Garments elongation improvement: The use of digital fabrication technology to develop rotational and re-entering auxetic designs on fabrics

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Abstract

The usage of auxetic patterns is growing in different industries from aeronautics to fashion. However, the development of these structures in fabrics for garments is still recent and there are few businesses using these technologies to enhance common garments. We propose to test modified fabrics with laser cut of the patterns for improving its elongation properties.

Since there are many kinds of fabrics used in the fashion industry, abrasion and elastic recovery were the main features to be considered for choosing standard clothes fabrics. Looking to test fabrics that could represent most of the kind of fabrics in the market 3 were selected as they fit the properties mentioned and were classified as rigid, suede and semi rigid fabrics respectively

The design of the pattern was extracted from a research on auxetic patterns on metamaterials and tested each fabric to choose one, depending on its behavior, that can be used in a garment.

The tensile strength and elongation were tested giving elongation ratios from over 100% and revealing different resistances in the samples depending on the direction of the pattern and the type of fabric.

Keywords

Auxetic structures, digital fabrication, garment expansion, laser cutter

1 Introduction

Quantis International, a specialized sustainable solutions Swiss consulting firm, stated in 2016 that the clothing and footwear industry was accountable for 5% to 10% of global pollution. Its operation and logistic processes' wastes pollute different natural resources. In Bangladesh, a 2019's study estimated

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that dyeing process in textile sector generates 217 million m3 of wastewater containing heavy metals (including zinc, mercury, lead, etc), and will reach a discharge of up to 349 million m3 by 2021.

The global average of textiles consumption per inhabitant has increased at an accelerated rate. While in 2000 the average consumption was calculated as 9 kg per person, in 2015 increase up to 13 kg, and its expected to reach, by mid century 15 kg. The 'Fast Fashion' business model has been appointed as the main responsible for this trend , which finally leads to increase the negative impacts to our environment. The current value chain is based on launching up to 50 fashion collections per year, instead of the traditional 4th seasonal ones.

The future scenario is environmentally unsustainable, and several initiatives advocate for a turn to a most environmentally responsible business model. As example, Filippa K, a Swedish fashion company, opened in 2008 a second-hand clothing store, oriented to revalue previous collections garments. Further, other organizations, push forward for a change on the design paradigm, and applied the concept of auxetic designs to produce adaptable garments. Thus, a negative Poisson coefficient signals for patterns' one axis expansion that facilitates the other axis adaptability. Petit Pli, is the most representative initiative, staking for long-life garment targeting infants segment, has developed auxetic structures, that allows garments' adaptability up to seven different sizes.

Despite auxetic designs great potential to lessen textile's sector environmental impact, a brief survey developed in 2014, revealed a minimal amount of academic research focused on its application on final products. A majority of academic articles focused on explore, analyze, and evaluate the application of different auxetic structures to produce fabrics that could enhance its expansion feature.

In this context, this study aims to explore the use of auxetic designs on patterns development for garments. Thus, we propose to test different fabrics to evaluate their elongation characteristics variations when applying auxetic designs.For this aim, two types of auxiliary structures are used for patterns development: re-entrant and rotating structures. As part of the comparison process, we applied pleating as a traditional technology, and laser cutting process as the application of digital manufacturing technologies. Pleated is applied to thin fabrics, where re-entering auxetic designs are used. Meanwhile, thick fabrics are exposed to laser cutting applying rotating auxetic designs.

Auxetic structures impact over garment elongability is evaluated for each fabric. Subsequently, the garments are subjected to elongation tests to measure samples' stretch rate in comparison to the original configuration. Our hypothesis, regarding the increase of garments' elongability when applying auxetic designs could significantly improve its usability, even though the variations could affect others garments' properties, such as joints' strength.

Auxetic structures applied in textile design have the potential to extend the garment duration and decrease clothing's commercial demand. This study opens a research stream on the application of auxetic designs for final products design, supporting the slow fashion movement that seeks a sustainable business model in the sector.

2 Fabrics

To achieve the required adaptability of the garment, different types of fabrics have been chosen taking into account mechanical properties such as abrasion, fatigue and elastic recovery, which favour the performance of the product.

Firstly, good resistance to repeated deformation will be required, and it is known that fibres with high elongation, elastic recovery and breaking work have a good ability to withstand it. This also gives a good degree of abrasion resistance (Nilgün Özdil, 2012). However, to be able to perform a diverse test, a stiff fabric, an elastic fabric and a combination that can take advantage of both mechanical properties will be chosen.

Polyamides (PAs), or commonly referred to as Nylon, are considered to have the best abrasion resistance, followed by polyester and polypropylene (Hu, 2008). PAs also have excellent performance due to their temperature and chemical resistance, good processability and mechanical properties (Kohan, 1995), which will be favorable for further application in garments. As mentioned by Umar (2015) those properties are stretch, recovery and compression, which are used to apply mechanical pressure on the surface of the body to stabilise, compress and support (MacRae, Cotter, & Laing, 2011).

In the case of elastane, the recovery percentage of fabrics increases with increasing linear density of elastane (Umar, 2015), so this property will be taken into account in the choice of fabrics.

