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Comparison of Poisson’s Ratio Measurement Methods: The Extensometer and the Universal Tensile Testing Devices

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ABSTRACT

Auxetic materials with a negative Poison’s ratio (PR) have the potential to meet the demand for different materials, especially technical textiles. Universal Tensile Test (UTT) devices and various experimental setups developed by researchers have been used in PR measurements. This study aims to investigate the PR of knitted fabrics with UTT and extensometer devices comparatively by using the same measurement parameters according to ASTM E132. Knitted fabrics with zigzag and foldable patterns were produced in the study because of their auxetic behaviour. It has been determined that the extensometer device can be used as an alternative to the UTT device for PR measurements. While the PR of foldable fabrics cannot be measured with the UTT device because of the fabrics' folding on themselves, it has been observed that it can be easily measured with the extensometer device thanks to the horizontal axis principle.

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KEYWORDS

Poisson's ratio, auxetic, knitted auxetic fabric, fryma, extensometer

1. INTRODUCTION

Poisson's ratio (PR) is a mechanical property representing the lateral behavior of materials under an axial load [1]. The Poisson's ratio (ν) is defined as;

$$\nu = -\frac{\varepsilon_{Trans}}{\varepsilon_{Load}} \qquad (1)$$

Where ε_{Load} is the strain in the loading direction while ε_{Trans} is the perpendicular strain or transverse to the loading direction. Typical natural materials possess a positive Poisson’s ratio, which means they contract when they are stretched in one direction (Figure 1). Unlike standard natural materials, auxetic materials are defined as solids with negative PR [1, 2]. PR is an important parameter for numerical simulation of garment pressure distribution, and garment dressing system [3].

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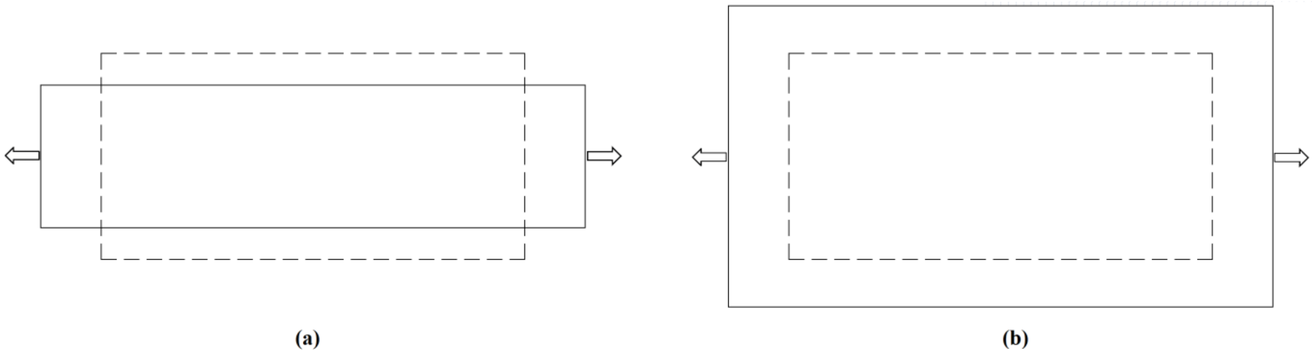


Figure 1. Schematic view of (a) conventional materials (positive PR) and (b) auxetic materials (negative PR)

Auxetic materials have the potential to meet the demand for different materials, especially in technical textiles. Properties associated with the PR can be listed as follows: friction resistance, better tensile strength, synclastic curvature (dome-shaped), increased fracture toughness and enhanced indentation resistance, increased shear stiffness, fiber pull out strength, variable permeability, extra friction resistance, acoustic behavior, superior energy absorption (impact, ultrasonic and sonic), adhesion (interface/matrix) strength, thermal impact resistance, improved drape, increased fracture toughness, tensile strength [4–7]. Potential applications include filter fabrics, geotextiles, reinforcements in advanced composites for aerospace and automotive sectors, and personal and sporting protective garments such as bulletproof vests and batting gloves [8].

In the literature, there are many studies on yarn [1,9–20], woven fabric [21–26], knitted fabric [8, 27–37], composite [38–41] production related to low PR or auxetic textile materials. Auxetic fabrics can also be produced with auxetic yarns or conventional yarns. Researchers changed the yarn properties and/or fabric patterns in literature to achieve low PR values [8,21–37]. These studies show that the researchers used Re-entrant (zigzag), Rotating, Chiral, Fibril-Nodule, and Foldable mesh structures [2,42,43]. Poisson's ratio and different methods for measuring this property have been the subject of many previous research studies due to their significant influence on fabric performance [44]. Reviews on the measurement of the PR of fabrics are as follows.

