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A physical soft tissue growth simulator for implantable robotic devices

Marco Pontin and Dana D. Damian

***Abstract*—In the development of surgical technologies, one of the challenges in their initial validation has been the creation of accurate bench-top tissue phantoms. Tissue phantoms made of elastomeric material have fixed mechanical properties and are not able to increase in size, so they cannot mimic growth process or change in mechanical properties of their real counterparts. In this work we present a novel real-time soft tissue simulator aimed at testing the in vivo dynamic behavior of robotic implants. The simulator is capable of reproducing mechanical properties of the biological tissue, e.g. viscoelasticity, as well as its metabolism, being able to grow up to 260 mm. A control strategy based on impedance control enables the simulation of changing mechanical properties in real-time, in order to recreate conditions such as fibrosis or tissue scarring. We finally show the platform in use with a soft implant. The electric actuation in conjunction with the 500 Hz control loop frequency guarantees fast and accurate response. We believe our platform has the potential to reduce the need for in vivo preclinical studies and shorten the path to clinical experimentation.**

***Index Terms*—Internal robots, Physical soft tissue simulator, Robotic implant, Tissue growth simulator**

I. Introduction

In the development of surgical technologies, one of the challenges in their initial validation has been the creation of accurate bench-top tissue phantoms [1], [2]. In vivo testing in animals still plays a key role in understanding the interaction between implants and the tissue they are operating on. Although these tests will remain an important step towards human implantation, reducing the need for these types of validation experiments should be a priority for researchers. A possible solution could be the development of bench-top soft tissue simulators that mimic the behavior of various soft tissues, making it possible to fully test the dynamic performance of the implants before in vivo experimentation. In the case of regenerative robotic implants (RI) that grow soft tissues as a result of mechanical stimulation [3]–[5], the tissue phantom should not only simulate the mechanical properties, but also simulate the metabolism of the tissue, e.g., its growth. This is of the utmost importance to fully test the safety and operation performance of such robots before in vivo implantation.

Soft tissue has been modeled using a number of approaches, ranging from simple linear elastic models to more complex and accurate viscoelastic ones [6]–[8]. In [9] the authors model the multi-layer esophageal soft tissue using Mooney-Rivlin, Ogden, and Neo Hookean models and then compare the three in terms of accuracy. Nekouzadeh et al. [10] propose an adaptive quasi-linear viscoelastic (QLV) model to simplify experimental tuning of the parameters and then test it by predicting the behavior of pure reconstituted collagen. In [11] the authors use a modified Voigt model to better describe the behavior of soft tissue at high frequencies.

Usual applications for these models are medical training, haptics, or for the automation and control of novel surgical tools [12], [13]. Computer based simulation is another possible use case, where the model is used in robotic surgical devices to provide feedback during surgical training. In [14], a model for esophageal tissue based on QLV is proposed and the parameters are tuned using samples of porcine esophagi. Ortiz and Lagos [15] develop a modified Kelvin model of viscoelasticity to be used in real-time surgical simulations. The same goal is pursued in [16], where the authors prefer an approach based on neural networks: both isotropic and anisotropic materials can be modelled and the resulting architecture is implemented in a physical haptic feedback device. Similarly targeting real-time simulation of soft tissues, Bao et al. [2] propose an hybrid model based on a multilayer structure of spheres interconnected using a three-parameter viscoelastic model.

