Material Modeling and Development of Soft Surgical Robots Using Transient Finite Element Analysis

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Abstract—An increasing research dedication has been devoted recently to soft robotics. Soft robots are best known for their compliance and safety that nominate them substantially for human-centered applications. Robot-assisted surgical operations are expanding worldwide where soft robots find their potential way for this application. Soft robots are fabricated from highly nonlinear soft materials like silicone rubbers that exhibit complex combined hyperelastic, viscoelastic, and hysteresis behaviors. Dynamic modeling of soft robots that incorporate different soft materials with fiber-reinforcement involves many considerations and depends on the underlying design concept. Establishing a certain dynamic model can be valid for a certain design configuration that may not be applicable to another one. This work proposes a transient finite element analysis-based methodology for design and dynamic simulation of fiber-reinforced soft robots for minimally invasive surgery. This methodology is based on cohesive material testing and modeling paradigms and aims to found a generalized theoretical framework for the development and experimentation of soft robots. A multi-camera vision tracking system is proposed for monitoring the 3D soft robot moving trajectory. Experimental validation of the proposed methodology proves its reliability and accuracy for estimating the soft robot dynamic response upon different actuation scenarios. The suggested methodology can be utilized in the future for developing new soft robots, devising, and testing new dynamic models or control algorithms for soft robots.

Index Term—soft robotics, material testing, material modeling, finite element analysis, vision tracking

I. INTRODUCTION

Nature inspiration has revolutionized many engineering innovations [1]. Many creatures can exhibit complex motions with soft skeletons like octopus tentacle and elephant trunk. Being inherently soft underlines the manifestation of safety, compliance, and agility. These merits of soft structures have conveyed the research devotion towards soft robotics. Traditional rigid robots are known for high accuracy, speed, and repeatability. They are ideal for fields of high productivity manufacturing and assembly, however, when it comes to human-centered applications, they are not fully safe to interact. Increasing demand for human-centered applications and dealing with unstructured environments has revealed the superiority of soft robotics.

Realization of soft robots proved potential successes in search and rescue devices [2], assistive and rehabilitative robotics [3], [4], and medical robotics [5]-[7]. Medical robotics has come across many developments throughout past decades [8]-[11]. This field has contributed in many robotic platforms and surgical techniques that helped physicians to conduct their tasks effectively and easily. Minimally invasive surgery (MIS) is the most well-known surgical technique that aims to access the human body via tiny incisions. Rather than traditional open surgery, MIS permits less bleeding and infection, fast recovery and healing, and enhanced cosmesis.

Most of MIS instruments or commercially available robotic platforms, like da Vinci system [12] by Intuitive Surgical Inc., employ rigid parts and joints. Rigidity limits the number of degrees of freedom (DOFs) and prevents the adaptability of the surgical system or instrument according to the tasks to be carried out. Many researchers used hyper-redundant and continuum robots to make the rigid surgical robots more dexterous [1], [13]. However, the use of motors and cable-driven mechanisms results in sterilization and maintenance issues [7], as well as rigid robots can cause damage to soft tissues if they were not carefully driven.

Recent advances in MIS has showed major advantage of soft robots over rigid robots, since they offer compliance, dexterity, and maneuverability [11], [14]. Soft robots can easily and safely conform to organs and adapt themselves to anatomical passages while they are progressively driven. Moreover, if they are reinforced with fibers, they can bend, extend/shrink, or twist depending on the fibers arrangement and angle [15]. As the name implies, soft robots are fabricated from soft materials such as silicone rubber that mostly comprises their underlying actuators. There are a lot
of different soft actuator designs and shapes according to their function [14]. In the field of MIS, the three parallel flexible fluidic actuator (FFA) [5], [6] is mostly adopted. Earlier designs of FFA were not considering fiber reinforcements and suffered from ballooning effect. Fraś et al. [16] proposed helical fiber-reinforcement for the three parallel FFA to hinder ballooning, which became the standard type of soft actuator for MIS applications [6], [11], [14].

