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# EXPERIMENTAL PROCEDURE FOR ESTIMATION OF POISSON FUNCTION OF HIPERELASTIC ANISOTROPIC MATERIAL

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**Abstract.** *The Poisson function is important because it describes the contraction/expansion behavior of a material in a direction perpendicular to the applied stress in finite strains. Due to disagreements in literature related to auxetic behavior in biological tissues and because of the complexity associated with the estimation of Poisson's function, there is the necessity of more reliable experimental data in this field. Testing of biomaterials pose the ultimate challenge in mechanical testing due to the complexity associated with fixing soft tissues and achieving the boundary condition reliably. Besides, estimate Poisson's function is a non-trivial task. Accordingly, the purpose of this paper is to propose an experimental procedure to estimate Poisson's function of a fibrous soft tissue. This procedure was performed on a composite of silicone rubber reinforced with cotton fabric because fibrous soft tissues are commonly studied in the context of hyperelastic anisotropic materials. Tensile tests were performed following three different test procedures. Two- and three-dimensional Digital image correlation method were used to access the displacement full-fields during the tests. The results showed that Poisson function values were bigger than the classic value of Poisson ratio for rubbers, what could be influenced by the cotton fabric. The inclusion of a PTFE support did not produce a substantial improvement. For specimens with strongest fibers positioned at 0°, the use of DIC 3D method presents the lowest standard deviations despite higher reprojection errors, while for the ones with strongest fibers angled 90°, the others procedures seem to produce more repeatable results.*

**Keywords:** *Poisson's function, digital image correlation, hyperelastic materials, composite materials*

## 1. INTRODUCTION

The Poisson's ratio is a fundamental material property that describes the contraction/expansion behavior of a material in a direction perpendicular to an applied stress (Gatt *et al.*, 2015). It is a constant originally defined for small strains. Taking into account large deformations, the concept of a Poisson function is commonly used for hyperelastic materials. It is known that the Poisson function is not constant considering these materials, but a function of stretch, i.e. depends on the strain measure used (Gorelik *et al.*, 1967; Starkova and Aniskevich, 2010). This fact is often related to changes in their microstructure. Unlike stiffness, the Poisson's function is a two-dimensional property and in anisotropic materials, its sign and magnitude may depend not only on the direction of stretching, but also on the orthogonal direction being measured (Gatt *et al.*, 2015). There is a complexity associated with measuring this orthogonal stretching.

Despite being a positive value to most of the materials known, negative Poisson's ratio has been found in a wide variety of materials including metals, foams, silicates and biological materials such as arteries, skin, tendons (Derrouiche *et al.*, 2020). A negative Poisson's ratio means the property of getting wider rather than thinner when stretched. The materials that present this feature are called auxetic materials (Volokh, 2017). This behavior has been reported in some biological soft tissue models, as by Horgan and Murphy (2017) and Murphy and Biwa (2017). However, Fereidoonzhad *et al.* (2020) have assumed that auxetic behavior in these tissues is unphysical. Due to this disagreement and the complexity associated with the estimation of Poisson function, there is the necessity of more reliable experimental data in this field.

Accordingly, the purpose of this paper is to propose an experimental procedure to estimate Poisson's function of a hyperelastic anisotropic material. The mechanical behavior of fibrous soft tissues is commonly studied in same theory of hyperelastic anisotropic materials. Tensile tests were performed on a silicone rubber reinforced with a cotton fabric with its strongest fibers positioned at 0° and 90° in relation to applied force. Digital image correlation method was used to access the displacement full-fields during the tests.