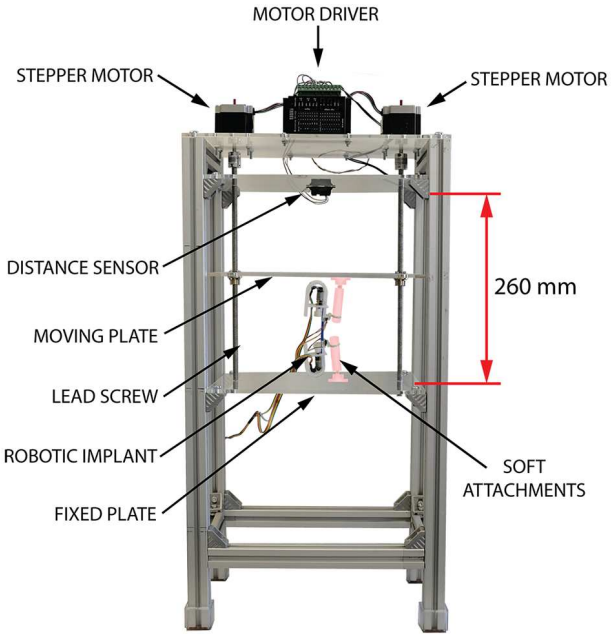

Fig. 1. The soft tissue simulator platform. The platform is used to validate robotic implants for tubular tissue growth.

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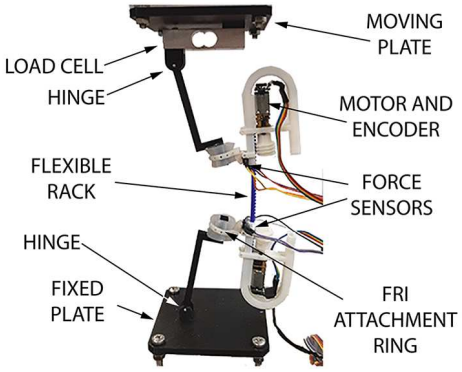

Fig. 2. Detail of the Flexible Robotic Implant (FRI) connected to the tissue simulator.

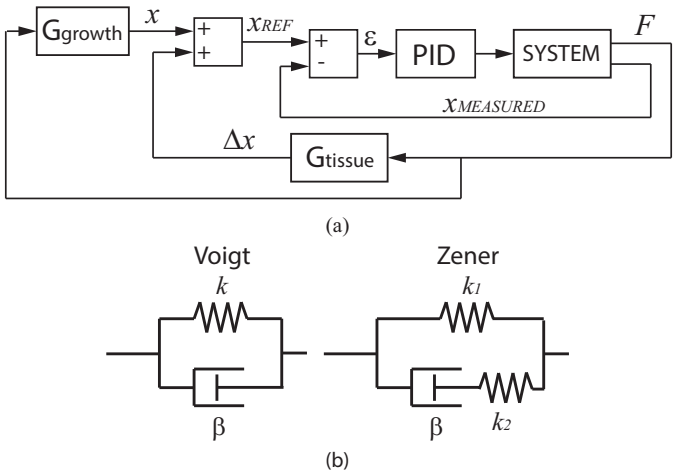

Fig. 3. (a) Block diagram of the system. x and Δx are the displacements due to growth and viscoelasticity, x_{REF} is the target displacement of the moving plate, ϵ the error between target and measured displacement $x_{MEASURED}$ and F is the measured force. (b) Mechanical equivalents of the Voigt and the Zener models.

The resulting architecture is then tested against a porcine liver specimen. While these works offer useful insights for modelling biological soft tissues, they mainly entail simulation and do not address tissue growth.

The aim of this work is to develop the prototype of a robotic platform, shown in Fig.1, that simulates both the mechanical properties of the tissue, as well as its growth.
In previous works from our lab, we developed robotic implants that grow tubular organs, such as the esophagus or the intestine, by applying mechanostimulation [3], [5], [17], [18]. Both implants, when interacting with the organs, need to adapt the treatment based on the changing status of the tissue, which could show inflammation, scarring or fibrosis. The development process of the physical soft tissue simulator was therefore guided by two main requirements: flexibility in the types of tissue models that can be implemented and the ability to change model parameters in real-time. Such capabilities will be highly relevant in testing the robotic implants' dynamic operation as expected in vivo. An approach resembling that of impedance control was therefore used to achieve these requirements and provide fully tunable performance. Another important design goal was to have a large enough growth simulation potential so that the platform could be used to test applications such as long-gap esophageal atresia, where the tissue is expected to grow up to 100 mm during the treatment.