The development process of soft robots for MIS application has many aspects including soft material behavior, robot’s dimensions, dynamics characteristics for motion and control, and environmental constraints. Soft robot in the form three parallel FFA is a kind of continuum robot, which has been extensively studied in literature and modeled with various paradigms. Constant curvature model (CMM) [13], [17] is a well-known kinematics framework that simplifies the modeling of continuum robots in terms of three arc parameters. However, it is not efficiently applicable in presence of external forces, gravity effect, and payloads. Trivedi et al. [18] combined Cosserat rod theory with the principle of virtual work to derive a dynamic model that showed higher accuracy than CCM, however, their model was computationally expensive. Godage et al. [19] introduced a lumped model employing Lagrangian dynamics that represents the soft continuum robot as a series of rigid links connected with springs and dampers. They also included a center of gravity dynamic model that was proved to be efficient in regards of computational cost and accuracy. However, this model included many configuration-dependent parameters that required experimental estimation beforehand. Sadati et al. [20] presented a dynamic model based on neo-Hookean hyperelastic material model with proper geometric assumptions in case of the braided three parallel FFA continuum robot. This model accounted for large deformations and cross-section variation upon pressure actuation and force application. Despite of geometry deformation model merits, its parameters were tuned for certain soft robot model configuration and cannot be generally applied in other designs.

The dynamic models discussed above were tailored with assumptions, or simplifications in terms of material representation, underlying modeling technique, or geometrical configuration. These models are more well-suited for control applications. The need for incorporating exact soft material behavior with accurate dynamic modeling is vital for any development cycle in soft robotics. This article proposes a transient finite element analysis (TFEA) methodology for designing and experimenting fiber reinforced soft robots for MIS applications. The suggested TFEA methodology is intended for developing soft robots and assessing their dynamic performance without the need to fabricate them beforehand. This study is targeted at offering a generic theoretical framework for exploring the capabilities of soft robots, paving the way for further developments in this field. This article expands the previously published conference paper [21] in the regard of material testing and modeling as well as the experimental setup for validating the proposed TFEA methodology. In the current study, detailed material testing and modeling are established to account for the combination of hyperelasticity, viscoelasticity and Mullins effect of the silicone rubber soft material. This in turn enhances the TFEA results in accordance with the real experimental results. Moreover, the vision system is augmented to include multiple cameras to monitor and cover much larger volume of the soft robot workspace.

II. SOFT ROBOT DESIGN CONCEPT

The main structure of the soft robot presented in this study follows the widely adopted soft robot design [6], [11], [14], [16] for MIS applications. Generally, the employed robots or actuators for MIS applications should have a diameter in between 12 mm and 30 mm [22]. The presented design through this work achieves a diameter of 25 mm for the proof of concept and convenient prototyping. However, this design can be scaled down to any smaller size, since the fabrication technique does not involve any limitations regarding that. The fabrication is carried out through successive molding steps and depends only on the size of the molding parts, which can be set according to the required need.

As depicted in Fig. 1, this design features three fiber-reinforced FFAs contained in a silicone rubber enclosure. Each FFA has outer and inner diameters of 8 mm and 4 mm, respectively. The soft robot is composed of two parts which are the main body and the distal cap. The main body is the part that encloses the three fiber-reinforced FFAs and it is made of Ecoflex 00-30 [23] silicone rubber with nylon threads.

![Fig. 1. Conceptual design of the soft robot. (a) Isometric view of the soft robot. (b) Cross sectional view at Main body.](image-url)

The robot is sealed at its end with the distal cap and it is made of Dragonskin 30 [24] silicone rubber that is much stiffer than Ecoflex 00-30. The purpose of using much stiffer silicone rubber at the robot’s end is to prevent it against bulging upon
Actuation with pressurized air. The surface of the distal cap that faces the environment has to remain flat, since it will be attached with a fiducial marker for visual position tracking and any deformation will influence the tracking accuracy. The base coordinate frame is set with its Z-axis pointing from its base center to the top face center of the distal cap, while its X-axis passes through the center of FFA1.