## 2. MATERIAL AND METHODS

### 2.1 Sample fabrication

The material studied in this paper was a silicone rubber from Moldflex Modelagem (São Paulo, Brasil) reinforced with a cotton fabric from Needs (São Paulo, Brasil). Silicone rubber was chosen because fibrous soft tissues are usually described in theory of anisotropic hyperelastic materials. The cotton fabric used in this work is made of two mutually perpendicular families of fibers. Due to fabric's structure, it is more resistant in the direction of one family of fibers than in the direction of the other. The samples followed the International Standard ISO 37 (2017), with shape of dumb-bell test pieces and dimensions as follows: test length of 25 mm, overall length of 115 mm, width of ends of 25 mm, length of narrow portion of 33 mm, width of narrow portion of 6.2 mm, outside transition radius of 14 mm and inside transition radius of 25 mm.

Samples with the more resistant direction of fibers in the longitudinal direction ( $0^\circ$ ) and in the perpendicular direction ( $90^\circ$ ) were fabricated with the purpose of studying the influence of the fibers direction. The samples were fabricated in a glass plate with three layers of a release wax. The silicone rubber was mixed with a catalyst in the proportion of 3% of silicone's mass. After 48 hours, the composite was ready to be demolded and tested. The samples were fabricated in a rectangular shape using a paint roller to spread the silicone rubber in alternated layers of fabric. Moreover, a spatula was used to remove air between layers to prevent defects in the composite structure. Each specimen was made with four layers of fabric and five layers of silicone rubber. The specimens were cut in the standard dimensions with a specific scissor that can be used to cut fabrics. No damage was observed on the cropped specimens.

The last step of the fabrication was to coat the samples with a spray of black paint to produce a random speckle pattern. This pattern is fundamental in the method that was used to access the displacement fields, i.e. the Digital Image Correlation (DIC) method. DIC is an optical numerical method that has the capability of measuring the displacement and deformation full-fields of a specimen being tested using images captured by a high-resolution camera. It presents some important advantages in experimental mechanics regarding the measurement domain of displacements and deformations. DIC can provide global measures, not only punctual (like strain gauges, for example), and do not need to be in contact with the specimen being measured. These features are especially important to access Poisson's function.

### 2.2 Experimental set up

The tensile specimens were tested under quasi static loading condition at room temperature ( $23^\circ\text{C}$ ) and using a controlled crosshead velocity of 8 mm/min. All specimens were attached to a tensile testing machine using grips with rough sides to prevent the composite from slipping. A high resolution camera (manufactured by Basler Ace model A1300-200um) coupled with macro zoom lens (manufactured by Computar model MLH-10X) was used in the experimental arrangement to capture images of the tensile specimens during test. The image acquisition was configured to take instantaneous pictures every 2 seconds. A 50 kgf load cell was used to measure the applied load simultaneously and light sources were implemented to highlight the contrast of the speckle pattern and homogenize the light on the surface of tensile specimens, reducing the effects of external lights on displacement measurement. Then, all images were post-processed in a homemade correlation program to access the displacement full-fields using DIC method.

Three different test procedures were used in this work. The experimental arrangement for first and most simple procedure is shown in Figure 1. In this procedure, one camera was positioned in front, at a constant distance and perpendicular to the plane surface of the specimen that was free to deform in any direction during the test. The difference between the first test procedure and the second is depicted in Figure 2. In the second test procedure, a plate of polytetrafluoroethylene (PTFE) was attached to the tensile machine as a support to avoid undesirable out-of-plane deformations in the specimen, as bending. PTFE was chosen due to its low coefficient of friction. Therefore, the PTFE support did not influence on the normal progress of tests. For both first and second procedures, two-dimensional DIC algorithm was used to obtain the displacement full-fields, with an average reprojection error of 0.02 pixel. Calibration was performed using the standard width of narrow portion of tensile specimens, giving a scale factor of 86.5 pixel/mm.