Acrylic has a lower strength, while wool, cotton and viscose have moderate abrasion resistance. However, blending nylon or polyester with wool and cotton has been found to increase abrasion resistance at the expense of other properties (Saville, 1999), which will also be taken into account.

Therefore, three types of fabrics were chosen: taffeta, suede, and the last one resulting from the combination of tartan as the rigid part and elastane, commercially known as Lycra for the elastic part.

We start with taffeta because of its rigidity as a flat fabric. This fabric is made of nylon fiber and has a high resistance to moisture and chemicals. (Erch, 2014) Is crunchy, and has a slick surface and a slippery smoothness (Patill, 2021).

The suede fabric to be used will be composed of 95% polyester and 5% elastane, so that it has elasticity and, at the same time, resists abrasion and rubbing of the fibres.

The last to be used will be a combination of 10% elastane or commonly known as Lycra and 90% Nylon or polyamide, and wool tartan with polyester additives, both joined by a thermoadhesive web, which uses polyester as a base and polyamides as an adhesive.

3 Design of Laser Cutting Fabric Systems

The auxetic patterns are known because of their negative Poisson ratio property, which means that if one axis expand, the perpendicular one expands as well, but since this was already proved by Mizzi et al. (2020) we only wanted to ensure the elongation and strength resistant of the garment was enough for a garment.

For this experimentation we took as base the paper on auxetic patterns on metamaterials by Mizzi et al (2020) since they designed their patterns and proved on the article to have worked. We decided to test those patterns in commercial use fabrics to demonstrate that this method could work in a different situation such as fashion.

The first thing we had to focus on was the size of the pattern, since it was originally designed for metamaterials the shortest spots of the designs were too small to work on a fabric. To solve it we escalated the designs by 3.75 times so that the smallest part goes from 0.4 mm to 1.5 mm which had proved to be a safe measurement to handle in fabrics.

As we had our fabrics and the designs prepared we used a TROTEC Speedy 400 (120W) laser cutter for making the samples for the test.

Settings:

- Power: 120W
- Speed: 3.55 cm/s
- Frequency: 3000 Hz

Classifying the geometries according to Mizzi et. al (2020) the results of the cuts in the fabrics are shown in Figure 1.