II. Materials And Methods

A. Physical Simulator

The platform simulates the viscoelastic properties of soft tissue, as well as its growth. It consists of a moving plate and a fixed one (Fig.1). The distance between these two plates represents the platform's capacity for growth simulation and, as displayed in Fig.1, this can reach 260 mm. A robotic device, able to extend itself (e.g. the FRI of Fig.2), is to be connected between the two plates and trigger the lengthening/shortening of the tissue phantom by applying forces. Two NEMA-23 stepper motors (57STH56, Phidgets), controlled by drivers (TB6600, TopDirect), move the top plate via a lead screw mechanism; meanwhile the force that the robotic implant is exerting is measured by a force sensor placed between the robot attachment and the same plate. The displacement is directly computed counting the motor's steps.

B. Controller

Controllers implemented in software dictate the behavior of the moving platform based on the interaction with the robotic implant. The viscoelastic controller designed for this application is shown in Fig.3a and was digitally implemented on an Arduino Nano microcontroller. In the block diagram, the transfer function $G_{tissue}(z) = \frac{\Delta x}{F}$ represents the model of the soft tissue and is used with the measured force to compute the appropriate displacement solely due to viscoelasticity. The force is also used in conjunction with the function $G_{growth}(z) = \frac{x}{F}$ to calculate the growth rate of the tissue. These two contributions, the one caused by the viscoelastic response of the tissue and that due to the growth, are then added together to generate the reference signal for the moving plate. A PID compensator finally serves as the position controller for the system.
To test the flexibility of the platform, G_{tissue} was first considered to be that of the Voigt model (Eq.1), whose mechanical equivalent is a spring and a dashpot in parallel as in Fig.3b; a second model, the Zener one (Eq.2) and Fig.3b, was then implemented. Meanwhile, G_{growth} was a simple linear function of the force applied by the robotic device.

$$F = kx + \beta\dot{x} \tag{1}$$

$$F + \frac{\beta}{k_2}\dot{F} = k_1 x + \frac{\beta\,(k_1 + k_2)}{k_2}\dot{x} \tag{2}$$

These two models are widely used in literature as benchmarks for describing viscoelasticity and have been also adopted to model the behavior of soft tissues [6]–[8], [11], [15]. Although being simple compared to other alternatives, we believe these two models strike a good balance between accuracy, ease of implementation, speed of computation and overall simplicity in parameter tuning, only requiring the knowledge

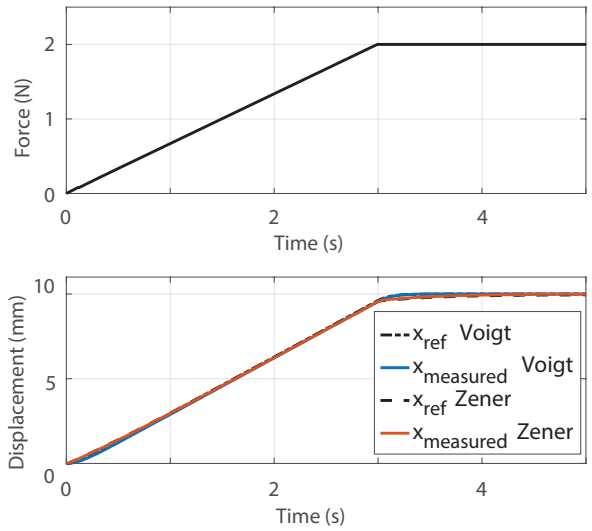

Fig. 4. Comparison between Voigt and Zener models with growth disabled and a ramp increase in the force input. (Top) Force input. (Bottom) Output target and measured displacements, using both the Voigt and the Zener models.