1.1 Studies with a Universal Tensile Tester (UTT)

In the studies of the PR of fabrics with UTT, many measurement points were marked on the sample placed between two (one fixed and the other movable) jaws vertically. While the samples were forced to elongate in one direction, images are taken at regular intervals to observe the other direction changes. The distances between the marked points were measured with the image processing program, and the PR is calculated [3,4,8,22,27,29,35, 36,43,45-48]. Literature survey on PR of knitted fabrics shows that researchers prepared the fabric samples in different sizes (170x150, 150x50, 200x50, 50x180, 40x100 mm), stretched at different speeds (30-50-60-200 mm/min) by using different jaw distances (100-150 mm) [3,8,22,35, 43,47-49].

1.2 Studies with other Measuring Methods

These studies are carried out by applying force to the fabric with various test equipment and then calculating the PR from the images obtained. Glazzard (2014) fixed 100 mm wide fabric samples in a 100 mm jaw distance (Figure 2). Markings were made on the sample with 10 mm intervals. The clamps on the frame are moved 10 mm and fixed into place. After each movement, a photograph was taken. The images are then analyzed using digital image analysis software [28]. Steffens (2016) developed a testing device for the evaluation of PR. The specimens were marked at specific two points in both course and wale directions. The fabrics were clamped at their two ends in the testing device and extended manually along the course direction. Steps of 1 cm deformed the knitted fabric, and the distance between the reference points along the course and wale directions at each deformation step was measured [49]. Liu (2010) clamped the knitted fabrics at both ends with a gauge length of 150 mm and then extended manually along the course direction. A digital camera photographed the fabric under each deformation step, and the distances between the markers along the course and wale directions were calculated [29].

Apart from these studies, Jinyun (2010) examined the relationship between PR and the materials' elastic modulus. PR of knitted fabrics was obtained by calculating the ratio between elastic modulus values. He studied the dimensional change of the samples under biaxial force by placing the knitted fabrics produced in the Kawabata Evaluation System (KES) [3]. Boakye (2018) also measured PR values of knitted fabrics using cylinders with different diameters. Different tension was applied to the samples by dressing the fabrics produced in a tubular form on cylinders of 5 different diameters. As a result of the tension, the fabrics' length direction changes were measured, and PR at different elongation values was calculated [30].

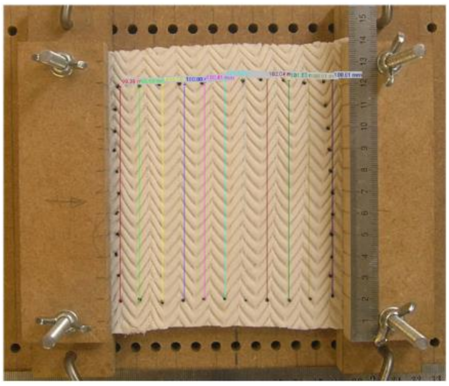


Figure 2. PR measurement equipment [28]

Former studies in this subject show that UTT devices were commonly used in PR measurements. Also, there are some other studies in the literature with self-designed measurement equipments. In these studies, an intermittent force-elongation test procedure was applied. Basically, PR measurement is a force-elongation test. Morton and Hearl (2008) indicate that the experiments' results will be affected by the time allowed and how the load is applied" [50]. In other words, the force-elongation test procedure acts continuously (not intermittently), and test parameters directly affect the test results. Therefore, it is thought that the studies that performed with intermittent test procedure do not simulate the force-elongation test accurately.

Fabrics with highly auxetic properties have a tendency to curl downwards positioned vertically in the UTT devices. While the fabric structures are susceptible to a small amount of force, gravity force acts as a pretension and deforms the fabrics' relaxed position. However, PR determination was calculated on minimal dimensional changes, and this deformation prevents the test accuracy for such kinds of fabrics that tend to curl downwards. This problem can be solved by using an extensometer. The materials are positioned horizontally in the extensometer devices. Extensometer devices are cost-friendly and easy to use compared to UTT devices. Therefore, this study investigates the extensometer devices' usability as an alternative to the UTT device in PR measurement of knitted fabrics. Zigzag and foldable pattern fabrics were knitted in the study because of their low PR (auxetic behavior).

This study aims to investigate the Poisson's ratio of knitted fabrics with UTT (Shimadzu AG-X HS) and extensometer (SDL ATLAS-Fryma Dual Extensiometer) devices comparatively by using the same measurement parameters according to ASTM E132 "Standard Test Method for Poisson's Ratio at Room Temperature." The extensometer device that was used in this study can apply continuous force and gives more accurate results. Morton and Hearl (2008) also indicate that "The dimensions of the specimen have a direct effect on the results of tensile tests" [50]. Therefore, in this study PR was measured with both UTT and extensometer devices with the same measurement parameters. The comparison of measurement results by these two methods was statistically evaluated.