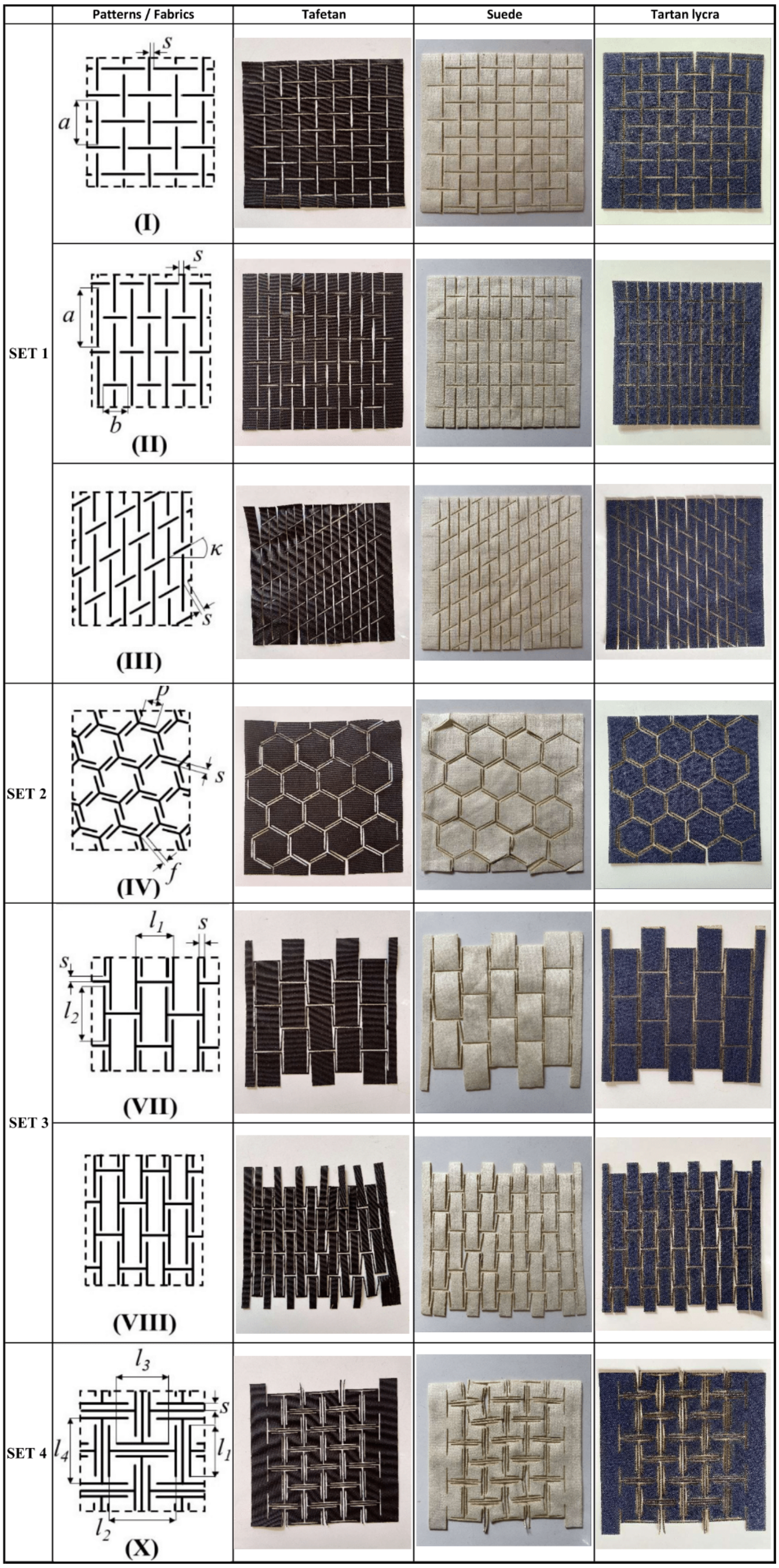

Figure 1: Diagram depicting the seven architectures studied here

4 Qualitative Analysis

The aim of the research focuses on the study of auxetic materials for their subsequent application in clothing, for which the patterns to be developed must comply with certain characteristics and mechanical properties that allow their performance in everyday use.

According to a study conducted in 2007 by Sibel Kaplan and Ayse Okur on the turkish population, they identified fit and comfort as the two main criteria when deciding on a purchase. These attributes were also found to be crucial in other research (Li and Wong 2006; Zhang et al. 2002) in which consumers' purchasing behavior and comfort evaluations have been assessed.

On the other hand, according to Pamuk in 2007, comfort is one of the most important aspects of clothing, so to achieve it, three factor will be considered: psychological, tactile and thermal comfort. For functional reasons, the study will consider only two of them: tactile and thermal comfort.

In terms of thermal comfort, as Pamuk mentions, static thermal properties such as conductivity, resistivity and diffusion need to be considered so that the transmission of air, heat and water vapor through the garment is efficient and the wearer can feel comfortable. The human body usually maintains its temperature at 37 +/- 0.5 C°, but this can change according to weather conditions or the heat produced by different activities (Pamuk, 2007), so it also needs adaptable attributes.

Tactile comfort is related to the surface of the fabric and its mechanical properties (Pamuk, 2007), so the fabrics chosen will avoid sensations such as itchiness, extreme heat retention and scratching.

In addition, because of the fit mentioned by Kaplan and Okur, three properties presented in the article by Richard Davis in 2014 will be considered, where they mentioned as principals in the mechanics to determine the elongation in a fabric:

- Elongation: ability of a fabric to stretch in a given direction using a predetermined amount of force.
- Modulus or Power: is the resistance that a material applies to a force.
- Recovery: ability of the material to return to its original state. It measures whether and how long it takes for a material to return to its original state after elongation or stretching

These will be the factors to be assessed for each arrangement presented:

- Fit
- Elongation
- Power
- Recovery
- Comfort
- Thermal comfort
- Sensations

SET 1

- Model I: Regarding the fit, as it opens in a concentric way, and presents quite small spaces, it will tend to fit properly to human curves. On the elongation, because of being such a compact model, with quite dense structures, the elongation is low compromised, and it’s not a easily malleable body, so it generates a greater resistance to the application of force in tension needing more force to perform a stretch. However, it has a good recovery and feeling of comfort, due to being a compact arrangement, the edges are not perceptible by the sensory organs, have a good support system and compression to the body that would contain, as well as an adequate thermal comfort thanks to the small size of the pores or separations that form.

- Model II: The fit of this arrangement again performs better in materials with higher recovery systems and solidity. The structures formed as wefts and warps through the connection of nodules, creates a solid and adaptable arrangement to different curvatures, which is why it is considered one of the patterns that gives greater stability to the fabric. The elongation it presents is moderate, and offers a moderate resistance that allows a convenient malleability, but being at the resistance of model III. The recovery is in an adequate range for use, and at the same time this weave allows containment, body shaping and a favourable thermal sensation, due to the fact that the spacing between the cuts is small, and these openings when opening and closing will allow for regulated ventilation according to the type of activity carried out by the user. Undoubtedly, one of the best candidates to be tested in the final test.
- Model III: A variation to model II is presented, with the cutting direction of the elements in the y-axis, being now oblique. The cuts generate a pattern similar to a warp and weft with uniform thicknesses, however, these oblique cuts provide a greater opening in the nodules which provides greater flexibility and openness of the material. The fit on the end user's body would be adequate as it has a solid and malleable arrangement, which offers containment to the body. The elongation is moderate but higher than Model II, and offers a lower resistance to stretching than Model 2. The recovery is in an adequate range for use, and in turn this weave allows containment and shaping to the body, due to the moderate spacing between the cuts. The thermal sensation that will allow the end user will be favourable, due to the fact that the spacing between the cuts is small, and these openings when opening and closing will allow a regulated ventilation according to the type of activity performed.

