MODELING THE VISCOELASTIC BEHAVIOUR OF ELECTROSPUN SCAFFOLDS USED FOR CARDIAC PATCHES DEVELOPMENT

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Abstract—The mechanical characterization of the electrospun scaffolds toward cardiac patch development was attained using existing theoretical viscoelastic models. When deformation is applied, especially on a large scale, the materials' response is the nonlinear increase of the required stress. This loading stage can be modeled using existing hyperelastic stable models that can be further used to predict similar deformation cases. Since electrospun scaffolds are considered viscoelastic materials, the stress relaxation response to constant strain has also been investigated using the multi-term Prony series. Stress softening and preconditioning of samples is a factor that must be considered not only during the experimental procedure but when modeling the viscoelastic behaviour of the electrospun scaffolds.

Keywords—electrospinning; electrospun helical fiber scaffolds; hyperelastic models; stress relaxation; stress softening.

I. INTRODUCTION

Finding the constitutive matrix for the material is a crucial step in achieving scaffold success for cardiac implantation. Evaluating the test data versus the existing theoretical models is the first step in meeting this primary objective in the tissue engineering field. While predicting the data using uniaxial test data only may result in accurate curve fitting, testing other test configurations, such as equiaxial or compression, it is favored to utilize more than one test data to increase the accuracy of the models. Furthermore, the assumptions concluded before the data evaluation are crucial to the model's precision compared to material responses. Hence, analytical models are utilized to simulate and predict material properties under complex loading condition that poses a challenge to examine in a controlled manner physically. Various modeling methods have been used to predict their mechanical behaviour accurately. Attaining the mechanical properties of the spring-like fibered electrospun scaffold will facilitate the development of an analytical model. A previous effort successfully derived models for straight-fibered electrospun scaffold manufacturing using poly (3-caprolactone) (PCL) [1], [2]. While similar models have been applied to multiple soft tissue and biological materials, including native heart tissue, synthetic polymers tend to have a nonlinear and viscoelastic (rate-dependant) behaviour [3], [4]. Other models were developed based on statistical mechanics and conventionally used mainly in rubber-based applications. Nonetheless, it was also applied to simulate human skin [5].

Attaining the mechanical properties of scaffolds is the first step to understanding the material behaviours. Conventional material testing does not provide an accurate comparison to the native cardiac tissue loading due to the complexity of the loading scheme. Analytical modeling will aid in simulating the complex loading, thus providing the expected material properties. To develop an accurate numerical model of a scaffold, specific properties, and characteristics must be investigated and used as building blocks of the model [1]. Specifically, electrospun samples experienced significant stress softening and stress relaxation due to stretching the helical fibers and the subsequent breakdown of weaker bonds between the fibers within the scaffold matrix. Nonetheless, as the deformation cycles continue, a further stress softening effect is witnessed until it reaches a stable level in the latter cycles. Furthermore, during the conditioning of the samples, some plastic deformation occurs and thus affects the specimen's length in the subsequent loading. Hence, applications require preconditioning before implantation as it is evident that the first loading cycle has a significant loading effect compared to the consecutive cycles [1].

In the current study, we used existing viscoelastic models to fit with experimental data provided by uniaxial tests on electrospun helical samples. Hyperelastic models were used for describing the loading stage, namely when the samples were subjected to nonlinear uniaxial tension. Furthermore, the electrospun coupons' response to constant deformation was stress relaxation; this viscoelastic behaviour can be modeled by applying the Prony series. Since the electrospun samples exhibit similar behaviour with other polymers, such as elastomers, and stress softening occurs after the initial stretching, we compared the modeling results of coupons subjected to cyclic preconditioning to the corresponding models of samples missing any prior conditioning. Considering
this behaviour is mandatory for gaining stable models and accurate future simulations.

II. MATERIALS AND METHODS

A. Materials and specimens’ geometry

The materials selected had a strict criterion of being biocompatible and bioabsorbable. Based on this criterion, we adopted the optimal parameters exported from our previous sensitivity study [6]. Hence, we selected Poly (3-caprolactone) (PCL) with an average molecular weight of 80,000 (Sigma-Aldrich) and the equally included Dimethylformamide (DMF) and Dichloromethane (DCM) as the solvents with 15% PCL concentration. For optimal homogeneous mixture, the solution was mixed for 12 hours on a magnetic stirrer while air-sealed to prevent the evaporation of the volatile chemical DCM. The solution was deposited in a 5ml syringe with a 20G needle, connected using a Luer lock mechanism, and emitted using a syringe pump at 1ml/hr flowrate. The positive terminal was attached to the needle, while the negative terminal was connected to the aluminum sheet that serves as the collector. The electrospinning setup used in our study can be seen in Figure 1. A constant 17.5kV was held throughout all the experiments. The tip-to-collector distance (TCD) was selected to be 15cm and the collector 0° angle (Figure 1).

After the scaffolds were left to dry, tensile sample preparation commenced. Samples were cut using a surgical scalpel. Additionally, the sample dimensions were governed using a mold. The size of the tensile coupons was 27.9mm x 10.48mm. The thickness of the samples varied among the tensile coupons because of the randomness of the electrospinning process and the randomized results.

![Figure 1. Electrospinning setup showing syringe holder, blunt needle and the collector.](image)

B. Viscoelastic behaviour modeling

Based on the results from the mechanical characterization of the scaffold, it was determined that further tensile testing was required to attain data for modeling the behaviour of preconditioned and non-preconditioned samples. Electrosprun samples experienced the same loading scheme of 20% strain and subsequently 2000s of constant strain at speeds of 0.01mm/s and 0.1m/s. Results attained were analyzed to obtain the hyperelastic and viscoelastic models. A curve fitting method was utilized using commercial software (ABAQUS 2020). Multiple numerical models were explored to determine the stable models for the hyperelastic segment, where the test results were implemented as uniaxial data.