2. MATERIAL AND METHOD

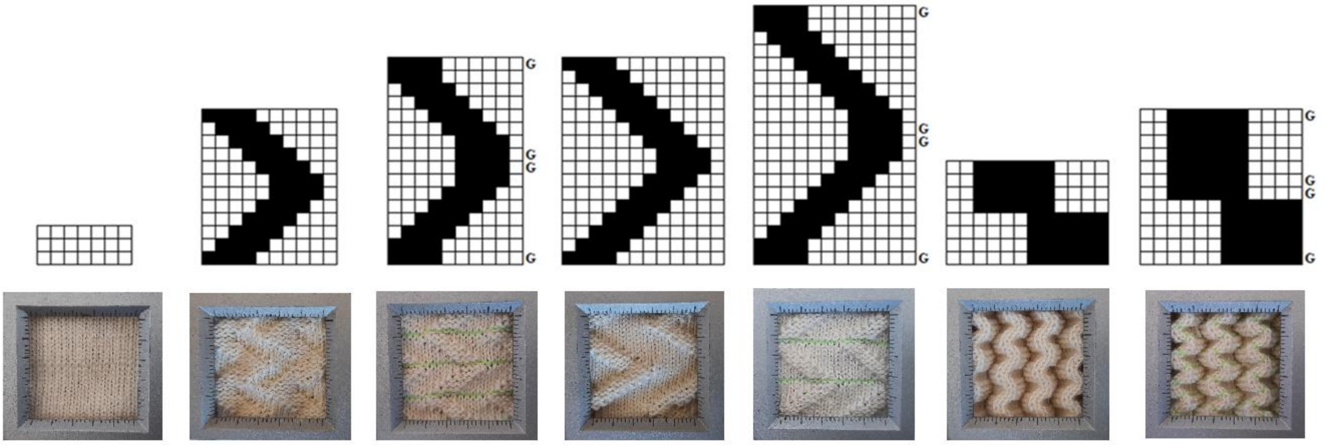
2.1 Material

Auxetic knitted fabrics with different knitting structures were produced, such as zigzag and foldable patterns knitted fabrics. Besides, plain knitted (RL) fabric was made with the same yarns for control purposes. Double-covered spandex yarn was added for increasing auxetic properties. The samples were knitted on a Stoll CMS 530 Hp E6.2 Multi gauge flat knitting machine using 60% cotton-40% acrylic, Ne 20/1 number yarns. The fourfold yarn was fed into the knitting machine. 240 dtex polyamide elastane texturized yarn was used as spandex yarn. The fabric samples were subjected to dry relaxation by laying samples on a smooth and flat surface in atmospheric conditions (20±2 ^{0}C, 65±4% relative humidity) for 48 hours. The following properties of the fabrics were measured in accordance with relevant standards: course and wale per cm, ISO 7211-2; fabric weight (g/m^2), ISO 3801; fabric thickness (mm), ISO 5084. Measurements were performed five times in a relaxed state of the fabrics (unextended). Dimensional properties of the produced fabrics are presented in Table 1, and knitted structures are shown in Figure 3.

Table 1. Dimensional properties of the samples

Sample Code	Courses per cm	Wales per cm	Thickness (mm)	Weight (g/m^2)
Zigzag structure				
4x6	8.2	6.1	3.1	410.6
4x6 - G	8.6	6.4	2.8	392.2
4x8	8.2	6.3	3.1	403.9
4x8 - G	9.0	6.5	3.1	399.6
Foldable structure				
Foldable	9.6	13.5	9.2	1203.7
Foldable - G	9.75	13.0	9.8	1173.6
Plain Knit				
RL	8.6	5.1	1.59	427.1

-G: Shows the use of double-covered spandex yarn in the sample. (with gimped)



PLAIN (RL) 4 x 6 4 x 6 - G 4 x 8 4 x 8 - G FOLDABLE FOLDABLE - G

Figure 3. Patterns and images (25.4 mm x 25.4 mm) of the knitted fabrics (*In the unit cell of the knit pattern, the white square "□"represents the face loop and the black square"■"represents the reverse loop. "G" represents double-covered spandex yarn usage.)*

2.2 Method

Two different methods were performed for Poisson's ratio (PR) measurements under ASTM E132 standard test method parameters using Shimadzu AG-X HS universal tensile tester (Figure 5.a) and SDL ATLAS M031 Fryma Fabric Extensometer (Figure 5.b).