Within SET 1, the model to choose will be the III, due to the fact that the oblique cuts produce nodules that generate a greater malleability in the material handled, the containment and thermal benefits potentially offered are the most optimal.

SET 2

- Model IV: This hexagonal model allows a pivot opening through edge connections. Aesthetically it is an interesting prototype, however for functional purposes, the thickness of these edges would affect the long-term durability of the material, as it would not resist factors such as abrasion and mechanical fatigue, as well as it would not be comfortable as it would not present an adequate containment of the body and would present sharp edges that would take away comfort generating stinging. The presence of angles produces a better fit to the body, so the fit could be adequate for the final consumer, according to the size of the arrangement that is presented. On the other hand, the larger the gaps between the weft elements of the auxetic pattern, the less heat retention there will be, which would also not satisfy with adequate thermal properties. The recovery of this arrangement depends on the material, so it is not a determining factor for the pattern, and the thermal sensation can still be manageable due to the hexagonal shape similar to circles, which creates relatively curved and small spaces that can be opened and closed according to the activity being performed.

SET 3

- Model VII: The arrangement presented for this model, although it fulfils the auxetic function of expanding in both two-dimensional axes, has very thin and weak connectors in proportion to the larger solid bodies. This would affect the fit and daily use of the end user, as it would not resist factors such as abrasion and mechanical fatigue caused by the friction and stresses of use. On the other hand, the elongation of the intervened material is favourable as the pattern makes it quite malleable, so the resistance to being stretched or subjected to tension is quite low. The recovery to its original shape is low, and depends very much on the material to be worked on due to the weak connections. Comfort is also affected due to the fact that the bodies are so separated, large and angular that they generate stinging and break easily, which is why they would be discarded from the study, as they do not comply with the required mechanical factors.

- Model VIII: This model has very similar characteristics, which would invalidate its use in the study. However, it should be taken into account that this arrangement, together with model III, are those that present a lower resistance to elongation, as well as a higher displacement or elongation than the others.

Within set 3, both options are discarded due to issues of low resistance to mechanical fatigue and abrasion.

SET 4

- Model X: This last model has a pattern that will be severely affected according to the type of material in which it is made. The higher the shrinkage or recovery factor, the tidier and more solid the arrangement will be. However, by containing very thin connections, as well as sharp edges, the comfort factor would be compromised because it would create stinging and a weak performance in terms of thermal properties that meet the needs of the consumer. Due to the type of opening of the pattern itself, which tends to open upwards, the functional factor could be affected, but the malleability is quite good, needing little tensile strength to achieve a stretch, and having a moderate containment because of the good recovery it possesses. On the other hand, the connections between figures are quite thin, but in proportion to the other bodies present in the pattern, it is not something that affects in the same magnitude as in the other models. As the structure is not so dense, the thermal sensation could be affected, as at times the structure can separate too much.

Within set 4, the best option would correspond to model X, due to its greater mechanical resistance and greater containment or support thanks to its recovery.

In conclusion, model III is chosen due to its resistant mechanical properties, the malleability of its structure, the solidity of the arrangement, the adaptability to different bodies without affecting its shape and the comfort it provides when in contact with the end user's skin.