C. Experimental procedure

To model the hyperelastic behaviour of the electrospun scaffolds, we subjected the developed samples to uniaxial tension until reaching 20% strain (Figure 2). As analyzed above, the electrospun scaffolds exhibit a softening in the required stress level after initially being stretched. Thus, we repeated the same experiment with prior coupon preconditioning (Figure 3); namely, we subjected our samples to 20 repeated loading-unloading cycles before performing the uniaxial tension test. To investigate the impact of the deformation speed on the samples’ behaviour, we performed the same configuration for two speeds, 0.1mm/s, and 0.01mm/s. Moreover, to attain a more accurate model, the strain was held constant for 2000s to capture the complete stress relaxation response. Furthermore, significant stress softening was recorded at both loading speeds tested for the electrospun samples investigated in the current study. Hence, applying prior conditioning of 20 cycles will drastically affect the coupons' hyperelastic and stress relaxation response. This impact was evident in the modeling results as well, resulting in misleading conclusions regarding the accuracy and stability of the models.

III. RESULTS AND DISCUSSION

A. Hyperelastic modeling

For modeling the mechanical behaviour of the electrospun scaffolds when subjected to uniaxial tension, we used existing hyperelastic models to curve fit the experimental data. However, the curve fitting procedure provided us with a model that might be unstable for further simulations. Figure 2 shows selected hyperelastic models for the case of coupons missing preconditioning. Specifically, only Arruda-Boyce and Reduced Polynomial (N=1) provide stable models for accurate simulations. Nevertheless, both are capable of modeling only linear hyperelastic behaviour.

Due to the abnormal behaviour when compared to elastomers, the non-preconditioned samples resulted in less than desired curve fitting results. The corresponding experimental data at both speeds increased with a positive slope until a certain strain level. Then, the stress values tended to grow at a slower pace. At the speed of 0.1mm/s, all stable models resulted in a linearly increasing curve, which led to a mismatch with the experimental data. The results of stable models’ evaluations are presented in Figures 2a and 2b for 0.1mm/s and 0.01mm/s, respectively.
Figure 2. Hyperelastic models vs experimental data of the samples’ behaviour when subjected to uniaxial tension until reaching 20% strain with no preconditioning for (a) 0.1mm/s and (b) 0.01 mm/s speed. Some of the hyperelastic models might be unstable for simulations.

Several unstable models for 0.1mm/s and 0.01mm/s loading speed cases have resulted in adequate curve fitting, as seen in Figure 2. A rationale behind the instability of the modes is due to the high deformation examined. Ogden N=1 is stable in uniaxial tension but deemed unstable for minor uniaxial compression and high biaxial tension loading. Conducting further tests in other loading configurations, such as compression, confined compression, biaxial tension, and equiaxial testing, will lead to more accurate models and stabilize other models. The unstable models visualized in Figure 2 are all unstable in high strains.

The change in behaviour due to conditioning resulted in better curve fitting when compared to non-preconditioned cases. Preconditioned samples are more relevant to the application of cardiac patches. As the scaffold will be cultivated with cardiac cells before implantation, thus will experience contractions. The applied load resulted in a steep increase in the stress-strain accounted for buckling. In both loading speeds tested, Ogden N=1 resulted in the best fit compared to other stable models. However, Yeoh and Van Der Waal models are deemed unstable in preconditioned samples at strains higher than 8.9% in tension. The results are visualized in both speeds in Figures 3a and 3b for 0.1mm/s and 0.01mm/s, respectively.

B. Stress relaxation modeling

The viscoelastic response has been accurately predicted using the Prony series. Samples at both speeds, 0.1mm/s and 0.01mm/s, have been indicated in both preconditioned and conditioned samples. In evaluating the data, the Prony series requires the experimental data to serve as input in shear test.
data under time-dependent data. Figure 5 shows the normalized stress response versus time. Furthermore, the four cases analyzed resulted in accurate curve fitting. An observation can be made when comparing results between two different speeds of similar conditioning schemes, the viscoelastic response recovery early in lower speeds. This conclusion can be made for preconditioned and conditioned samples. The corresponding viscoelastic coefficient models are listed in the table for each case evaluated.

![Stress relaxation plots](image)

Figure 4. Stress relaxation at 20% strain of experimental data and Prony series modeling of preconditioned and non-preconditioned samples subjected to (a) 0.1mm/s and (b) 0.01 mm/s loading speed.

Examine the viscoelastic response of preconditioned coupons compared to the corresponding samples’ behaviour missing prior to repeating cyclic deformation, it was recorded that the material experienced a more significant drop in stress values before altering to a more linear response. This observation was evident for both speeds concerning the difference in stress value decrease at each speed. The comparison can be visualized in Figure 4.

IV. CONCLUSIONS

In the current study, existing hyperelastic models were used for modeling the mechanical behaviour of electrospun samples subjected to uniaxial tension. When the specimens were used directly for the experimental investigation, the resulting hyperelastic models that provided adequate curve fitting resulted in unstable configurations. On the contrary, when the stress softening was considered by subjecting to repeating cycling preconditioning of the coupons, the hyperelastic models succeeded in modeling the nonlinear behaviour with stable models. Since electrospun scaffolds with helical fibers exhibit viscoelastic behaviour, we modeled the stress relaxation response to constant strain using the Prony series. Similar to the case of the hyperelastic behaviour, the preconditioned samples resulted in more accurate curve fitting and hence, modeling of the viscoelastic behaviour.

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REFERENCES