ASTM E132 standard defines the test method as "the tested length of the specimen should be at least five times the tested width, and the length between the grips should be seven times the tested width." [51]. Within the scope of the study, samples were cut in 50 mm width, and markings were made at 30 mm intervals on the horizontal and 150 mm on the vertical. The distance between the jaws is 210 mm. PR measurements were performed in the course and wale directions for three fabrics. Course-wise measurements (A1-B1, A2-B2, A3-B3) and wale-wise measurements (C1-D1, C2-D2, C3-D3) were performed three times in each fabric sample. Average values of the measurements were calculated. Markings made on samples are shown in Figure 4.

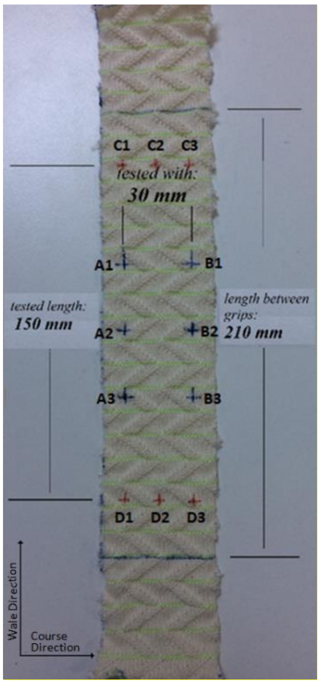
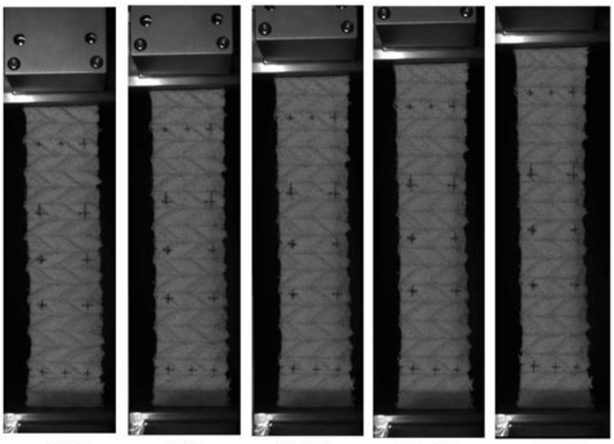


Figure 4. Markings on the sample

(a) (b)

Figure 5. Placement of samples in (a) UTT device (zigzag pattern) and (b) Fryma extensometer (foldable pattern)

The ASTM E132 test standard recommends low operating speed, but an exact value is not specified. Sloan (2011) defined low working speed at approximately 1/10 of jaw distance per minute [14]. Based on this, the force was applied at a rate of 20 mm/min for both measurement techniques. The images recorded during the test were transferred to the ImageJ image processing program. Changes in width and length in specific elongation values (1%, 2%, 3%,…, 20%) were measured, and the PR values were calculated (Figure 6).



(%0) (%5) (%10) (%15) (%20)

Figure 6. Images of samples at certain elongation rates (UTT)

A two-factor completely randomized ANOVA model was used with SPSS 22 for pattern type (RL, 4x6, 4x6-G, 4x8, 4x8-G) and % elongation (1%, 2%,…. 20%) values for both UTT and extensometer devices in order to demonstrate the significance of pattern type and % elongation on the PR of fabrics. In addition, a three-factor completely randomized ANOVA model was also used for measurement method (UTT, extensometer), pattern type, and % elongation in order to demonstrate the significance of measurement methods.

3. RESULTS AND DISCUSSION

PR measurements were performed in both UTT and extensometer devices with the same parameters according to ASTM-E132. The changes in width and length in specific elongation values were measured, and PR values were calculated.

3.1 Universal Tensile Test (UTT) Results

Poisson's ratio measurements were made in the UTT device for plain (RL) and zigzag structured (4x6, 4x6-G, 4x8, 4x8-G) knitted fabrics are presented in Figure 7. It is seen that as the % elongation increases in the samples, the PR increases. Plain knitted (RL) fabric has the highest, 4x8 zigzag structure fabric with double-covered spandex yarn (4x8-G) has the lowest Poisson's ratio values.

Two-factor variance analysis was applied for pattern type (RL, 4x6, 4x6-G, 4x8, 4x8-G) and % elongation (1%, 2%,…. 20%) values using the SPSS 22 program for the results of Poisson's ratio measurements made on the UTT device. According to variance analysis, the knitting structure (p:0) and % elongation (p:0) values were statistically effective on the Poisson's ratio of the fabrics. SNK analysis results for knitting structure and % elongation values are presented in Table 2.