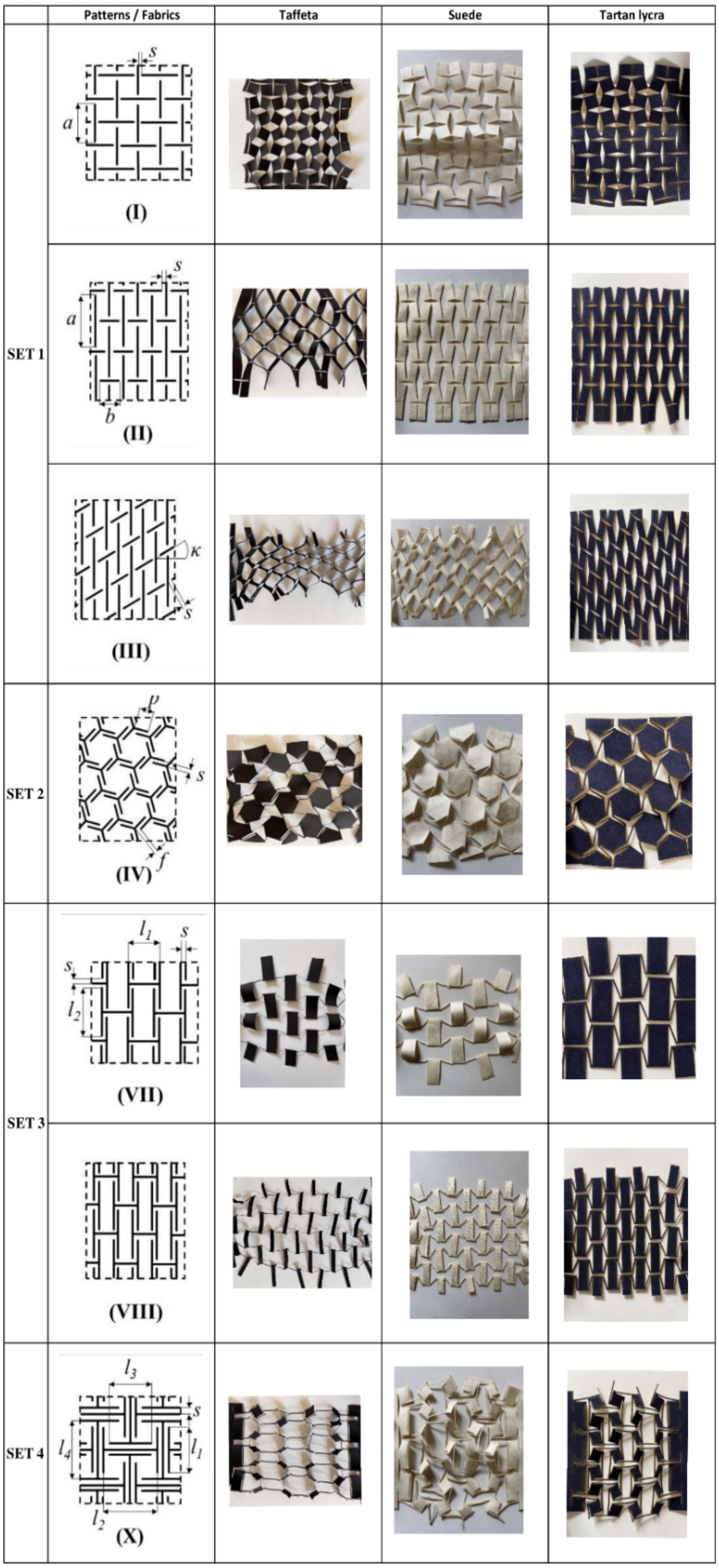

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Figure 2: Samples behavior

5 Quantitative Analysis

Despite the use of auxetic patterns in fabrics is not new, there are no standard tests we could find to prove that this technique will successfully elongate the modified fabric as we wanted. Since our proposition is that the auxetic pattern can help to the elongation of the fabrics beyond they usual limits, in order to ensure our proposition is correct we needed a tensile and elongation test, and to make sure everything is correct the ISO 13934/1 standard was elected as guideline to the test.

Following the ISO standard as best as we could for taking samples from each fabric we proceed to set the test on the University of Lima textile lab. Using a Mesdan Tensolab 2512A tensometer we set the gauge length at 100 mm as requested by the ISO and calibrate the software to the ISO 13934/1 preset so that everything runs as needed.

Even though the ISO require an specific range of temperature and humidity, we used the room values we had:

- Temperature: 20°C
- Air Humidity: 90%

The software asked for the density of the material in use and since we didn't have a data sheet for the fabrics, we weighed the strips and calculated each density by hand using the 200 mm x 50mm for the area.

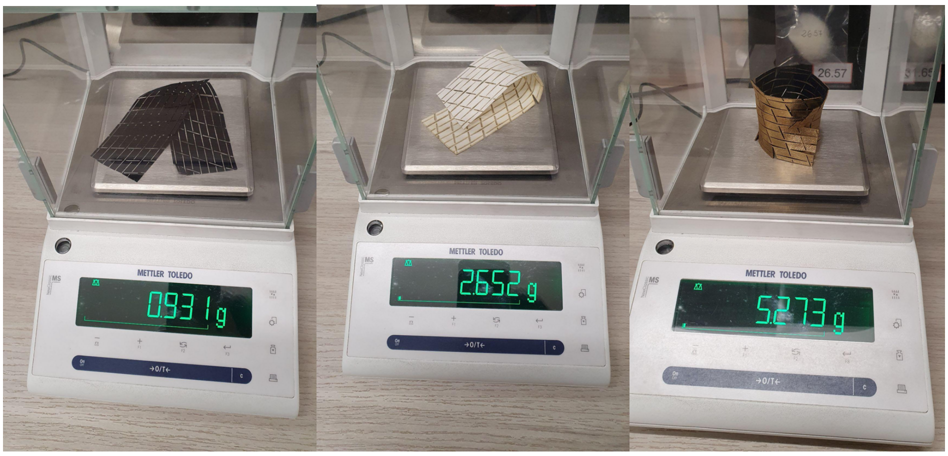

Figure 3: Strip samples being weigthed

	Taffeta (Black)	Suede (White)	Tartan + Lycra (Gold)
Weight (g)	0.931	2.652	5.273
Area (m2)	0.01	0.01	0.01
Density (g/m2)	93.1	265.2	527.3

Table 1: Fabric density calculation

The standard request for at least 5 samples in each direction (warp and weft) for each test. The gauge length was 100 mm as the ISO standard state for expected elongations over 75%.

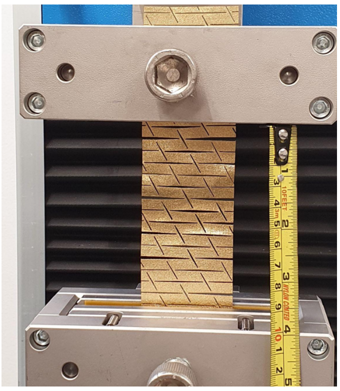

Figure 4: Verification of the 100 mm gauge length before the compound fabric test

As we were looking to test the auxetic pattern cut on the fabrics we use the direction of the pattern in the fabric instead of the direction of the woven.

