A Constitutive Model For the Warp-Weft Coupled Non-linear Behavior of Knitted Textiles With Potential Use in Tissue Regenerative Implants

M.S. Yeoman
Continuum Blue Ltd., Forest Row, England

B.D. Reddy
Centre for Research in Computational and Applied Mechanics, University of Cape Town, Rondebosch, South Africa

H.C. Bowles
Finite Element Analysis Services (Pty.) Ltd., Parklands, South Africa

D. Bezuidenhout, P. Zilla, T. Franz
Cardiovascular Research Unit, Chris Barnard Department of Cardiothoracic Surgery, University of Cape Town, Observatory, South Africa

Abstract

Knitted textiles have been used in medical applications due to their high flexibility and low tendency to fray. Their mechanics has, however, received limited attention compared to woven fabrics used as technical textiles e.g. in aerospace and as composite reinforcements. A constitutive model for soft tissue using a strain energy function was extended, by including shear and increasing the number and order of coefficients, to represent the non-linear warp-weft coupled mechanics of coarse textile knits under uniaxial tension. The novel constitutive relationship with ten coefficients was implemented in a commercial finite element package. The model and its implementation were verified and validated for uniaxial tension and simple shear using single- and multi-element patch tests and data of physical uniaxial tensile tests of four different knitted fabrics, respectively. The numerically predicted stress-strain curves exhibited non-linear stiffening, characteristic for fabrics and confirmed experimentally for
the selected fabrics. Three of the ten model coefficients, \(a_1\), \(a_2\) and \(a_4\), greatly affected the non-linear stiffening. The Poisson’s effect of the fabric was mainly affected by \(a_1\), \(a_4\), \(a_5\), \(a_8\) and \(a_9\). For three fabrics, the predicted mechanics correlated well with physical data, at least in one principal direction (warp or weft), and moderately in the other direction. The model exhibited limitations in approximating the linear elastic behavior of the fourth fabric. With proposals for addressing this limitation and to incorporate time-dependent changes in the fabric mechanics associated with tissue ingrowth, the constitutive model offers a tool for the design of tissue regenerative knit textile implants.

**Keywords:** Fabric, Finite element method, Material model, Tissue ingrowth, Medical implants

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1. **Introduction**

The study of fabric mechanics dates back to the work of Haas and Dietzius (1917) on the development of airship fabrics. However, the first real model for fabric forces was presented by Peirce (1937) who simplified the structure of a woven fabric as ideal rods. This work has led the way for theories on the geometrical and mechanical behavior of fabrics.

Much work has been done in forming mathematical relations for modeling the tensile deformation of fabrics. Kawabata et al. (1982) looked at a linearization method in two zones to describe the tensile behavior of fabrics. Predicted stress-strain relationships based on strain energy principles were presented by Hearle and Shanahan (1978) and more recently by King et al. (2005), solving two systems of equations (geometric and mechanical) with physical yarn properties. Grosberg and associates presented a function which displayed an initially high modulus (Grosberg and Kedia, 1966; Hearle et al., 1969). Alsawaf (1985) characterized the tensile behavior of fabrics into two straight segments, one with an initially low modulus where decrimping occurred and another with a higher modulus representing yarn extension which occurred after a critical point.
Polynomial functions have also been used to describe nonlinear stress-strain tensile behavior of fabrics (Sun, 1992). However, the use of high degree polynomials for function fitting has given rise to polynomial "wiggling" (Mathews, 1992), where a number of maxima and minima are observed. Due to this, alternate functions have been proposed, such as exponential and logarithmic functions. Hu and Newton (1993) established a number of exponential constitutive equations for woven fabrics under tension. These exponential expressions used one or two parameters to describe fabric behavior. The resulting solutions compared well with experimental data. However, only simple tensile tests were modeled, thus these models only represent a specific deformation state. They also use two separate sets of parameters for the warp and weft directions, and hence do not include coupling effects between the fabric warp and weft behavior. Since the early 1980s, advancement in this field has slowed due to the complex nature of the mathematical expressions needed to describe fabric behavior.