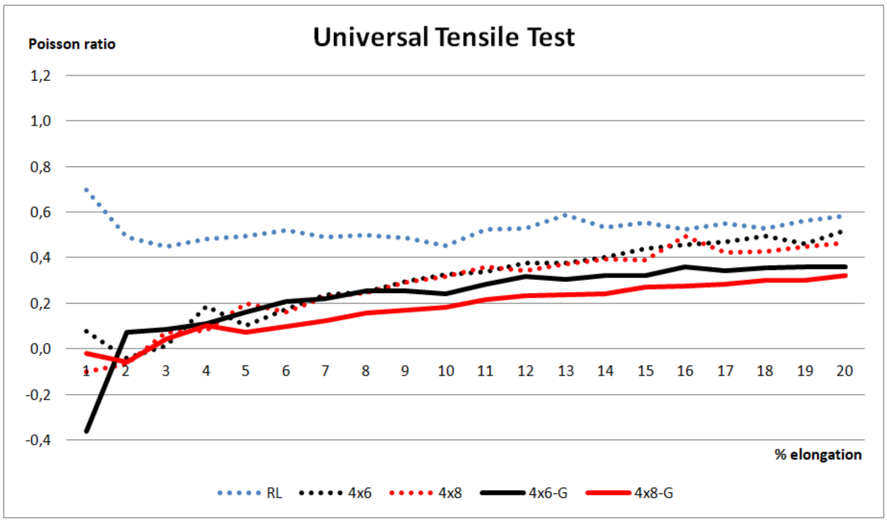


Figure 7. Graph of the Poisson’s ratio obtained in the UTT

Table 2. SNK ranking at 5% significance level after at ANOVA model. (UTT)

Knitting Structure	Poisson's Ratio (%)	
4x8 - G	0.18 (a)	
4x6 - G	0.23 (a)	
4x8	0.28 (a)	
4x6	0.30 (a)	
RL		0,53 (b)

Elongation (%)	Poisson's Ratio (%)			
%1	-0.04 (a)			
%2	0.02 (a)	0.02 (b)		
%3	0.08 (a)	0.08 (b)	0.08 (c)	
%4	0.15 (a)	0.15 (b)	0.15 (c)	0.15 (d)
%5	0.16 (a)	0.16 (b)	0.16 (c)	0.16 (d)
%6	0.19 (a)	0.19 (b)	0.19 (c)	0.19 (d)
%7	0.23 (a)	0.23 (b)	0.23 (c)	0.23 (d)
%8		0.25 (b)	0.25 (c)	0.25 (d)
%9		0.27 (b)	0.27 (c)	0.27 (d)
%10		0.28 (b)	0.28 (c)	0.28 (d)
%11		0.32 (b)	0.32 (c)	0.32 (d)
%12			0.33 (c)	0.33 (d)
%13			0.34 (c)	0.34 (d)
%14			0.35 (c)	0.35 (d)
%15			0.37 (c)	0.37 (d)
%17			0.39 (c)	0.39 (d)
%18			0.40 (c)	0.40 (d)
%19			0.41 (c)	0.41 (d)
%16			0.41 (c)	0,.41 (d)
%20				0.43 (d)

Note that lower case a,b,c,d indicate a significant difference between the values. "a" shows the lowest value, and "d" shows the highest value.

The SNK test results show that zigzag pattern fabrics (4x6, 4x6-G, 4x8, 4x8G) affect the PR values in a similar way. The PR of the zigzag patterned fabrics was lower than the RL. 4x8 and 4x8-G samples have a lower PR than the 4x6 and 4x6-G. The zigzag angle with the horizontal axis for 4x8 and 4x8-G is lower than 4x6 and 4x6-G fabrics. In other words, when the angle with the horizontal axis decreases, PR decreases. This result is consistent with Liu [29] and Boakye [30].

4x8-G and 4x6-G coded samples containing spandex yarn have a lower PR than the 4x8 and 4x6. This result can be explained by the increase of the wales per cm values by the usage of spandex yarn.

3.2 Extensometer Measurement Results

Poisson's ratio measurement results of RL, zigzag (4x6, 4x6-G, 4x8, 4x8-G) fabrics with extensometer are presented in Figure 8. Similar to the UTT device results, it has been determined that while RL fabrics have the highest values, 4x8-G coded fabrics (with spandex yarn) have the lowest PR values.

Two-factor variance analysis was applied for the pattern type (RL, 4x6, 4x6-G, 4x8, 4x8-G) and % elongation (1%, 2%,…. 20%) values using the SPSS 22 program for the results of Poisson's ratio measurements made with the extensometer device. According to this, knitting structure and % elongation were statistically effective in the fabrics' PR. The SNK analysis results for knitting structure and % elongation values are presented in Table 3.