After testing the fabrics, we had some results presented on the following charts. Since each fabric was different at some properties we had different results for each fabric in the tensile strength test.

The results on Taffeta, the first fabric tested, had some impressive results in terms of the elongation because it presented more than 100% of elongation from its original size.

	Main Direction			Cross Direction		
	Max Strenght [N]	Elongation at max strenght [%]	Elongation at breakage [%]	Max Strenght [N]	Elongation at max strenght [%]	Elongation at breakage [%]
Mean Value	11.884	117.05	119.1	230.69	19.12	24.678
Maximum	13.67	120.59	127.43	275.39	20.34	29.31
Minimum	9.44	110.06	110.19	187.72	18.19	22.66
Range	30.94%	8.73%	13.53%	31.83%	10.57%	22.69%
Deviation	1.77	4.63	6.30	34.96	0.78	2.70
#	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**
1	12.32	114.52	116.73	275.39	20.34	23.93
2	13.67	120.14	120.28	254.43	19.14	24.53
3	10.75	120.59	120.87	226.8	19.09	22.96
4	9.44	110.06	110.19	209.11	18.84	29.31
5	13.24	119.96	127.43	187.72	18.19	22.66

Table 2: Taffeta results summary

After the first tests we tested the Suede fabric, which had the following results:

	Main Direction			Cross Direction		
	Max Strenght [N]	**Elongation at max strenght [%]**	**Elongation at breakage [%]**	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**
Mean Value	21.158	123.41	125.2984	20.248	17.154	35.59
Maximum	23.45	135.181	135.341	22.28	20.14	38.96
Minimum	18.29	116.151	118.71	17.82	14.61	33.13
Range	22.00%	14.08%	12.29%	20.02%	27.46%	14.96%
Deviation	1.86	7.31	6.50	1.70	2.22	2.49
#	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**
1	18.29	116.151	118.71	19.8	20.14	38.96
2	20.95	125.107	125.586	19.96	15.49	33.13
3	21.6	120.629	126.386	21.38	18.43	33.13
4	21.5	119.989	120.469	22.28	17.1	36.06
5	23.45	135.181	135.341	17.82	14.61	36.67

Table 3: Suede results summary

Our last fabric was a complex fabric, made with by a combination of Tartan and Lycra which make a strongest and elastic fabric for was expected a highest point for the max strength in the following results:

	Main Direction			Cross Direction		
	Max Strenght [N]	**Elongation at max strenght [%]**	**Elongation at breakage [%]**	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**
Mean Value	87.91	143.08	147.0525	172.99	28.88	42.736
Maximum	108.02	150.48	156.05	260.07	32.98	51.45
Minimum	76.57	138.74	138.77	108.87	23.56	30.12
Range	29.11%	7.80%	11.07%	58.14%	28.56%	41.46%
Deviation	14.28	5.13	7.58	62.99	3.54	8.53
#	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**	**Max Strenght [N]**	**Elongation at max strenght [%]**	**Elongation at breakage [%]**
1				117.99	30.81	45.33
2	108.02	150.48	156.05	260.07	23.56	38.47
3	88.03	141.04	143.34	171.12	27.78	30.12
4	79.02	138.74	138.77	206.9	29.27	48.31
5	76.57	142.04	150.05	108.87	32.98	51.45

Table 4: Compound fabric result summary

Note: The first strip from the main direction on the compound fabric's data was lost because of a failure in the software.

5.1 Systematic sampling

The ISO 13934/1 request for a specific way to get the samples from the fabrics for testing, in this case we used strips with 50mm Width and 200mm Long, as the gauge length would be 100mm between the tensometer clamps. For further information check the ISO 13934/1 Annex B.

5.2 Technical testing

We tested our samples on a Mesdan Tensolab 2512A tensometer, which software already had the ISO 13934/1 preset for testing.

As the standard requested we tested our samples strip by strip until they broke beyond their elongation point taking note of the direction of the pattern and each density for every material. Each test was made on dry material.

On each material we started testing with the main direction of the pattern followed by the cross direction, each analyzed independently for each material.

The speed of the clamp movement during the test was set to 100 mm/min.

6 Results

As displayed on the previous tables in every fabric the main direction of the pattern had an elongation higher than 110% from its original size while the cross direction only had an elongation of 28% in the compound fabric. This first result is due to the design of the pattern, even though the strips had an auxetic behavior for a while our focus was on the maximum elongation the modified fabric could get.

As the pictures show, the highest point of elongation (Fig.5 E) was no longer auxetic because the pattern started to break earlier (Fig.5 D) but the test ended when the whole strip shattered or had enough broken points to make any tensile strength. Since the pattern direction was the same as the direction of the force applied, the machine used a low amount of Newtons [N] to pull the strip, but in the cross direction of the pattern, the results on elongation were significantly lower than before while the force applied was substantially higher.