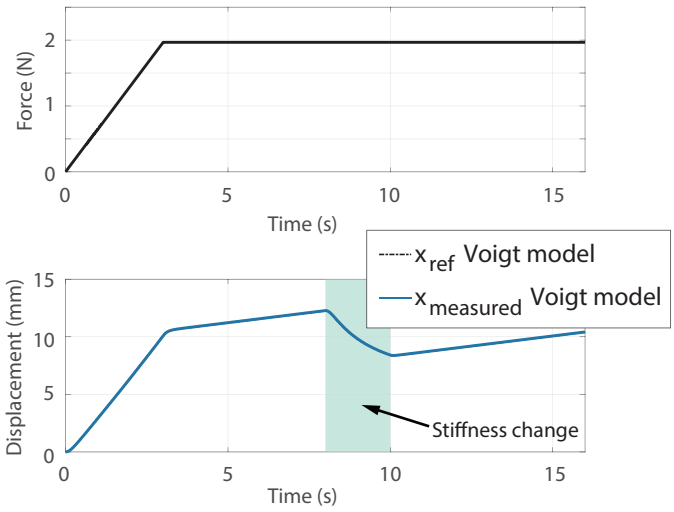

Fig. 5. Results of an experiment with tissue growth enabled and stiffness change at $t = 8$ s from 200 N/m to 300 N/m in 2 s. (Top) Force signal. (Bottom) Target and measured displacement of the moving platform of the tissue simulator.

of up to three coefficients to describe the viscoelastic behavior of the tissue. In particular, the ability to perform the simulation in real-time is key for this application. Both the PID controller loop and the tissue model that serves as input to the controller are updated at a frequency of 500 Hz. This frequency suffices for the envisaged application, as high frequency phenomena, over tens of Hertz are unlikely to occur.

C. Flexible Robotic Implant (FRI)

Before analysing the results, we briefly present the FRI, as this was used to explore the potential of the platform to mimic tissue properties while interacting with a real implant. The FRI uses a worm gear-rack mechanism to extend/retract with changing tissue length. The rack is flexible for mechanical compliance and force sensors transduce the tension applied to the tissue. During normal operation, a force controller ensures that the desired target mechanostimulation is maintained [3], [5]. As detailed in Fig.2, the FRI is coupled to the plates of the simulator using custom designed 3D printed components. The connection is achieved by sliding the Ecoflex 00-30 cylinders inside the implant's attachment rings. Hinges at the top and the bottom provide the necessary degrees of freedom during operation.

III. Results

In order to test the performance of the platform, preliminary experiments were conducted, generating the force signal directly in the software. Fig.4 shows the results of a ramp increase in the force input, from 0 to 2 N, with the growth disabled. The value of 2 N is consistent with what is realistically applied to the esophageal tissue during the Foker technique in the treatment of long-gap esophageal atresia [4]. One can observe the nonlinear behavior of the tissue due to G_{tissue}, mostly in the beginning and end of the transient phase. Both the Voigt and the Zener models were used: in the first case, the stiffness k was equal to 200 N/m, while the damping factor β was 20 Ns/m; in the second k_1 was 200 N/m, k_2 was 100 N/m and β was 20 Ns/m. These values were selected to make visualisation of the viscoelatic behavior easier. The test also shows that the PID controller is capable of following the desired reference signal with no overshoots. Fig.5 shows the results of a test where the growth was enabled and equal to 0.35 mm/s and the simulated stiffness changed in a ramp from 200 N/m to 300 N/m in 2 s, from $t = 8$ s to $t = 10$ s. The viscoelastic model used for this test was the Voigt one. A similar experiment was then performed, but in this case the growth was enabled within the entire range, from 0 to 260 mm (Fig.6). Also, two tissue stiffness changes were simulated, one at $t = 2.6$ min and the second at $t = 5.3$ min, with each transient lasting 1 min. The stiffness varied from 200 N/m to 400 N/m and finally to 600 N/m. The Voigt model was used to simulate viscoelasticity. The ability to change the model in real-time means one can also simulate different conditions of the tissue, like scarring and fibrosis. This could be important in testing customized reaction strategies by the robotic implant, designed to prevent excessive strain on the tissue.

