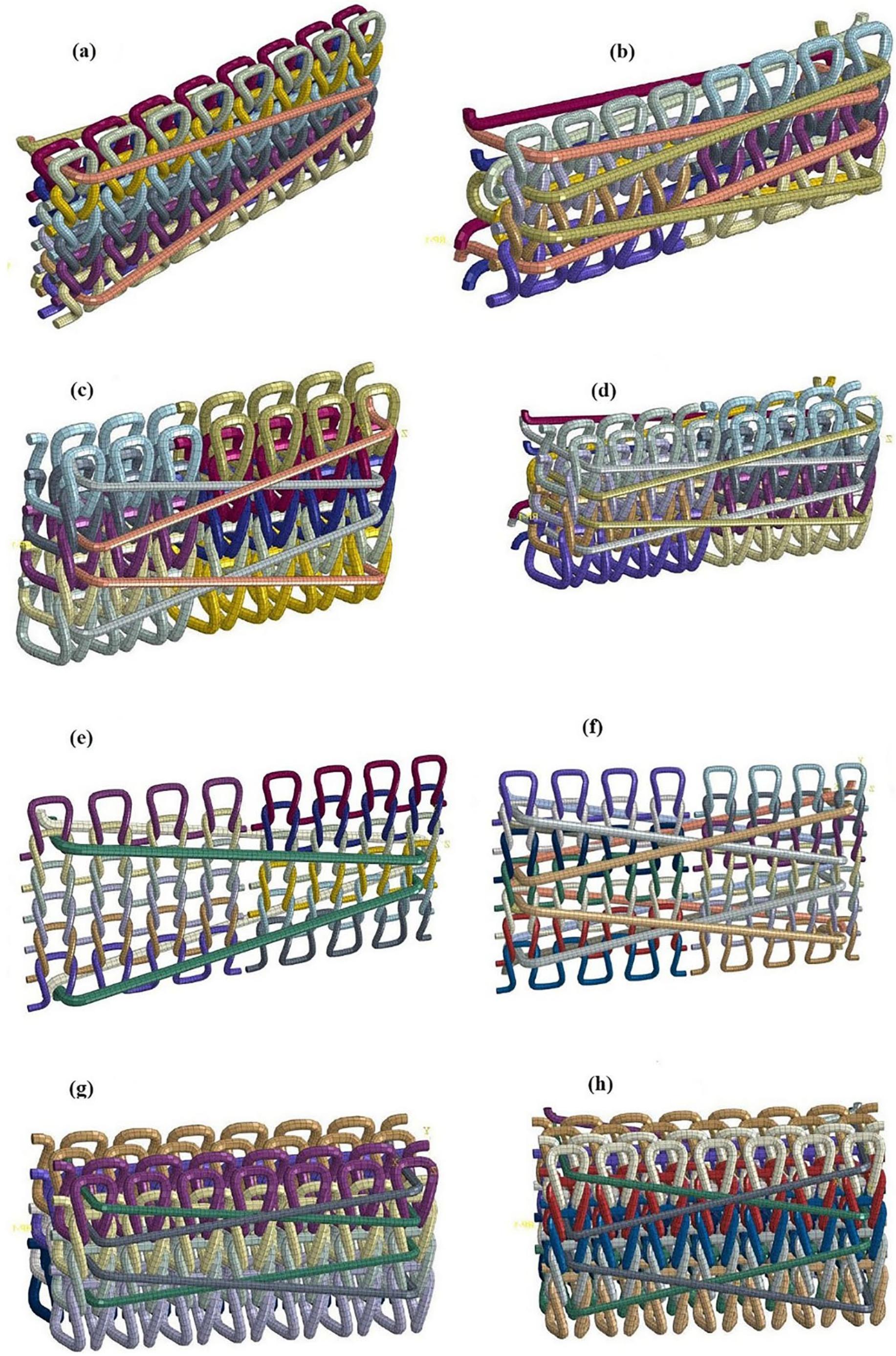

Fig. 2 All unit-cells of samples, **a** T1, **b** T2, **c** T3, **d** T4, **e** T5, **f** T6, **g** T7, **h** 151T8

models with one and two unit-cells in terms of the energy value. The numerical results for the samples with stitch class 304 showed a better agreement with the experimental results, in comparison to the models with stitch class 607. The reason for this difference could be more friction between yarns in the stitched fabrics and stitch class 607. Moreover, a high pucker during the pull-out test for stitch class 607 could increase the error