In the cross direction the auxetic property can be seen clearer (Fig.6 d), but the elongation is low so the strip starts breaking after a short distance (Fig.6 e) and ends the test completely shattered.

The mean maximum force applied in the cross direction increased significantly in the Taffeta (from 11.884 N to 230.69 N) and the compound fabric (from 87.91 N to 172.99 N) while in the Suede the force remain almost the same (from 21.158 N to 20.248 N).

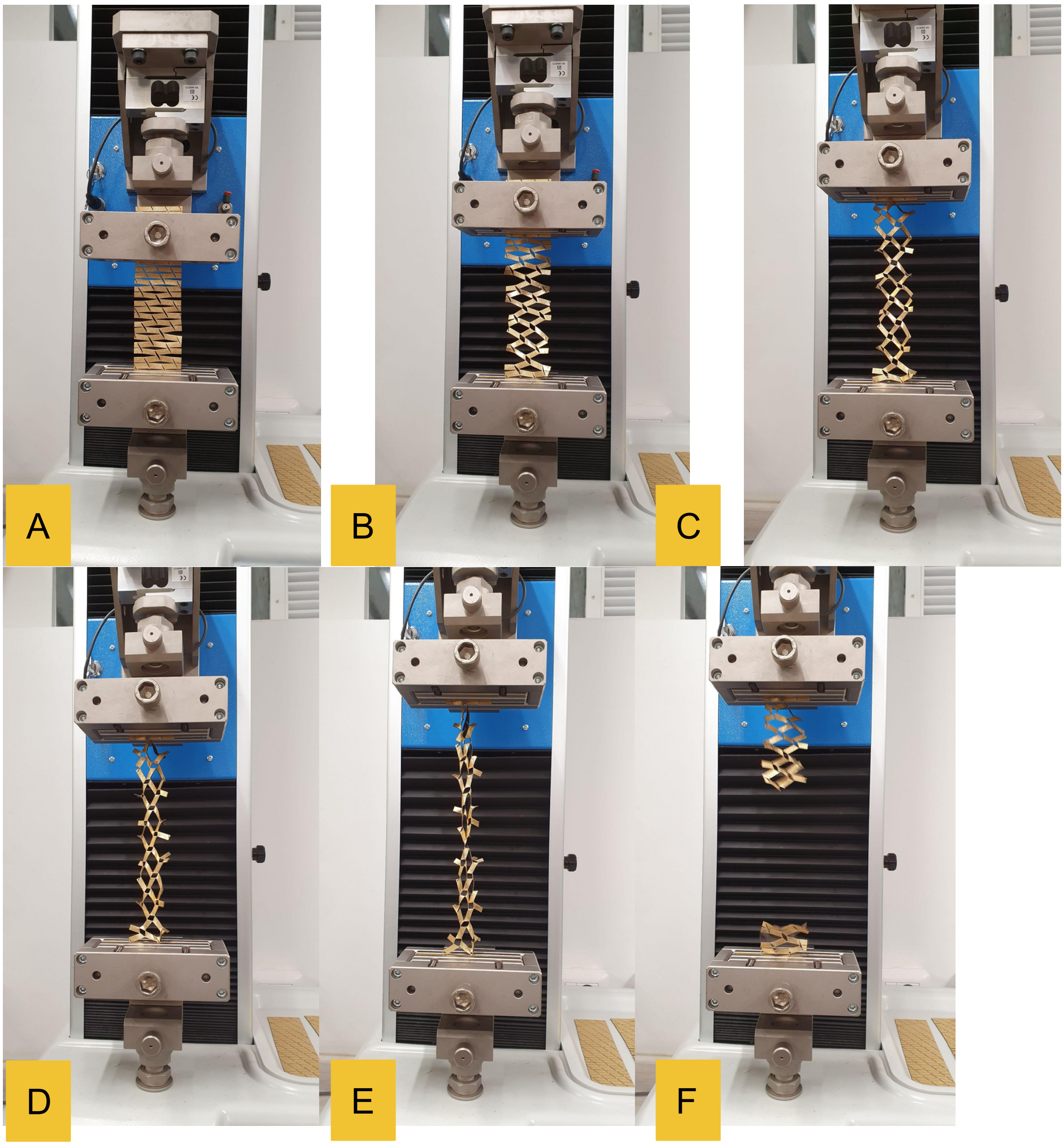

Figure 5: Compound fabric being tested and shattered in the main direction of the pattern