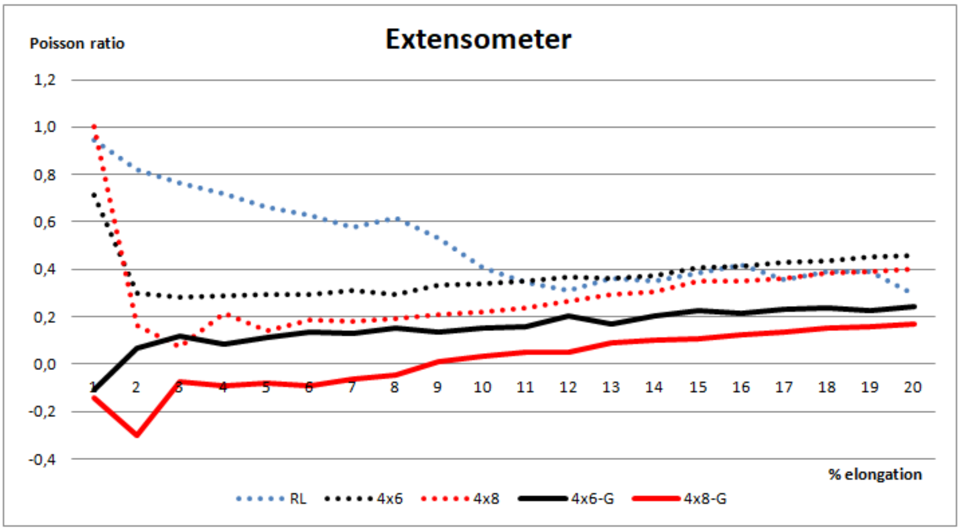


Figure 8. Graph of the Poisson's ratio obtained from the extensometer device

Table 3. SNK ranking at 5% significance level after at ANOVA model. (Extensometer)

Knitting Structure	Poisson's Ratio (%)				
4x8 - G	0.01 (a)				
4x6 - G		0.15 (b)			
4x8			0.30 (c)		
4x6				0.37 (d)	
RL					0.51 (e)

Elongation (%)	Poisson's Ratio (%)	
%2	0.12 (a)	
%3	0.15 (a)	
%5	0.16 (a)	
%4	0.17 (a)	
%6	0.17 (a)	
%7	0.17 (a)	
%8	0.18 (a)	
%9	0.20 (a)	
%10	0.20 (a)	
%11	0.21 (a)	
%12	0.23 (a)	0.23 (b)
%13	0.24 (a)	0.24 (b)
%14	0.25 (a)	0.25 (b)
%15	0.28 (a)	0.28 (b)
%16	0.29 (a)	0.29 (b)
%17	0.29 (a)	0.29 (b)
%18	0.31 (a)	0.31 (b)
%19	0.31 (a)	0.31 (b)
%20	0.31 (a)	0.31 (b)
%1		0.41 (b)

Note that lower case a,b,c,d,e indicate a significant difference between the values. "a" shows the lowest value, and "e" shows the highest value.

The results of the variance analysis reveal that PR of the zigzag patterned samples was lower than the RL pattern. 4x8 and 4x8-G coded samples have a lower PR than the 4x6 and 4x6-G. 4x8-G and 4x6-G coded samples containing spandex yarn have lower PR than the 4x8 and 4x6 fabrics without spandex yarn.

3.3 Comparison of UTT and Extensometer Test Device Measurement Results

The results of the PR measurements of RL and zigzag knitted fabrics with UTT and extensometer devices are parallel to each other. The PR values of the knitted fabrics were ordered from low to high is 4x8-G, 4x6-G, 4x8, 4x6, RL for both measurement techniques. In addition to this, as the % elongation increases, PR values also increase for both measurement techniques, except % 1 elongation of the extensometer device measurement result. PR measurement is a measurement technique that needs to be done very precisely. The changes in % elongation values are measured by counting pixels on the computer and calculating the distance. Relatively small changes in positioning the samples onto the device can affect the results. Therefore, some irregular results can be obtained especially at low % elongation values.

Comparing PR test results of RL and zigzag knitted fabrics with UTT and extensometer device was performed by applying a 3-factor variance analysis using the SPSS 22 program. When the variance analysis results were examined, it's seen that there were no statistically significant difference (p:0.101) between measurement methods. This result shows that the both methods can be used as alternatives to each other (Table 4).