A second part of the experiments was devoted to a more realistic case study, with a robotic implant interacting with the simulator. The robotic device we used is the FRI. Fig.7 shows some preliminary results. The target force of the FRI, visible in the top chart of the figure, has a sudden drop from 0.45 N to 0.15 N. Consequently, the FRI starts retracting and the signals corresponding to the output of the force sensors and the force sensed by the load cell of the tissue simulator drop to the new value as well. The bottom chart shows the retraction of the platform, as a result of the decreased tension on the tissue phantom, according to a Voigt model with $k = 200$ N/m and $\beta = 80$ Ns/m. The results demonstrate good agreement between the various signals. Moreover, we can conclude that the dynamic performance of the platform is in line with that required for the application.

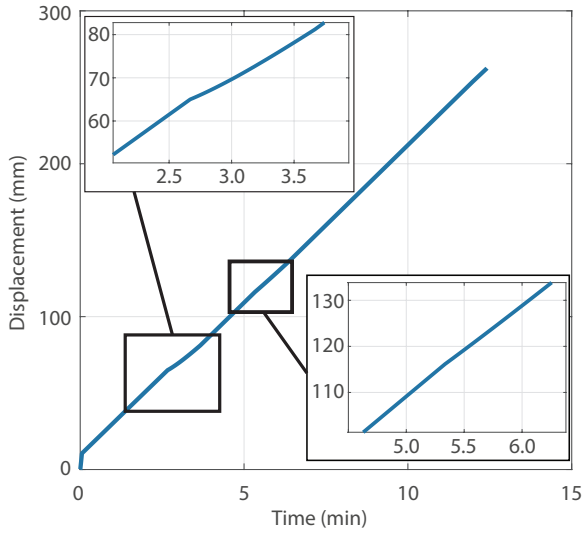

Fig. 6. Results with growth enabled throughout the experiment and two stiffness changes at $t = 2.6$ min and $t = 5.3$ min; with each transient lasting 1 min. The stiffness was first increased from 200 N/m to 400 N/m and finally to 600 N/m. The experiment shows the growth simulation potential of the platform, which can reach 260 mm.

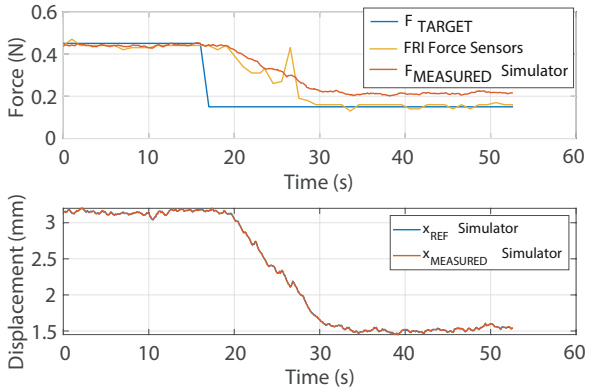

Fig. 7. Experiment with the Flexible Robotic Implant connected to the platform. (Top) The target force is decreased from 0.45 N to 0.15 N; (Bottom) as a consequence, the moving plate of the tissue simulator also retracts following the desired viscoelastic behavior. For this test the Voigt model was used with $k = 200$ N/m and $\beta = 80$ Ns/m.

Discussion And Conclusion

In this work we presented a physical soft tissue growth simulator. The envisaged application is in conjunction with robotic implants in order to test their capabilities in a dynamic physical environment that can simulate dynamic changes in metabolism, e.g., tissue growth, and physiology, e.g. tissue fibrosis, relaxation. The approach is flexible, enabling different viscoelastic models to be simulated, as shown in the results section of the paper. The architecture makes it also possible to introduce real-time changes in the parameters, in order to simulate variations in the characteristics of the tissue itself such as increased stiffness. Although the biological tissue growth rates are lower, the values in this study were used to visualize the simulator's operation; the same holds true for the parameters k and β.

The physical platform could find broader applications in tissue engineering, control engineering and computer science as it enables the real-time simulation of viscoelastic tissue behaviors. Future developments include the use of the simulator in conjunction with the FRI to further study its fault-tolerant control strategy [3] and with soft implants [17], [18] to characterize their dynamic behavior.

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