Bais-Singh and Goswami (1995, 1998) modeled the non-uniform deformation of spun-bound fabrics under uniaxial and biaxial tension. A bilinear relation similar to that proposed by Alsawaf (1985) was utilized and showed good comparisons with experimental data. Orthotropic linear elastic (Collier et al., 1991; Kim, 1991; Gan et al., 1991; Yu et al., 1993; Kang et al., 1994; Dong et al., 2000) and orthotropic hypoelastic material models (Badel et al., 2007, 2009) were employed to analyze drape tests and forming processes of textiles. Yu et al. (2005) proposed a constitutive model representing separately the contribution of fiber directional properties (Yu et al., 2002) and shear properties of the fabric. Numerical results correlated well with experimental data in some cases (Collier et al., 1991; Badel et al., 2007) while predictions varied by 10% in other cases (Kim, 1991). However, drape tests and fabric forming exhibit small strains and large deflection deformation which is not ideal for the large strain tensile deformation modes needed for knitted structures. Due to the complexity of the problem these models have taken specific deformation modes into consideration and have ignored others.

Nadler et al. (2006) presented a multiscale constitutive model combining the woven fabric as a continuum membrane at macroscale with a constitutive law for a pair of overlapping
yarns at microscale. A mesoscale approach was applied to model monofilament woven textiles (Carcelli, 2009; Carcelli et al., 2008), using the Ramberg-Osgood isotropic nonlinear elastic constitutive model (Ramberg and Osgood, 1943) for the fibers.

In this study, a new constitutive relation was proposed for knitted fabrics under uniaxial tensile behavior. The implementation in a commercial finite element (FE) package (Abaqus®) was demonstrated. Provision is made for the implementation of constitutive relations in Abaqus® through a user material subroutine (UMAT).

2. Materials and Methods

2.1. Structure of Knits

Knits are fabrics where yarns are inter-looped. Generally, knitted structures are not as stiff as their woven counterparts and are highly porous. Knitted fabrics encompass warp and weft knits. Warp knits, found in many medical implants, are complex compared to weft knits. Weft knit structures tend to be highly extendable but are structurally unstable, unless interlocking occurs. This interlocking tends to reduce extensibility but does help with elastic recovery. Advantages of knitted fabrics include their flexible, comfortable nature, and their tendency not to fray and unravel at the edges.

2.2. Formulation and Implementation of the Fabric Material Model

Large strain formulations are required when describing coarse knit fabrics under tension. The fabric constitutive model assumed that the material is highly elastic and compressible. Viscoelastic effects were neglected and incompressibility was not enforced. Due to the small thickness compared to the in-plane dimensions of the fabric, plane stress was implemented under consideration of tension and shear deformation.

Since the non-linear stress-strain characteristics of fabrics are similar to those of soft tissue, it was proposed to adopt a strain energy function for soft tissue proposed by Chuong and Fung (1983):

$$w(E) = C \frac{C}{2} \exp \left( a_1 E_{\theta \theta}^2 + a_2 E_{zz}^2 + 2a_4 E_{\theta \theta} E_{zz} \right).$$

(1)
By including shear and increasing the number and order of coefficients, the proposed fabric strain energy function in general two-dimensional form was obtained as

\[ w(E) = \frac{C}{2} \exp x \]

\[ x = a_1 E_{11}^2 + a_2 E_{22}^2 + a_3 (E_{12}^2 + E_{21}^2) + a_4 (E_{11} E_{22}) + a_5 E_{11}^3 + a_6 E_{22}^3 + a_7 (E_{12}^3 + E_{21}^3) + a_8 (E_{11}^3 E_{22}) + a_9 (E_{11} E_{22}^3) \]

where \( C \) and \( a_i \) (\( i = 1 \) to \( 9 \)) are fabric material coefficients.