III. SOFT ROBOT FABRICATION

The fabrication process is conducted through consecutive molding steps as shown in Fig. 2. Each step involves casting a certain part of the soft robot using whether Ecoflex 00-30 or Dragonskin 30 materials. Both materials are platinum-cure silicone rubbers that come into two parts, namely part A and part B. The preparation step of each material initially includes mixing the two parts A and B with a volumetric ratio of 1:1 in a plastic cup for five minutes. The stirring operation brings about air bubbles formation inside the mixture. If the entrapped air bubbles are allowed to exist in the cured silicone rubber, they will create undesirable stress concentration spots and will result in degraded mechanical properties. For that reason, the mixture has to be exposed to a vacuum of about -0.9 bar for ten minutes after finishing the mixing operation to get rid of all the air bubbles. After the mixture is degassed, it is injected into a mold and left for curing. The mixing and curing temperatures are kept to the room temperature. The required curing time periods for Ecoflex 00-30 and Dragonskin 30 are 4 and 16 hours, successively. The mold is composed of the following: mold cylinder, top and bottom covers, top and bottom guides, and rods. Three 8 mm rods are placed through top and bottom guides inside the molding cylinder (Fig. 2a). Each of these rods is wrapped up with a taut helical fiber at a tight pitch.

The used fiber is a nylon thread with a diameter of 0.36 mm. The placement of the top and bottom guides ensures accomplishing a height of 60 mm for casting the main body.

The first molding step (Fig. 2b) is to establish the main body of the soft robot that encloses the three FFAs. An adequate amount of Ecoflex 00-30 A and B mixture is prepared and degassed as discussed before so as to be injected to the mold. The injection is done using a standard medical syringe into one of the three holes existing at the top plate, while the other two holes are for air vent. After the main body is left for total curing, the mold is gently disassembled leaving the casted main body inside the mold cylinder. The second molding step (Fig. 2c) is to create three internal tubes of 2 mm thickness, which are placed inside the three chambers of the main body. The mold is reassembled again, but with three 4 mm rods which are placed between different guides and covers. Ecoflex 00-30 is prepared and injected into the gaps between the cavities of the main body and the three rods to shape the internal layers for FFAs. The third molding step (Fig. 2d) involves casting the distal cap on top of the previously casted main body with internal tubes. The three 4 mm rods are pushed downwards gently till their top face becomes coincident with the top face of the main body. The top guide is replaced with a bush originating a distance of 10 mm between its bottom surface and the top surface of the main body. Dragonskin 30 is prepared and injected to the top of the mold and is left for full curing. These three molding steps create the whole body of the soft robot. The last step of fabrication process (Fig. 2e) is to establish a basement for the soft robot body and connect air inlets to its three FFAs. Finally, the tip of the distal cap is attached with a fiducial marker for vision motion tracking.

Fig. 2. Soft robot fabrication. (a) Mold preparation (b) Casting of main body. (c) Casting of internal tubes. (d) Casting of distal cap. (e) Real fabricated prototype fixed to a basement and attached with a fiducial marker.
IV. MATERIAL TESTING AND MODELING

A. Material Constitutive Laws

Soft robots are typically made of elastomeric materials such as Ecoflex, Dragonskin, Elastosil, and polydimethylsiloxane (PDMS). These materials undergo high level of stretchability and behave nonlinearly in terms of stress-strain curve, stress relaxation over time, and hysteresis. Both static and dynamic performance of elastomers are governed by fabrication process including the influence of processing and curing temperatures. Elastomeric materials mainly follow the hyperelastic behavior with viscoelastic effects. Several constitutive laws have been proposed to capture the nonlinear hyperelastic and viscoelastic responses of elastomers. The Ogden [25] and Yeoh [26] hyperelastic material models have been widely employed by many researchers [22], [27], [28] for modeling Ecoflex and Dragonskin silicone rubber materials. The $n$th order Ogden model for incompressible materials is defined by a strain energy potential $W$ that depends on the deviatoric principal stretches $\lambda_i$ as follows:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i} (\lambda_1^{\alpha_1} + \lambda_2^{\alpha_2} + \lambda_3^{\alpha_3} - 3)$$

where $\mu_i$ and $\alpha_i$ are material constants which are determined by fitting to experimental data. On the other hand, the $n$th order Yeoh model is expressed as follows:

$$W = \sum_{i=1}^{N} C_{10} (I_1 - 3)^i$$

where $I_1$ is the first deviatoric strain invariant and $C_{10}$ are material model constants.