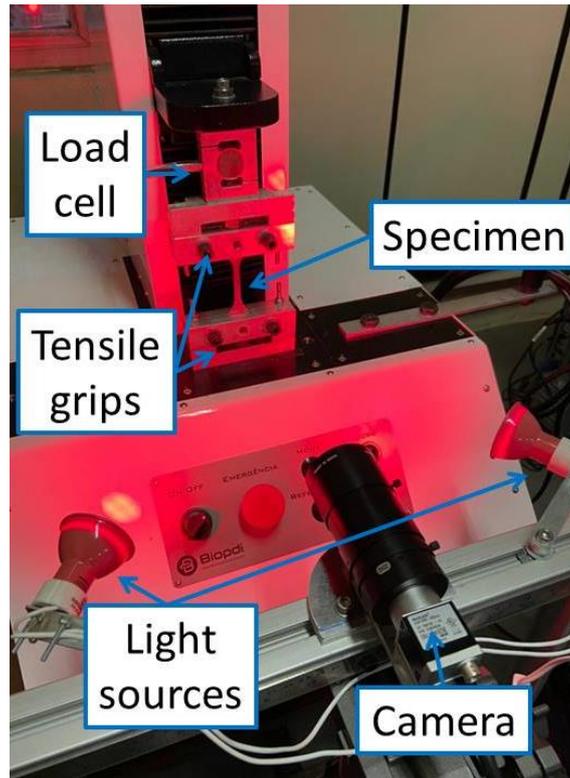


Figure 1. Experimental set up for first test procedure.

The third test procedure used in this work is illustrated in Figure 3. In this procedure, the DIC 3D method was used to measure three-dimensional displacement full-fields. To achieve this goal, the images were acquired by two cameras positioned at different angles and at a constant distance in front of the specimen. Since stereo vision must be calibrated using standardized patterns, in this work an 8x7 1mm checkerboard calibration pattern was used to obtain the camera's extrinsic and intrinsic parameters and lens distortion coefficients. See (Pan *et al.*, 2012) for details. Here, the mean reprojection error of 0.2 pixel was encountered. For each test procedure, three specimens were tested.

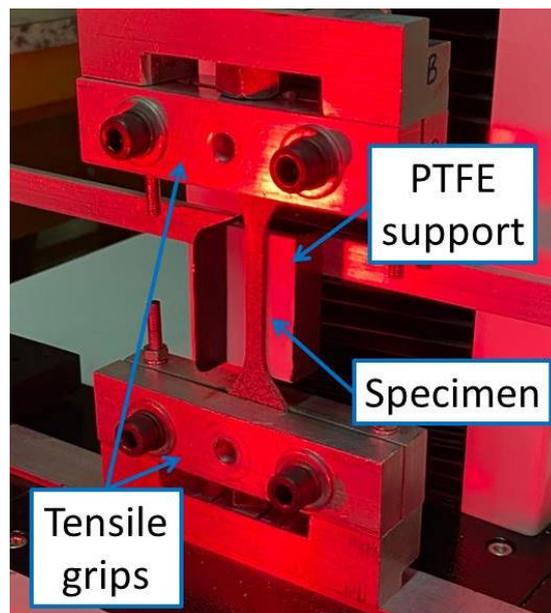


Figure 2. PTFE support for second test procedure.