3.4 Poisson's Ratio Measurement Results of Foldable Fabrics

The fabric sample is placed vertically between the jaws in the UTT device. Foldable fabrics have a tendency to curl downwards when positioned vertically. The gravity force acts as a pretension and deforms the fabrics' relaxed position while the fabric structures are susceptible to a small amount of force. In other words, the foldable fabric elongates, and its original form changes. While marks on the fabrics with zigzag patterns could be seen clearly (Figure 9.a and 9.b), marks on the fabrics with foldable structure (Foldable and Foldable-G) could not be seen because of the buckling (Figure 9.c and 9.d). Since some of the markings on the fabric cannot be seen due to buckling, PR cannot be measured for the Foldable and Foldable-G fabrics with UTT.

Table 4. SNK ranking at 5% significance level after at ANOVA model (comparison UTT and extensometer).

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	18,486^{a}	199	0,093	2,372	0,000
Interception	35,123	1	35,123	896,916	0,000
Method	*0,106*	*1*	*0,106*	*2,697*	*0,101*
Fabric Pattern	7,206	4	1,802	46,004	0,000
% Elongation	1,863	19	0,098	2,503	0,001
Method * Fabric Pattern	1,000	4	0,250	6,386	0,000
Method * % Elongation	1,774	19	0,093	2,384	0,001
Fabric Pattern* % Elongation	2,761	76	0,036	0,928	0,646
Method * Fabric Pattern * % Elongation	1,454	76	0,019	0,488	1,000
Error	12,531	320	0,039		
Total	63,593	520			
Corrected Total	31,017	519			

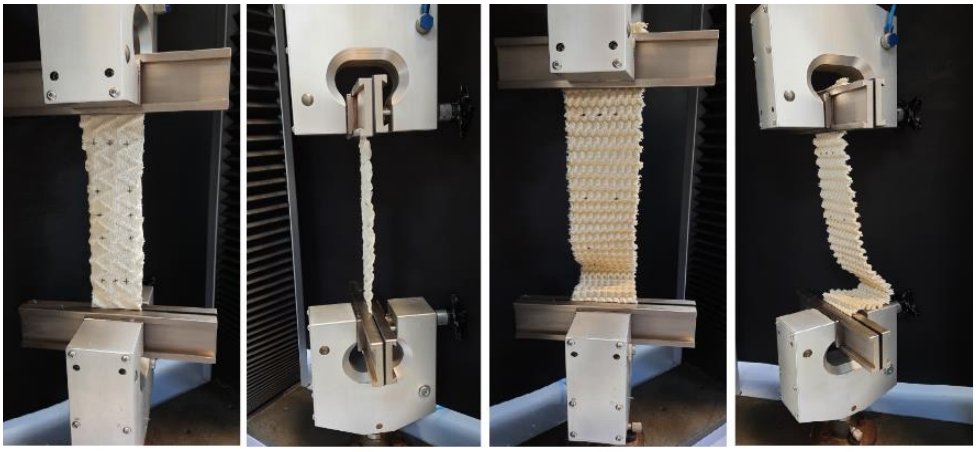

(a) (b) (c) (d)

Figure 9. Zigzag pattern fabrics' (a) front view, (b) side view and foldable fabrics' (c) front view, (d) side view at UTT device

PR measurements of the foldable fabrics were measured with SDL ATLAS M031 Fryma Fabric Extensometer (Figure 4.b). The materials are positioned horizontally in the extensometer device. The results are presented in Figure 10. When the measurement results are examined, it is seen that the PR of foldable fabrics is below "0," and Foldable-G is negative after 5% elongation. This result shows that Foldable and Foldable-G have auxetic properties, unlike RL and zigzag fabrics. This result can be explained by the high thickness of the foldable fabrics. As it is also seen from Table 1, while RL and zigzag fabrics have a thickness of 1,59-3,1 mm, foldable fabrics have a thickness of 9,2- 9,8 mm. Because of their unique pattern, these fabrics fold on themselves and generate a 3D structure. By extending the fabric, these folds flatten, and fabrics' course-wise dimensions increase contrary to conventional fabric structures.

A two-factor variance analysis was applied for pattern type and % elongation values for the results of PR measurements made on the extensometer device for all the fabrics examined within the scope of the study. SNK analysis results are presented in Table 5.

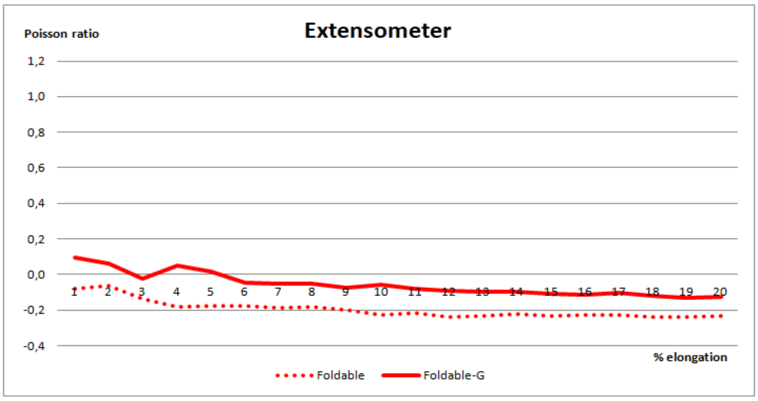


Figure 10. Poisson's ratio of foldable fabrics obtained from the extensometer device

Table 5. SNK ranking at 5% significance level after at ANOVA model.