Inherent viscoelastic behavior can be modeled by Prony series mathematical model [28] that can be fitted to a stress decay over time for uniaxial tension test. For the incompressible materials, Prony series is expressed in terms of shear relaxation as follows:

$$G(t) = G_0 - \sum_{i=1}^{N} G_i \left[ 1 - e^{-\frac{t}{\tau_i}} \right]$$

where $G_0$ is shear modulus obtained at the end of initial loading just before relaxation begins, and $G_i$ and $\tau_i$ are model fitting constants. Silicone rubber materials experience internal material damage upon loading and unloading cycles, which is known as Mullins effect [29]. This leads to a decrease of material stiffness over subsequent loading cycles. The Ogden-Roxburgh model [30] is adopted throughout this work for modelling Mullins effect, which has the following strain energy potential:

$$W = \eta W_0 + \phi(\eta)$$

where $W_0$ is strain energy potential of pure material without damage, $\eta$ is the damage variable, and $\phi(\eta)$ is the damage function [30], [31] that is defined as follows:

$$\phi(\eta) = \int_1^{\eta} [(m + \beta W_m) erf^{-1}(r(1 - \eta) - W_m)] d\eta$$

$$\eta = 1 - \frac{1}{r} erf \left[ \frac{W_m - W_0}{m + \beta W_m} \right]$$

where $r$, $m$, and $\beta$ are material parameters, $W_m$ is the maximum strain energy potential in the cyclic test history and $erf$ is the error function.

B. Material Testing Procedures

Evaluating the mechanical properties of both Ecoflex 00-30 and Dragonskin 30 materials was done according to ASTM D412-C [32] as shown in Fig. 3b. Test specimens were fabricated by injecting liquid silicone rubber mixture inside a dumbbell-shaped mold with a thickness of 3 mm. Preparation of the liquid silicone rubber mixture followed the same practice as discussed in the previous section. All of the material testing experiments were carried out with uniaxial tension test type. The used testing machine was Lloyd Instruments LFPlus as depicted in Fig. 3a, which has a load cell capacity of 500 N. Three testing procedures were conducted, namely pull-to-tear, stress relaxation, and cyclic loading. Each test was repeated three times at the same environmental conditions. After that, the median response curve was considered for material modeling stage.

In the pull-to-tear test, the specimen was clamped at a distance of 14 mm from both ends. One end was fixed to a stationary pneumatic grip while the other end was clamped to a moving grip. The specimen was then dragged upwards at a travel speed of 500 mm/min till it ruptured. The stress relaxation test started with travel speed of 1000 mm/min till reaching 75% of the failure strain that was estimated from the pull-to-tear test. Afterwards, the stretched specimen was held still at that strain for 5 mins. The cyclic loading test involved repeated stretching and retraction cycles of the specimen.
Starting from scratch, each subsequent cycle was concluded at 100% more of stretch ratio with a travel speed of 500 mm/min. Meanwhile each of the three previous tests, both engineering stress and strain were recorded with respect to time. The results of these tests for Ecoflex 00-30 and Dragonskin 30 are presented in Fig. 4.

### C. Material Modeling in ANSYS

The modeling of Ecoflex 00-30 and Dragonskin 30 materials started basically with defining the hyperelastic parameters. This was done by fitting the pull-to-tear test data in ANSYS Mechanical Workbench to all orders of Ogden and Yeoh models. The 3rd order Ogden model was the best constitutive law for Ecoflex 00-30, while the 1st order Ogden model was the best for Dragonskin 30. The next step in material modeling was to define the viscoelastic behavior of the materials. This was carried out by fitting Prony series to the shear modulus relaxation data resulted from stress relaxation test. After fitting relaxation data in ANSYS, the 4th order Prony series yielded the best fitness for modeling viscoelasticity.