An Abaqus® UMAT subroutine was utilized for implementation of the fabric constitutive model. The subroutine provided the material elasticity tensor, stress and solution dependent variable updates at each increment.

The discrete elasticity tensor is defined by

\[ K_{ijkl}^{\sigma \varepsilon} = \frac{\partial \Delta \sigma_{ij}}{\partial \Delta \varepsilon_{kl}}, \]

where \( \Delta \sigma \) and \( \Delta \varepsilon \) are the stress and strain increments. For large strain computations an appropriate conjugate stress-strain measure is needed. Since the proposed strain energy function is already defined in terms of Green strain \( E \) an appropriate conjugate pair is Green strain and the second Piola-Kirchhoff stress \( S \), which are defined as

\[ E = \frac{1}{2} (\nabla u + (\nabla u)^T + (\nabla u)^T \nabla u) \]

and

\[ S_{ij} = \frac{\partial w}{\partial E_{ij}}. \]

The stress was explicitly defined as Cauchy 'true' stress using the relationship between Cauchy stress and second Piola-Kirchhoff stress in the form

\[ \sigma_{ij} = J^{-1} F_{ik} S_{kl} F_{jl} . \]

Unlike for the Fung model, Eq. (1), incompressibility was not enforced. For the implementation in Abaqus®, the following special operators were used. **Orientation:** defined
the transverse fabric directions to ensure the material properties remained orientated as elements rotated and deformed; *Membrane element thickness:* A thickness of 100 µm was assigned to the membrane elements that were used to model the fabric; *Poisson’s ratios* \( \nu_{13} \) and \( \nu_{31} \): The use of membrane elements ensured a state of plane stress, thus deformation through the thickness was assumed to remain constrained.

2.3. Assessment of Constitutive Model Coefficients and Implementation in Abaqus

Single and multiple element patch tests were utilized to assess the influence of the material coefficients \( (C, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8 \text{ and } a_9) \) and the effects of element orientation and type under uniaxial tensile and simple shear deformation. The single element models used a four-noded bilinear membrane element with boundary and load conditions describing the two modes of deformation, as illustrated in Fig. 1(a) and (b). Arbitrary fabric coefficients were employed and varied slightly to observe their influence on stress and strain behavior. The effect of element type and orientation was assessed, in tension and shear, with a uniform mesh with consistently ordered four-noded membrane elements and a non-uniform mesh with three and four-noded membrane elements, Fig. 1(c) and (d).

2.4. Validation of the Fabric Constitutive Equation and Implementation

Four random fabrics were chosen to assess the ability of the constitutive model to simulate the physical fabric mechanics: 1) basic warp knit, 2) warp knit with Lycra\textsuperscript{R} support, 3) coarse warp knit and 4) monofilament warp knit. Figure 2 provides scanning electron micrographs of the fabrics. Uniaxial tensile tests were performed on samples with dimensions 60 × 20 mm at 37°C (Instron\textsuperscript{R} 5544, Instron Corp., Norwood, MA). The loading protocol comprised: 1) Pre-load to 1% nominal strain at a strain rate of 50 mm/min to reduce material inconsistencies, and 2) Extension to 50% nominal strain at a strain rate of 200 mm/min, the strain rate stipulated by medical implant authorities (AAMI, 1994; ISO, 1998). Due to difficulties in monitoring lateral strain effects during the Instron\textsuperscript{R} tests, caused by curling effects at the sample edges, fabric samples were strained on a flat bed at 37°C in steps of 10, 20 and 30%. A 5 × 5 mm grid was marked on each sample to visualize localized strain.
effects. Strengthening stitches were sewn at both ends of the samples to minimize localized stress concentrations. Using digital images recorded during the tests, the longitudinal and transverse strain was determined from a single grid cell located in the center of the sample.