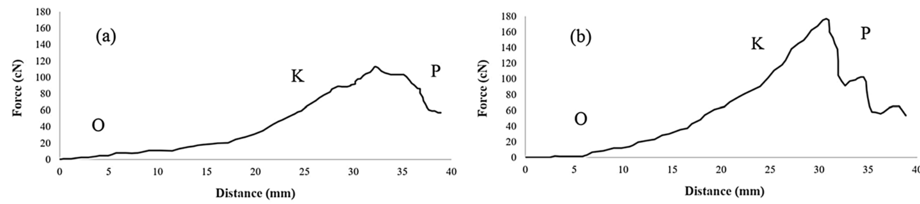

Fig. 3 Force-distance curve of pull-out test for **a** T1 and **b** T2 samples in the wale direction

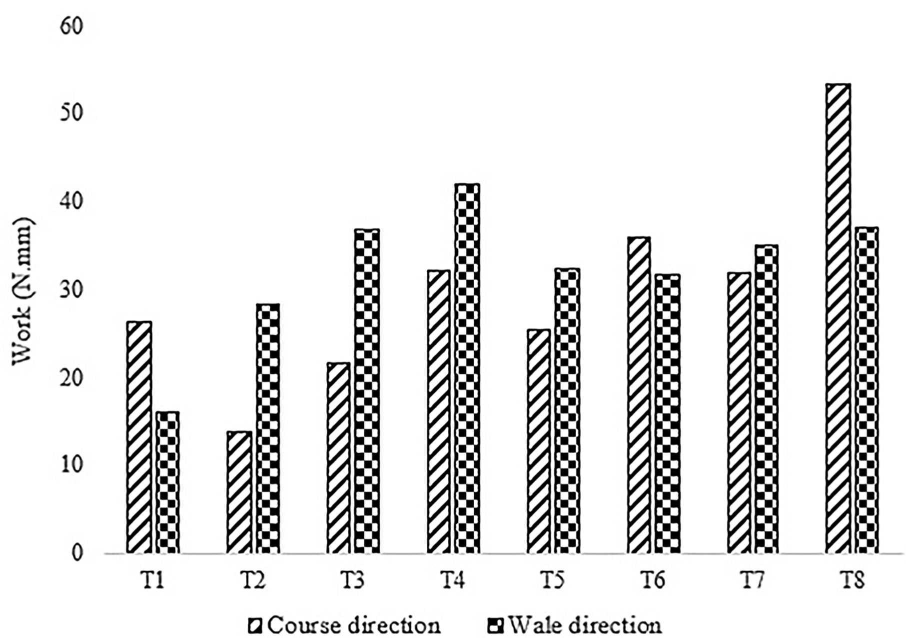

Fig. 4 Work values for pulling out of stitch yarn for all samples

values. Besides, using the same constant (1.3) for all fabric structures could be taken one of the error factors. Table 6 shows the work values for the experimental and numerical results with the error values by the following equation (Eq. 2).

$$error\ value(\%) = \frac{|Numerical\ work - Experimental\ work|}{|Experimental\ work|} \times 100 \quad (2)$$

As can be observed, samples with 6 stitch yarns showed more error values in comparison with those with 2 stitch yarns.

Although the FE model can simulate the yarn pullout force–displacement profile, which consists of an initial static part and a dynamic part, with a high estimate, the results of the model do not show the stick–slip behavior observed in the experiment. The reason for this matter is the fact that the friction coefficient was considered constant, which causes the predicted dynamic friction to be greater than the actual value (Valizadeh et al., 2010).