Mullins effect for Ecoflex 00-30 and Dragonskin 30 are presented in Table I.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Ecoflex 00-30</th>
<th>Dragonskin 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperelasticity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ogden model)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>((\mu_1, \alpha_1))</td>
<td>(-35.799 MPa, 0.899)</td>
<td>(0.201 MPa, 2.635)</td>
</tr>
<tr>
<td>((\mu_2, \alpha_2))</td>
<td>(15.992 MPa, 1.061)</td>
<td>N/A</td>
</tr>
<tr>
<td>((\mu_3, \alpha_3))</td>
<td>(21.738 MPa, 0.704)</td>
<td>N/A</td>
</tr>
<tr>
<td>Viscoelasticity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Prony series)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>((G_1, \tau_1))</td>
<td>(0.041 MPa, 0.424 s)</td>
<td>(0.043 MPa, 0.985 s)</td>
</tr>
<tr>
<td>((G_2, \tau_2))</td>
<td>(0.067 MPa, 4.536 s)</td>
<td>(0.047 MPa, 4.401 s)</td>
</tr>
<tr>
<td>((G_3, \tau_3))</td>
<td>(0.057 MPa, 20.871 s)</td>
<td>(0.058 MPa, 15.859 s)</td>
</tr>
<tr>
<td>((G_4, \tau_4))</td>
<td>(0.089 MPa, 159.416 s)</td>
<td>(0.101 MPa, 118.685 s)</td>
</tr>
<tr>
<td>Mullins effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(r)</td>
<td>1.657</td>
<td>1.456</td>
</tr>
<tr>
<td>(m)</td>
<td>0.154 MPa</td>
<td>0.513 MPa</td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.041</td>
<td>0.152</td>
</tr>
</tbody>
</table>

The last step is to model the material damage upon loading/unloading cycles that represents the Mullins effect. Matlab constrained optimization function “fmincon” was employed to find the best fitting parameters for Mullins effect. Material constants defining hyperelasticity, viscoelasticity, and Mullins effect for Ecoflex 00-30 and Dragonskin 30 are presented in Table I.

### V. Finite Element Analysis

This section describes the proposed soft robot finite element modeling and analysis using ANSYS software. As shown in Fig. 5, the soft robot is composed of main body, internal tubes, helical fibers, and distal cap. The soft robot is
directed downwards to match its experimental setup orientation. The main body (Fig. 5b) encloses the internal tubes (Fig. 5c) within its three chambers. The helical fibers (Fig. 5d) lies between the three cavities of the main body and the internal tubes. These fibers act to restrain ballooning of the internal tubes upon pneumatic actuation. The distal cap (Fig. 5e) is mated at the bottom end of the main body. Main body, internal tubes, and distal cap are modeled as solid bodies and meshed with SOLID186 element type. SOLID186 is a higher order 20-node 3D solid element that has a quadratic displacement behavior. It also supports mixed u-p formulation that overcomes convergence difficulties while simulating incompressible rubber-like materials. Helical fibers are meshed with BEAM189 element type which is a quadratic three-node 3D beam element. The meshing sizes for main body, internal tubes, distal cap, and helical fibers are set to 2 mm, 1.5 mm, 2 mm, and 1 mm, respectively.

Solid bodies are meshed with consistent elements, where all common imprints of the neighboring faces are meshed congruently. In other words, the meshing nodes of each touching pair of bodies are coincident in all the tangent areas. This results in fewer nodes generation, enhanced convergence and performance, and lower computing times. The restrictive action of the helical fibers is induced between the main body and the internal tubes. This is done via CEINTF command in ANSYS APDL which constrains each beam node of the helical fibers to the nearby solid elements of the main body and the internal tubes within given tolerance. The dynamic simulation of the soft robot is carried out using the transient structural module in ANSYS Workbench. The soft robot is set fixed at the top face of the main body. Pneumatic actuation is applied as a distributed pressure load on the inner cylindrical faces of the internal tubes. Additionally, it is applied to three areas of the distal cap’s top face that are enclosed by the internal tubes. Gravitational acceleration is added to the previous boundary conditions. Mass densities for Ecoflex 00-30 and Dragonskin 30 are set to 1070 kg/m³ and 1080 kg/m³, respectively. All material properties are summarized in Table 1 in the previous section.

VI. EXPERIMENTAL WORK

This section presents the details of experimental work for validating the TFEA results, which consists of three subsections. The first subsection describes the setup layout and lists all the constituting components. The second one sheds the light on the vision tracking system that aims to register the moving trajectory of the soft robot’s tip. The third subsection includes case studies that involves different actuation practices and compares the experimental results to the TFEA results.