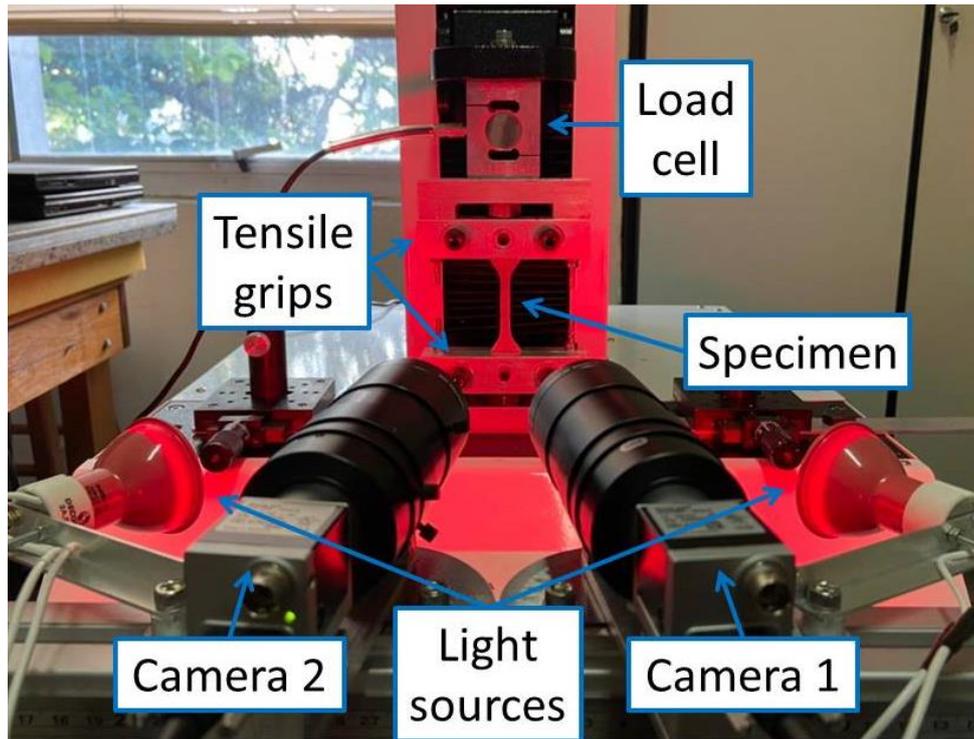


Figure 3. Experimental set up for third test procedure.

Poisson function can be estimated from the displacement fields obtained by DIC using logarithmic (Hencky) strains, given by

$$\varepsilon_L^{ln} = \ln(\lambda_L), \quad (1)$$

where  $L$  represents the longitudinal direction and  $\lambda_L$  is a principal stretch ratio, that is defined as

$$\lambda_L = \frac{l}{l_0}. \quad (2)$$

In which  $l_0$  is the initial length of the specimen and  $l$  is the length after tensile was applied. Therefore, the Poisson function can be defined as

$$(Poisson\ function)_{ij} = -\frac{\varepsilon_T^{ln}}{\varepsilon_L^{ln}}, \quad (3)$$

where T represents the transversal direction. This definition was used by Kugler et al. (1990), Pritchard and Terentjev (2013), Skacel and Bursa (2016) and Starkova and Aniskevich (2010).

### 3. RESULTS AND DISCUSSIONS

The results are presented by the mean curves of the three specimens tested under each test procedure with their standard deviation. Figure 4 shows the curves of tensile stress versus the principal stretch in longitudinal direction. It can be observed that specimens with strongest fabric's direction positioned at  $0^\circ$ , i.e. at longitudinal direction, are stiffer than the ones with strongest fabric's direction positioned at  $90^\circ$ , i.e. at perpendicular direction, as expected. It can also be seen that the methods converge for a very similar behavior. The third procedure (with DIC 3D method) presents the lowest standard deviation for specimens with strongest fabric's direction positioned at  $0^\circ$ . While it shows the highest values of standard deviation for specimens with strongest fabric's direction positioned at  $90^\circ$ . It was observed that out-of-plane movements occurred on specimens with strongest fabric's direction at  $0^\circ$ . Figure 5 shows the curves of tensile stress versus the principal stretch in transversal direction. Different that in longitudinal direction, in transversal, there are a contraction of the specimens. It can be seen once more that specimens with strongest fabric's direction positioned at  $0^\circ$  are stiffer than the ones with strongest fabric's direction positioned at  $90^\circ$ .