The experimental data was utilized in a genetic algorithm (Yeoman et al., 2009) to obtain the model coefficients $C$, $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, $a_6$, $a_7$, $a_8$ and $a_9$ which best described the mutually orthogonal tensile behavior of the fabrics. A FE model simulating the physical uniaxial tensile tests was used to obtain the stress-strain curves for a fabric with a particular set of material coefficients. The quarter-symmetric model, see Fig. 3, utilized a mesh of four-noded membrane elements. The boundary conditions were selected such that edge AB was free to move horizontally but constrained vertically, while edges AD and DC were free to move vertically but constrained horizontally. Displacement at 200 mm/min was applied to edge DC as loading using a quasi-static analysis. The loaded boundary DC and the edge BC were expected to have a greater variation in stress and deformation. Hence the element mesh was refined toward these edges.

The mesh sensitivity was assessed by increasing and biasing the element density toward edges BC and DC and center point A until the stress, strain and displacement fields became consistent.

3. Results

3.1. Verification of Constitutive Relationships and Effect of Fabric Material Coefficients

3.1.1. Single Element Models

Figure 4 displays the stress-strain curves and the normalized stress, obtained from dividing the stress values obtained at 20% tensile strain and 10% shear strain by the stress values achieved with that of the model with $C = 10000$ and $a_i = 10$. The numerically predicted stress-strain curves (Fig. 4a) exhibit a nonlinear stiffening effect characteristic for fabrics. Defining the subscripts $i$ and $j$ to denote the direction of uniaxial tension and the transverse direction, respectively, the following was observed. Figure 4 displays the stress-strain curves and the normalized stress, obtained from dividing the stress values obtained
at 20% tensile strain and 10% shear strain by the stress values achieved with that of the model with \( C = 10000 \) and \( a_i = 10 \). The numerically predicted stress-strain curves (Fig. 4a) exhibit a nonlinear stiffening effect characteristic for fabrics. Defining the subscripts \( i \) and \( j \) to denote the direction of uniaxial tension and the transverse direction, respectively, the following was observed (Note: The results in Fig. 4 are for \( i = 2 \) being the direction of uniaxial tension). As expected, the magnitude of stress increased proportionately with \( C \). The nonlinear stiffening effect: greatly increased with increasing coefficients that affect terms containing \( E_{ii}^2 \), i.e. \( a_1 \) and \( a_2 \); moderately increased with increasing coefficients that affect terms \( E_{ii}^3 \), i.e. \( a_6 \); slightly increased with increasing coefficients that affect \( E_{jj}^3 E_{ii} \), i.e. \( a_8 \); greatly decreased with increasing coefficients affecting \( E_{ii} E_{jj} \), i.e. \( a_4 \); slightly decreased with increasing coefficients that affect \( E_{jj}^3 \) and \( E_{jj}^3 E_{ii} \), i.e. \( a_5 \) and \( a_9 \); and was not affected by changing coefficients that affect \( E_{ij} \), i.e. \( a_3 \) and \( a_7 \). The effect of changing \( a_1 \) through \( a_9 \) depended on the power of the strain terms to which they contribute. Those that affect lower order terms had a larger influence, as expected.

Further information was gained from the normalized stress and the associated transverse strain (Fig. 4b). The magnitude of axial and transverse stress was proportional to \( C \); however, transverse strain was not affected by \( C \). The transverse strain, or Poisson’s effect: increased with increasing coefficients that affect product terms \( E_{jj} E_{ii} \) and \( E_{jj}^3 E_{ii}^3 \), i.e. \( a_4 \) and \( a_9 \); decreased with increasing coefficients that affect \( E_{jj}^2, E_{jj}^3 \) and \( E_{jj}^3 E_{ii} \), i.e. \( a_1, a_5 \) and \( a_8 \); and was not affected by \( a_2, a_3, a_6 \) and \( a_7 \). The axial and transverse stress: both increased with increasing coefficients that \( a_2 \) and \( a_6 \) that affect terms \( E_{ii}^2 \) and \( E_{ii}^3 \), with axial stress being dominant; both decreased with increasing \( a_4, a_5, a_8 \) and \( a_9 \), with a predominant change in transverse stress for the latter two; and increased and decreased, respectively, with increasing coefficients that affect \( E_{jj}^2 \), i.e. \( a_1 \).