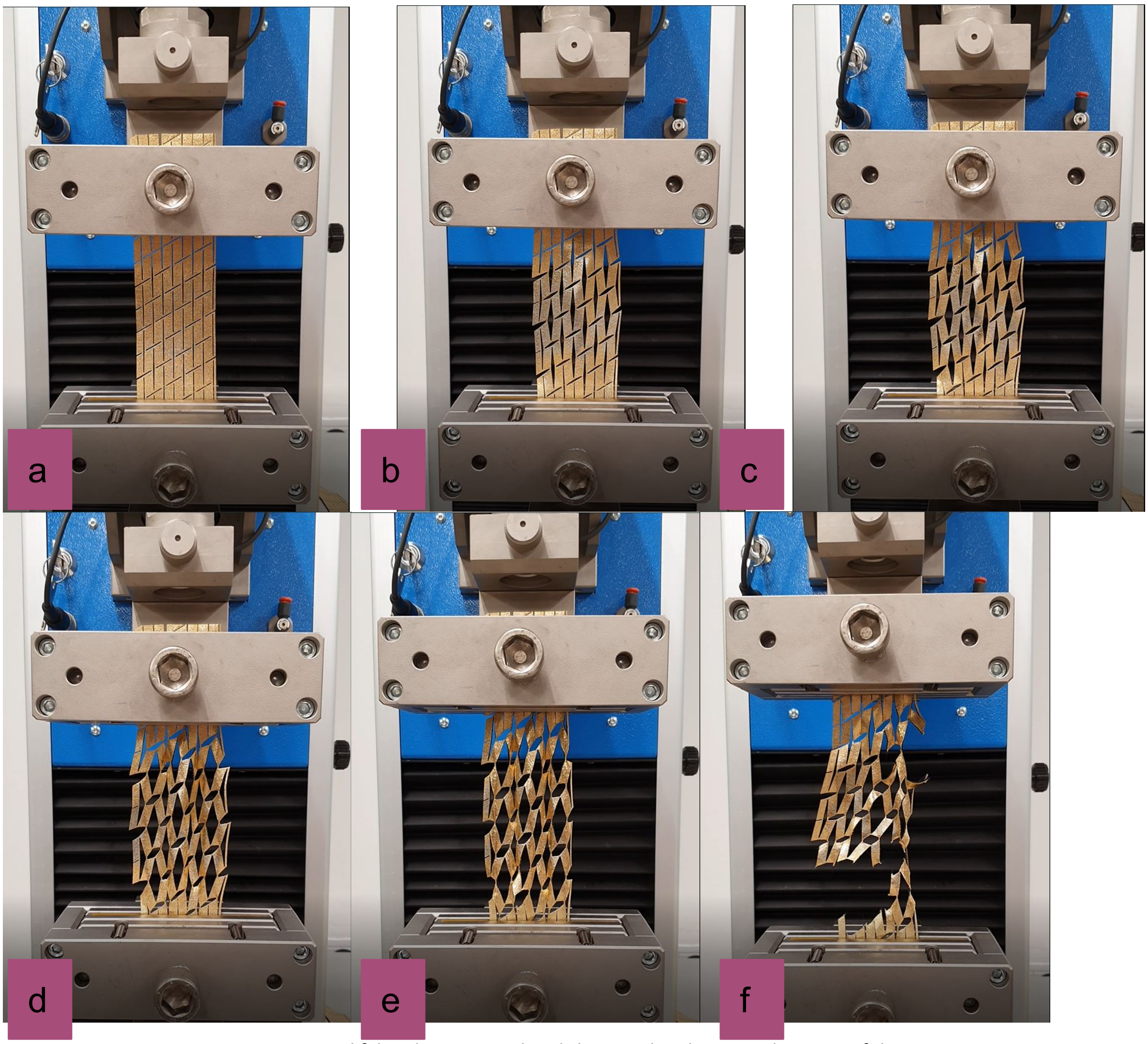

Figure 6: Compound fabric being tested and shattered in the cross direction of the pattern

7 Conclusion

The pattern studied have proven to be surprisingly stretchable in the main direction with low forces applied on every material tested, but in the cross direction the tensile strength was very high in rigid or semi rigid fabrics but had almost no difference in the elastic one (suede) which behavior was similar to the other fabrics in elongation, but with very low tensile strength.

The patterns or arrangements used will always be directly affected by the type of material used, so it is necessary to study what the purpose will be, in order to determine the appropriate mechanical characteristics that will allow optimal functional performance.

Using digital fabrication for development modifications on traditional fabrics is viable and can add some more value to the fabric due to the complex geometries that can be generated just by cutting over the fibers with extremely precision.

The presented structures can be used in clothing, depending on the purpose. They fulfil the objective of adaptability, as long as the purpose of the application of the arrangement is taken into account.

The comfort and mechanical factors will be the most important factors when determining the acquisition of a material, which is why they are characteristics that must be taken into account when developing a textile development.

8 Future research suggestions

This article was focused on the elongation of materials without taking count on the main property of the auxetic structures. The materials studied are thought to be used in garments, so we suggest testing the max elongation before permanent deformation on garment pieces to determine the limit of the pattern on real clothing.

The results we revealed in our study have let us learn about the elongation capability of the pattern selected in different kind of materials with some different characteristics, but to expand this information there must be some research that compares these results with the tensile strength in the materials unmodified, so that we can assure that the pattern is not just an aesthetic variation of the fabric, but really a useful one.

After watching the auxetic behavior on the strips while applying transversal force, it may be needed further research to determine scientifically how much of the cross elongation generates the pattern we studied to decide if it would add some more useful properties in a day-to-day garment.

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