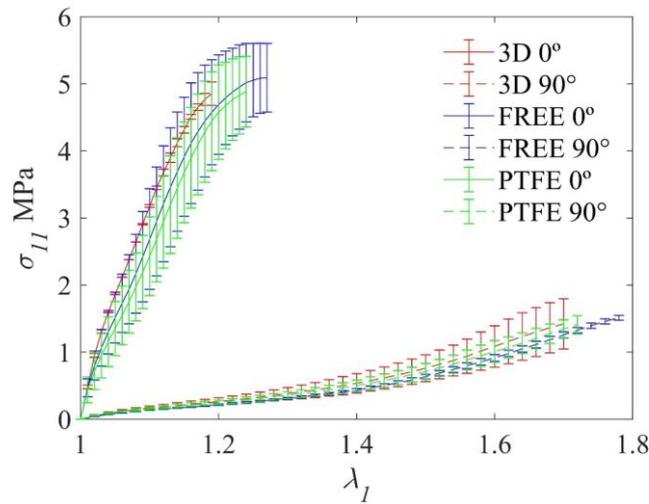


Figure 4. The tensile stress versus the stretch in longitudinal direction. The first test procedure is represented by FREE, the second by PTFE and the third by 3D.

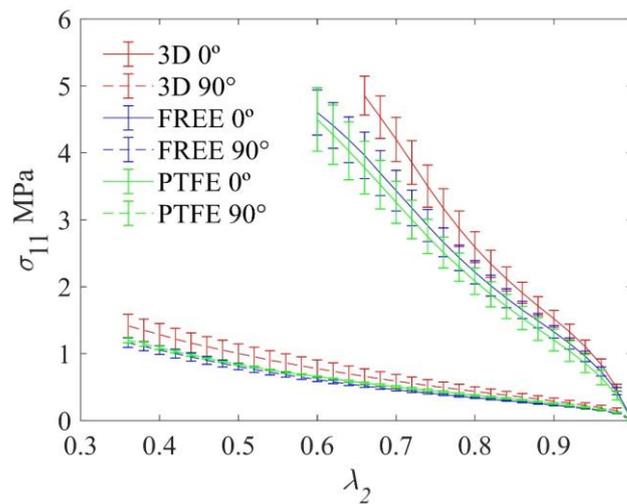


Figure 5. The tensile stress versus the stretch in transversal direction. The first test procedure is represented by FREE, the second by PTFE and the third by 3D.

Figure 6 shows the Poisson function estimated using logarithmic (Hencky) strains versus the tensile stress. The Poisson function values are greater than the common value for rubbers that is 0.5. This is probably related to the cotton fabric. It can be observed that the standard deviations of specimens with strongest fabric's direction positioned at 0° are much bigger than the ones of specimens with this fabric's direction angled at 90°. Despite this, it can be seen that the Poisson function seems to present higher values for specimens with strongest fabric's direction positioned at 0°. Besides, the third test procedure (using DIC 3D method) seems to be better to estimate Poisson function of specimens with strongest fabric's direction at 0° while the first and the second (using PTFE support) procedures shows lower deviations for specimens with this fabric's direction angled 90°.