Negative coefficients \( a_i \) typically reduced transverse strain. A negative \( a_4 \) produced a negative normalized transverse strain, indicating positive strains in this direction. Negative \( a_2 \) and \( a_6 \) reduced the stress values but did not affect the transverse strain. Negative \( a_4 \) and \( a_9 \) increased the axial stress while reducing the transverse stress. Negative \( a_5 \) did not change the axial stress but reduced the transverse stress. Negative \( a_2 \) and \( a_6 \) caused compressive
axial stress whilst in tension, which is unrealistic. Negative $a_8$ reduced both the axial and transverse stress values considerably. Negative $a_7$ did not affect the stress and transverse strain. (Note: the FE models did not converge upon a solution for negative $a_1$ and $a_3$.)

Figure 4(c) shows typical curves of shear stress versus shear angle obtained from the simple shear model. Although not clearly observed, the shear stress-strain relation became slightly curved by increasing coefficients $a_3$ and $a_7$.

### 3.1.2. Multi-element Fabric Meshes

Table 1 summarizes the results of the comparative tests with the uniform and non-uniform multi-element models and the single element model for uniaxial tensile and simple shear. Figure 5 illustrates the corresponding stress fields of the shear test models. No differences were observed between the two multi element models, and the single element model.

<table>
<thead>
<tr>
<th></th>
<th>Multi Element</th>
<th></th>
<th>Single Element</th>
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<tbody>
<tr>
<td></td>
<td>Uniform</td>
<td>Non-uniform</td>
<td></td>
</tr>
<tr>
<td>Tensile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}$ (Pa)</td>
<td>6.776</td>
<td>6.776</td>
<td>6.776</td>
</tr>
<tr>
<td>$S_{22}$ (Pa)</td>
<td>$0.168 \times 10^7$</td>
<td>$0.168 \times 10^7$</td>
<td>$0.168 \times 10^7$</td>
</tr>
<tr>
<td>$S_{12}$ (Pa)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$U_1$ (mm)</td>
<td>$-0.581$</td>
<td>$-0.581$</td>
<td>$-0.581$</td>
</tr>
<tr>
<td>Shear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}$ (Pa)</td>
<td>$-0.24 \times 10^5 \rightarrow 1.75 \times 10^5$</td>
<td>$-0.23 \times 10^5 \rightarrow 1.73 \times 10^5$</td>
<td>$0.41 \times 10^5$</td>
</tr>
<tr>
<td>$S_{22}$ (Pa)</td>
<td>$-0.188 \times 10^5 \rightarrow 4.92 \times 10^5$</td>
<td>$-0.193 \times 10^5 \rightarrow 4.82 \times 10^5$</td>
<td>$0.59 \times 10^5$</td>
</tr>
<tr>
<td>$S_{12}$ (Pa)</td>
<td>$0.072 \times 10^5 \rightarrow 2.86 \times 10^5$</td>
<td>$0.097 \times 10^5 \rightarrow 2.81 \times 10^5$</td>
<td>$0.86 \times 10^5$</td>
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Table 1: Patch test results for uniform and non-uniform multi-element model and single element model for uniaxial tension and simple shear. Ranges are given for the simple shear test. Notations: $S_{11}$, $S_{22}$ Normal stress in 1 and 2 direction; $S_{12}$ Shear stress; $U_1$ Displacement in 1 direction.

### 3.2. Validation of the Fabric Constitutive Equation and Implementation

Figure 6 illustrates the comparison of experimental data obtained in Instron tests (Fig. 6a) and flat-bed tests (Fig. 6b) with numerical data for the warp and weft directions of fabrics 1
to 4. The model predictions were obtained using the coefficients identified with the genetic algorithm, see Table 2.