A. Experimental Setup

The experimental setup includes seven main components: aluminum frame, soft robot assembly, pressure sensors, proportional solenoid valves, vision tracking system, power supply, and air compressor. The general outline of the experimental setup is depicted in Fig. 6a, while Fig. 6b shows the real-world implementation. The soft robot has three internal chambers which serve to move the robot upon pressurized air supply. Each chamber is actuated through two 2/2 proportional solenoid valves (PVQ33-5G-16-01F) [33], where one valve is for air inlet and the other one is for air outlet. A pressure sensor (MPX5500) [34] is attached to each chamber for monitoring the interior pressure value. A Teensy microcontroller [35] is employed for controlling the proportional solenoid valves, acquiring the readings of pressure sensors, and communicating with the vision system. The used Teensy microcontroller encompasses a 32-bit 180 MHz ARM Cortex-M4 processor with floating point unit. Teensy is interfaced through USB connection to a PC which sends pressure commands and receives the robot movement simultaneously.

B. Vision System Description

This work introduces a low-cost multi-camera vision system for tracking the 3D movement of the soft robot. This vision system involves four cameras which are compatible with Raspberry Pi single board computer [36]. The motion tracking and pose estimation principal is based on fiducial marker detection [37]. Each camera is calibrated beforehand, so the estimated pose is defined with respect to each camera coordinate frame. A fiducial marker is printed on a typical paper, then it is glued to the distal cap end of the soft robot. Marker detection process along with camera calibration data results in 3D pose estimation. Each Raspberry Pi is connected to the Teensy microcontroller via Inter-Integrated Circuit (I²C) protocol for sending and receiving commands between them. Teensy is treated as master, while every Raspberry Pi is treated as slave in the I²C protocol. Four led bars are attached
to the aluminum frame as shown in Fig. 6b. Each of these led bars is directly mounted above every Raspberry PI camera and serve to offer a high intensity lighting for fast video capturing, where the exposure level is set to the minimum. As a result of that, the vision system is able to capture 90 FPS at a resolution of 640x480.

A test experiment was conducted to figure out the accuracy of the proposed vision system as shown in the supplementary video SV1. This experiment included a Denso robotic arm [38] that was used to generate a 3D zigzag-like path in the view field of a Raspberry PI camera (Fig. 7a). This robot arm achieves a repeatability of ±0.02 mm. The robot end-effector was attached with a plate on which a fiducial marker was glued. The camera was set with a fixed focus that was adjusted for edge sharpness at a distance of 100 mm. As the robot was moving, the marker’s instantaneous 3D position was being recorded. After completing the experiment, the acquired point cloud of 3D marker detection points was aligned with the commanded robot arm zigzag path. 3D alignment was carried out using constrained optimization function “fmincon” in Matlab to find the homogenous transformation matrix that best matched the robot arm path to the marker detection point cloud. Fig. 7b shows the plot of marker detection points colored according to each point tracking error. Fig. 7c depicts the tracking error versus the distance between the marker and the camera. As the marker was going far from the camera, the tracking accuracy was decreasing. According to Fig. 7c, the maximum tracking error is under 1.2 mm within a distance range of 140 mm between the camera and the fiducial marker, while the root mean square (RMS) of the tracking error is 0.3 mm.

**C. Experimental and TFEA Results**

This subsection validates the suggested TFEA methodology through experimental verification. Two actuation scenarios are presented, where each scenario involves certain routine of pressure application to every FFA of the soft robot. The pressure command for every FFA is congruently applied to the fabricated prototype as well as the developed finite element model. The soft robot response is
determined by registering the X, Y, and Z coordinates of its distal cap’s tip trajectory. The normalized error percent between the experimental and TFEA responses is computed as the ratio of Euclidean distance to the original length which is 70 mm.

In each actuation scenario, two TFEA simulation studies were conducted to show the effect of material modeling principles. The first simulation study (HVM-TFEA) involved the incorporation of hyperelasticity, viscoelasticity, and Mullins effect behaviors. The second simulation study (H-TFEA) included only the hyperelasticity behavior. The basic aim of conducting two simulation studies is to show the difference of the dynamic responses between the combined soft material behaviors and the hyperelastic-only behavior which was studied in the conference paper [21].