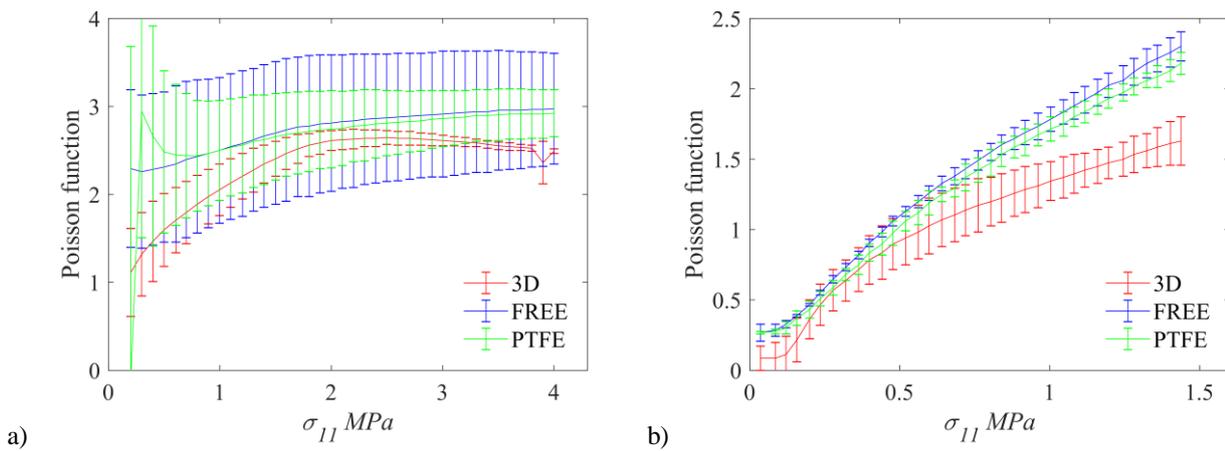


Figure 6. The Poisson function estimated with logarithmic (Hencky) strains versus the tensile stress. The first test procedure is represented by FREE, the second by PTFE and the third by 3D. a) 0° b) 90°.

In Figure 7, the numerator and the denominator that composes Poisson function estimated with logarithmic (Hencky) strains were plotted. Constant values of Poisson function are represented in this plot as a straight dashed line. It is expected that Poisson function varies in the beginning and then stabilizes, as can be seen in literature (Derrouiche *et al.*, 2020; Skacel and Bursa, 2016). This material behaves the opposite considering logarithmic (Hencky) strains. Therefore, it could be interesting to verify if this behavior maintains the same using a different strain model.

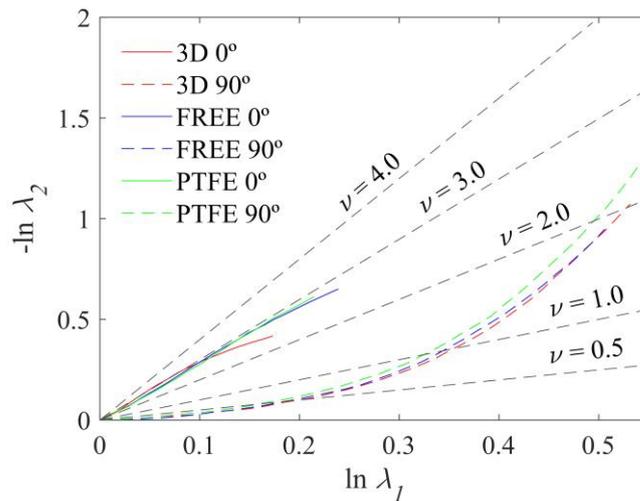


Figure 7. Logarithm (ln) of the stretches in transversal versus in longitudinal direction. The first test procedure is represented by FREE, the second by PTFE and the third by 3D. The black dashed lines represent the curves for Poisson constant values for comparison.

#### 4. CONCLUSIONS

In this paper, tensile tests on specimens of silicone reinforced with a cotton fabric were made to investigate the Poisson function. The samples were tested under two different fibers direction and three experimental procedures were tested. The results showed that the inclusion of a PTFE support did not produce a substantial improvement. For specimens with strongest fibers positioned at 0° (longitudinal), the use of DIC 3D method presents the lowest standard deviations despite higher reprojection errors, while for the ones with strongest fibers angled 90° (transversal), the others procedures seem to produce more repeatable results. In fact, the out-of-plane movements seen on specimens with strongest fibers positioned at 0° can produce substantial errors on two-dimensional DIC measurements. Poisson

function values were bigger than the classic value of Poisson ratio for rubbers, what could be influenced by the cotton fabric. Poisson function considering logarithmic (Hencky) strains varies with applied stress.

This is a preliminary work. The authors suggest continuing this investigation by studying the Poisson function of the cotton fabric and by using different models for the strains used to estimate the Poisson function of the composite.

## 5. ACKNOWLEDGEMENTS

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