For experimental axial stress and axial strain (Fig. 6a), fabric samples 1, 3 and 4 showed high degrees of anisotropy and nonlinear stress-strain relations in both the warp and weft directions. Fabric 2 showed a lower degree of anisotropy and a nearly linear stress-strain relation in the weft direction. The model solution found for fabric 1 followed the physical weft stress-strain curve accurately up to 28\% strain, and thereafter overestimated the stress. In the warp direction, there was marked difference between the model solution and physical data after 13\% strain. This, and the model solutions of fabrics 3 and 4 showed excellent fits to test data in either warp or weft direction, and a reasonable solution in the transverse direction. However, considerable deviation between the model and physical data was observed for fabric 2.

For transverse versus axial strain (Fig. 6b), close correlation was obtained for fabric 1, with small differences of < 1\% and 1.5\% of transversal strain in the warp and weft direction, respectively. The warp transversal strain curves of fabric 2 exhibited a difference < 1.2\% and < 20\% in transverse and axial strain, respectively. However, the solution obtained for fabric 2 was largely linear, while fabric 1 showed an increase in Poisson’s effect with an increase in axial strain. Large differences were observed for fabrics 3 and 4, except for the weft direction for fabric 3 with a small between model and test data of < 2\% in transverse strain.

4. Discussion

The novel anisotropic nonlinear elastic constitutive model proved feasible to describe the nonlinear mechanics of a variety of fabrics under tensile loading and a linear characteristic under shear. These characteristics depended heavily on the fabric model coefficients used to describe the material properties. The exponential strain energy model does, however, not include anisotropic viscoelastic and plastic components which are complex to model and implement Gadala (1997), and which falls outside the scope of this study.
It was found from the fabric patch tests that $C$, $a_1$, $a_2$, $a_3$ and $a_4$ should remain positive to ensure realistic fabric uniaxial tensile solutions. Negative coefficients would produce unrealistic compressive stresses. It is apparent from Eq. (3) that the magnitude and ratio of the coefficients contribute to the change in stress and strain. Thus, the observations were only made for specific changes in the magnitude of the coefficients, namely, $1.5 \times$ and $-1 \times$. The predicted stress distributions were equal and uniform throughout the elements for the various patch test models employed, indicating that the material model was implemented correctly in the FE package. The stress-strain curves for simple shear did not exhibit an initial high modulus, a characteristic of fabrics under shear reported by Hatch (1993). This feature was, however, reported for a shear angle of between $0 - 0.8^\circ$ only, after which the relation became predominantly linear which agreed with the predicted solutions presented here.

The fabric model was validated against uniaxial tensile test data for four different fabrics. Good correlations were observed for three fabrics (Fig.6). For fabric 2 exhibiting a linear stress-strain relationship, the model failed to provide a satisfactory solution. To possibly
overcome this limitation, a combined polynomial and exponential function could be used, e.g. as proposed by Tong and Fung (1976):

\[ W = P + \frac{C}{2} e^Q, \]

\[ P = \frac{1}{2} \left[ \alpha_1 E_{11}^2 + \alpha_2 E_{22}^2 + \alpha_3 \left( E_{12}^2 + E_{21}^2 \right) + \alpha_4 E_{11} E_{22} \right], \quad (7) \]

\[ Q = a_1 E_{11}^2 + a_2 E_{22}^2 + a_3 \left( E_{12}^2 + E_{21}^2 \right) + a_4 E_{11} E_{22} + \gamma_1 E_{11}^3 + \gamma_2 E_{22}^3 + \gamma_3 E_{11} E_{22}^2 + \gamma_5 E_{11} E_{22}. \]

This strain energy function was shown to give greater anisotropy and variation in the transverse directions. A similar function could be utilized to cater for the linear stress-strain components. However, 13 coefficients would need to be solved when using this function, and the term \( P \) in Eq. (7) may cause ”polynomial wiggling”, giving unrealistic fabric behavior (Faires and Burden, 1993).