The pressure inputs (P1, P2, P3) in the first actuation scenario were rectangular pulses which were applied consecutively to each of the three FFAs as plotted in Fig. 8. Each pulse drove the soft robot to bend in a plane that encompassed the soft robot Z-axis and the initial axis of the corresponding actuated FFA. This experiment was recorded in the supplementary video SV2 for the HVM-TFEA study. During this experiment the maximum distance between the fiducial marker and the vision system cameras was 115 mm, which ensures a tracking error within 0.8 mm. The normalized error plot in Fig. 8 shows the effectiveness of HVM-TFEA over H-TFEA on the intervals of constant pressure application and restoration to original position. This is due to fact of material stress relaxation over time. For instance, on the time intervals of 1 to 2 s, 4 to 5 s, and 7 to 8 s, HVM-TFEA achieved a steady state error of 1% compared to 4% and increasing for the H-TFEA. During these time intervals of constant pressure application, the soft material was undergoing stress relaxation. Consequently, the material became a little bit softer, and hence the soft robot moved very slowly rather than staying stationary. Regarding the restoration to the original position on the time intervals of 2.5 to 3.5 s, 5.5 to 6.5 s, and 8.5 to 9 s, HVM-TFEA also achieved a steady state error of 1% compared to 2% for the H-TFEA. The maximum observed normalized error due to transient pressure changes was 11% for HVM-TFEA and 13% for H-TFEA, which happened only on tiny time interval. The root mean square (RMS) of the normalized error was 3% for HVM-TFEA and 4% for H-TFEA.

The second actuation scenario involved supplying a phase shifted sinusoidal waves of air pressure to each FFA as plotted in Fig. 9. That actuation pattern caused the soft robot’s tip to move in a nearly circular path. The supplementary video SV3 shows the details of this movement for the HVM-TFEA study.

![Fig. 8. Dynamic response of rectangular pulses actuation. Experimental data is compared to two TFEA studies, where one study (HVM-TFEA) models hyperelasticity, viscoelasticity, and Mullins effect, while the other study (H-TFEA) only models hyperelasticity.](image-url)
In this actuation scenario, the two TFEA studies performed almost the same because the applied pressure rate was quite fast that did not allow the soft material viscoelasticity to make influence during the experiment. The maximum observed normalized error due to transient pressure changes was 11% for HVM-TFEA and 13% for H-TFEA. The root mean square (RMS) of the normalized error was 5% for both HVM-TFEA and H-TFEA.

It can be concluded from the previous case studies that in the cases of fast actuation, the effect of viscoelasticity is not prominent and the hyperelasticity is majorly contributing to the modeling and simulation results. Contrarily, in the cases of slow actuation and quasi-static pressure application, which is the case of using soft robots for MIS, viscoelasticity has to be considered with hyperelasticity. The Mullins effect starts to make influence if the soft material undergoes very high strains. However, it is not a good practice to design a soft robot for MIS that might be susceptible to high strains so as to prevent permanent material damage. The maximum strain happened in the previous case studies was 0.8 for Ecoflex 00-30 and 0.3 for Dragonskin 30 as computed using FEA. Comparing these maximum strain values with the plots of material damage in Fig. 4 indicates that the soft materials did not experience any noticeable internal damage. However, in order to ensure the best TFEA results in accordance with the experimental results, the three material behaviors have to be considered together.

VII. CONCLUSION

Dynamic modeling and simulation of soft robots is vital for real-world applications, especially in precise minimally invasive surgical operations. Devising the proper control algorithm for soft robots counts on the accuracy of dynamic modeling. Since the used materials for fabricating soft robots have complex nonlinear behaviors, their dynamic simulations cannot afford any simplifying assumptions. This work presents a generic framework for designing and experimenting fiber-reinforced soft robots. The proposed methodology utilizes transient FEA which relies on modelling all the nonlinear behaviors of the soft materials that involve combined hyperelasticity, viscoelasticity, and Mullins effect.

Experimental realization validates the estimated TFEA dynamic system response of the soft robot. Results for different actuation routines show a good agreement between the TFEA and experimental responses. The maximum normalized error is 11% at transient steps, while the maximum steady state normalized error is 1%. The root mean square (RMS) of the normalized error is 5%. Consequently, the proposed methodology can be used to predict the dynamic response of soft robots without the necessity of fabricating them, since it depends only on material modeling and does not involve any assumptions. Once the soft material parameters are determined, any new soft robot design concept or configuration can be examined using TFEA without the need to do real-world prototype fabrication and that greatly shortens the development cycle of new surgical soft robots. In addition...
to that, testing any new dynamic model or control algorithm can be carried out directly with TFEA. These merits widely pave the way for any futuristic developments in the field of soft robotics.

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