Knitting Structure	**Poisson's Ratio (%)**						
Fold.	-0.20 (a)						
Fold-G		-0.06 (b)					
4x8-G			0.01 (c)				
4x6-G				0.15(d)			
4x8					0.30 (e)		
4x6						0.37 (f)	
RL							0.51 (g)

Note that lower case a,b,c,d,e,f,g indicate a significant difference between the values. "a" shows the lowest value, and "g" shows the highest value.

It is seen that Foldable fabrics without spandex yarn (Fold) have a lower PR compared to foldable fabrics containing spandex yarn (Foldable-G). This is the opposite of the zigzag fabrics due to the wales per cm values. While zigzag fabrics with spandex yarn (4x6-G and 4x8-G) have higher wales/cm than zigzag fabrics without spandex yarn (4x6 and 4x8), foldable fabric with spandex yarn (Fold-G) has lower wales/cm than foldable fabrics without spandex yarn (Fold).

4. CONCLUSION

The main objective of this study was to investigate the usability of the extensometer devices as an alternative to the UTT device in PR measurement of knitted fabrics. Poisson's ratio of the fabrics were measured with UTT (Shimadzu AG-X HS) and extensometer (SDL ATLAS-Fryma Dual Extensiometer) devices comparatively by using the same measurement parameters according to ASTM E132 "Standard Test Method for Poisson's Ratio at Room Temperature."

RL and zigzag pattern knitted fabrics' PR were measured with both UTT and extensometer devices. Variance analysis results of UTT and extensometer devices reveal that there were no statistically significant differences between the measurement methods. This result shows that these methods can be used as alternatives to each other. The Extensometer device is a practical and cost-friendly device that is widely used in the sector compared to UTT devices.

It was observed that the fabrics with zigzag and foldable pattern structure have lower PR than RL knitted fabrics. As the force is applied to the RL knitted fabric in the wale direction, the shape of the loops changes. While the loop height increases, the loop width decreases. The decrease of the loop's width makes the RL fabric narrow. This behavior is also common for most conventional knitted fabric structures. Zigzag pattern fabrics have R and L loops in diagonal positions. The position of R and L loops conduce to increase the fabrics wales per cm values and make the fabric thicker. Essentially, a foldable fabric pattern is also a type of zigzag pattern. The diagonal position of the R and L loops make the foldable fabrics much thicker and conduce the fabrics to fold on themselves and generate a 3D structure. When the force is applied to the fabric, firstly fabrics get smooth and lose their 3D shape. While RL fabrics have a thickness value of 1.59 mm, zigzag pattern fabrics have 2.8-3.1 mm, and foldable pattern fabrics have 9.2-9.8 mm thickness values. Therefore, while the foldable pattern fabrics have the minimum PR values, zigzag pattern fabrics have lover PR values than RL fabrics.

4x8 zigzag pattern knitted fabrics have lower PR than 4x6 zigzag pattern fabrics. For the zigzag samples, when the angle with the horizontal axis decreases, PR decreases. This result is consistent with the study of Liu [29] and Boakye [30]. Zigzag pattern fabrics containing spandex yarn (4x6-G, 4x8-G) have lower PR than the fabrics without spandex yarn (4x6, 4x8). This result can be explained by the increase of the wales per cm values by using spandex yarn.

Foldable fabrics have a tendency to curl downwards when positioned vertically in the UTT device. Since some of the markings on the fabric cannot be seen due to buckling, PR cannot be measured for the Fold and Fold-G fabrics with UTT. PR test results of foldable fabrics measured by extensometer device reveal that foldable fabrics without spandex yarn (Fold) have a lower PR compared to containing spandex yarn (Foldable-G). This result is the opposite of the zigzag fabrics due to the wales per cm values. While zigzag fabrics with spandex yarn (4x6-G and 4x8-G) have higher wales/cm than zigzag fabrics without spandex yarn (4x6 and 4x8), foldable fabric with spandex yarn (Fold-G) has lower wales/cm than foldable fabrics without spandex yarn (Fold).

Consequently, it is observed that the extensometer device can be used for PR measurement as an alternative to the UTT device and made possible to measure the PR of fabrics that have a tendency to curl downwards when positioned vertically.

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