Another possible fabric material model could be derived from the constitutive model for artery layers proposed by Holzapfel et al. (2000). This models ensures convexity for all possible sets of material parameters, thus avoiding material instabilities, and takes the form:

\[ \bar{\psi}(\bar{I}_4, \bar{I}_6) = \frac{k_1}{2k_2} \sum_{i=4,6} \left[ \exp \left( \bar{I}_i - 1 \right)^2 - 1 \right], \quad (8) \]

where, \( \bar{I}_4 = \bar{C} : A_1 \) and \( \bar{I}_6 = \bar{C}^2 : A_1 \), \( A_i \) is defined as the tensor product of \( a_{0i} \otimes a_{0i} \), where \( a_{0i} \) is a material reference direction vector. This particular anisotropic material model uses only two coefficients, \( k_1 \) and \( k_2 \) for two dimensional problems making it easier to implement and utilize. \( k_1 > 0 \) is a stress-like material parameter and \( k_2 > 0 \) is a dimensionless parameter.

Other alternatives may be discrete models that simulate individual fibre structures and a function similar to that proposed by Alsawaf (1985). Discrete models are, however, not preferential due to the computational expense they incur.

Alsawaf (1985) proposed a two stage linear function to describe uniaxial deformation of a weave, however instead of linear functions, two exponential functions could be used, one with an initially low stiffness and curvature and a second, which is only implemented when a critical point is reached which has a higher stiffness and curvature. This method may
however be difficult to implement, where continuity along the function would need to be enforced and transverse interplay would be difficult to define.

5. Conclusions

The novel nonlinear anisotropic elastic strain-energy function proofed feasible to realistically describe the coupled warp-weft mechanics of a variety of coarse knit fabrics. Although time and effort may be spent modeling the fabric and its behavior ex vivo, the mechanics of the fabric will change considerably over time in vivo. When implanted, cells will seed themselves to the fabric, changing its mechanical nature. To account for tissue regeneration processes, the constitutive relationship presented may be extended to incorporate a time dependent model for tissue in-growth. An increase in stiffness with time can be obtained by increasing $C$ while the orthogonal anisotropy and orientation may be adjusted by varying the $a_i$, i.e. $C, a_i = f(t)$ such that $C, a_i \rightarrow \text{Limit}$ when $t \rightarrow \infty$. The time-dependent change will require extensive experimental data to obtain a realistic relationship, with variation in material type and fabric construction.

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Conflict of Interest

The authors confirm that they do not have conflicts of interest in connection with the work and data presented in this paper.

References


Figures

Figure 1: Patch test models: Single element models for a) uniaxial tension and b) simple shear; Multi element models with c) uniform and d) non-uniform mesh.
Figure 2: Scanning electron micrographs (50x) of the fabrics tested; (A) sample 1: basic warp knit, (B) sample 2: warp knit with Lycra® support, (C) sample 3: coarse warp knit and (B) sample 4: monofilament warp knit. (Arrows indicate warp/weft direction.)

Figure 3: Finite element model for fabric uniaxial tensile test utilizing symmetry.
Figure 4: Effects of fabric material coefficients $C$ and $a_1$: Stress-strain curves (a) and normalized stress and transverse strain (b) for uniaxial tension; Shear stress - shear angle curves (c).
Figure 5: Contour plots of normal stresses ($S_{11}$, $S_{22}$) and shear stress ($S_{12}$) for a) uniform and b) non-uniform multi-element shear patch test models.
Figure 6: Stress and strain data of physical tensile tests and model predictions for the warp and weft direction of fabrics 1 to 4: a) Uniaxial stress versus strain, b) Transverse strain vs. longitudinal strain.