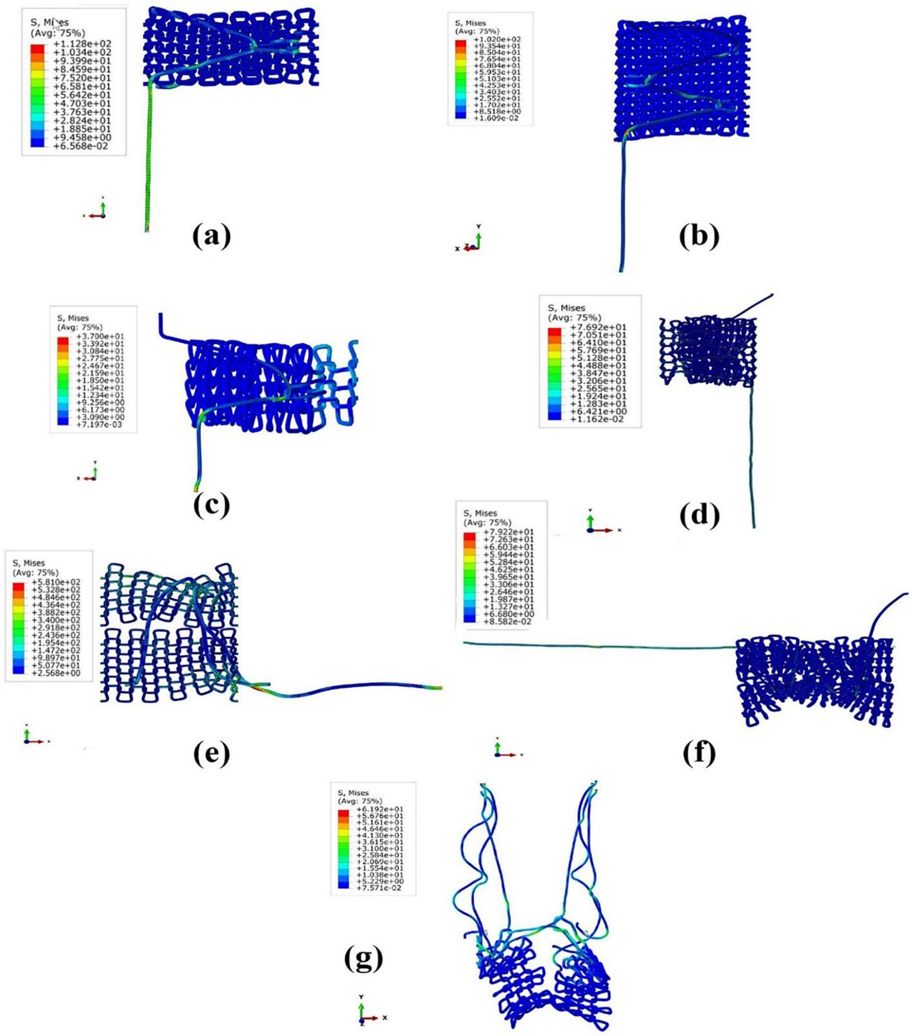

Fig. 5 Stress contours of the meso models during pull out test, **a** T1 in course direction, **b** T1 with two unit-cells in course direction, **c** T3 in course direction, **d** T3 with two unit-cells in course direction, **e** T5 in wale direction, **f** T5 with two unit-cells in wale direction, **g** T4 in course direction

Table 6 Work values for experimental and numerical results with the error values

Sample code	Work in course direction			Work in wale direction		
	Experimental (N.mm)	Numerical (N.mm)	Error (%)	Experimental (N.mm)	Numerical (N.mm)	Error (%)
T1	26.38	32.71	23.99	15.95	18.06	13.22
T2	13.79	20.06	45.49	28.25	34.71	22.82
T3	21.62	26.35	21.87	36.84	27.55	25.21
T4	32.14	41.86	30.21	41.97	49.67	18.34
T5	25.30	29	5.33	32.39	44.15	36.30
T6	35.84	48.70	35.88	31.74	38.52	21.36
T7	31.89	38.47	17.10	35.02	43.29	23.61
T8	53.30	70.02	31.36	37.00	51.71	39.75

The complex structure of the samples with 6 stitch yarns is one of the reasons accounting for the difference between numerical and experimental results. Moreover, in some samples with the lapped stitch type, more differences could be seen between results. The reason for this error was the high interaction between yarns, leading to yarn locking during the pull-out process.

Conclusions

In this study, the energy absorption of the seam area of sportswear during the pulling-out of the stitch yarn was investigated. Since sports apparel is constantly affected by cyclical forces, they experience fatigue and the stress-relaxation phenomenon in the stitch area, leading to their break over time, so, it can be said that friction and entanglement of the yarns will increase by increasing the number of stitch yarns, which leads to extending the lifetime of sportswear. Therefore, it is recommended to use stitch class 607 and lapped seams in the production of sportswear. Besides, the finite element model results showed a good agreement with the samples with 304 stitch class; however, in other samples, the error values were increased. The same interaction for all samples and the high interaction between components in the sample with 607 stitch class could be regarded as the reasons for the discrepancy between experimental and numerical results. For the samples with 304 stitch class, the FE model could predict the energy absorption of the sample with less than 30% error. In the continuation of this research, several topics can be noted for more investigations. The investigation of fatigue strength and determining the life span in the modeling of sportswear is one of the interesting topics for expanding this study. Also, the fracture mechanism and damage model can be used to investigate the failure of the sportswear seam. Furthermore, the increase in plastic elongation and the plasticity equations can be applied in the finite element modeling of sportswear seams.

Author contributions
AS carried out the experiments, developed the theoretical formalism, performed the analytic calculations and the numerical simulations. SAH, SA and MM supervised the project. All authors read and approved the final manuscript.

Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 19 February 2022 Accepted: 12 January 2023
Published online: 05 March 2023

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