The Biophysicist

Take-home Tensile Testing System for Biomechanics Education

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ABSTRACT Characterizing the load–deformation relationships in both engineering materials and biologic tissues is a key component of undergraduate biomechanics and mechanobiology courses. These relationships are essential to determining the suitability of a given material for biomedical applications, such as identifying the root causes of implant failure and injury and quantifying the effects of mechanical cellular mechanotransduction. Typically, material characterization is done by using industry standard and research-grade material testing systems, which can cost tens to hundreds of thousands of dollars and require large amounts of dedicated laboratory space. This article presents a new design for a low-cost and portable alternative to these commercial systems, consisting of off-the-shelf and 3-dimensional printed components for teaching purposes. Student groups assemble their own devices and conduct material characterization experiments for both elastic and viscoelastic materials on their own time, outside of traditional laboratory settings. The "take-home" labs were pilot tested over a single semester, and preliminary results showed increased understanding of elastic and viscoelastic theory compared with lecture alone. These results suggest that the take-home tensile testing systems may be an effective means of providing a hands-on educational experience in courses in which traditional lab activities are not otherwise possible.

KEY WORDS mechanobiology; tensile testing; lab activities; take-home; undergraduate

I. INTRODUCTION

Opportunities for practical hands-on learning activities are an integral part of science, technology, engineering, and math (STEM) education. Traditionally, these activities have taken the form of structured lab activities conducted during set times, with an instructor or teaching assistant present to guide students through the activities. However, this lab structure poses a number of potential obstacles that can reduce individual student involvement and ultimately hinder student success in these settings. Limited availability of lab space and instructional support often results in large class sizes. Expensive lab equipment may not be accessible for all institutions, particularly those in low-resource settings. Offering labs only during set times with structured hours forces students to try and learn at a set pace, rather than at the speed at which they are most comfortable (1, 2). Recently, educators have begun to turn to low-cost and open-source platforms for developing "take-home" labs that allow students to maximize learning outcomes by providing low-cost alternatives to expensive lab equipment and allowing a student to learn at his or her own pace outside traditional classroom and laboratory settings (1–5).

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II. SCIENTIFIC AND PEDAGOGIC BACKGROUND

Characterization of material properties is a central component across many scientific and engineering disciplines. In the fields of biomechanics and mechanobiology, the bulk mechanical properties, that is, how materials respond to applied loads, of both biologic tissues and traditional engineering materials are of particular interest. Understanding of these properties is a critical component to predicting how biologic tissues, orthopedic implants, and prosthetic devices will perform during use, evaluating the causes of material failure, and identifying the effects of substrate materials on mechanotransduction at both tissue and cellular levels (6, 7). Uniaxial tensile testing is the most common method used to quantify bulk mechanical properties and is, therefore, a mainstay of most mechanical, biomedical, and material engineering curricula.

Variations on uniaxial tensile testing methods are used for different types of metals, ceramics, polymers, and biologic tissues and include both quasistatic and time-dependent loading, depending on the material model being used. Material models describe the load–deformation relationship of a given material. For most engineering metals and ceramics, a simple linear elastic relationship is most often used. The stress–strain (σ–ε) relationship for these materials is modeled by using Hooke law (Eq. 1). Uniaxial tensile testing can determine properties, such as the elastic modulus (Young modulus, E), yield strength, ultimate tensile strength, and work to fracture:

$$\sigma = E\varepsilon \tag{1}$$

For linear elastic solids, these material properties are independent of the rate of loading, and a single uniaxial tension test is sufficient to characterize the linear elastic properties. Conversely, biologic tissues, such as muscle, tendon, ligament, and cartilage, as well as synthetic polymers, require more sophisticated material models that incorporate nonlinear, hyperelastic, or time-dependent elements into their constitutive equations. Although numerous models of varying complexity exist, the standard linear solid (SLS) model, shown in Eq. 2 and Figure 1, can be used to roughly approximate the material behavior of viscoelastic materials under applied loads and small deformations (8).

$$\sigma + \tau\dot{\sigma} = E_1\varepsilon + (E_1 + E_2)\tau\dot{\varepsilon}, \tag{2}$$

where $\tau = \eta/E_1$ is a time constant used to represent the relationship between elastic parameter E_1 and the viscous parameter η. Simple tension tests are not sufficient to characterize these viscoelastic materials, and time-dependent tests such as stress relaxation and creep deformation must be performed.

Uniaxial tension tests are typically performed with large material testing systems (MTS), which can accurately measure both the applied force and elongation of the test specimens. These systems typically use strain gage–based load cells to record force measurements and extensometers or other displacements sensors to measure the specimen deformation. Commercial MTS typically cost at least tens of thousands of dollars and are substantial in size, constraining the number and quality of systems available for student use at educational institutions. Although smaller, more affordable educational systems do exist, they still cost thousands of dollars and are large enough that they must remain in traditional laboratory settings (9). Furthermore, these systems are all self-contained, often require proprietary software, and do not help students gain an appreciation for how the force and deformation measurements are made or how they are affected by the system settings (such as load rate and sampling rate). Recent work by Arrizabalaga et al. showed that an economical uniaxial tensile testing system can be constructed by using open-source software and off-the-shelf hardware, but the design still required a large wooden frame and the manual loading mechanism made some forms of uniaxial testing impractical (1). Therefore, the objective of this work was to develop a low-cost and portable tensile testing platform that students can assemble and then conduct tests with to characterize both elastic and viscoelas-

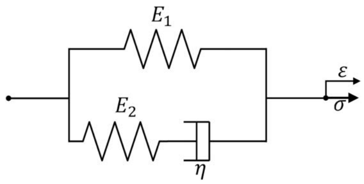

Fig 1. The Kelvin–Voigt representation of the SLS model consisted of two elastic spring elements with moduli E_1 and E_2 and a single dashpot (viscous) element with parameter η. For stress and relaxation tests, the specimen is stretched to a fixed strain value, ε, and the stress $\sigma(t)$ is recorded as a function of time.

tic materials outside of traditional laboratory settings and on their own time.

III. MATERIALS AND METHODS

A. Lab kits

Because the goal of the take-home labs is to provide the student with the opportunity to construct his or her own tensile testing system, each student was provided with a lab kit containing all of the necessary hardware, electronics, and test materials. Each kit was accompanied by written and pictorial instructions for how to assemble the tester and begin collecting data. When materials are purchased in bulk, each kit costs approximately US$80. A photo of the complete contents of each kit is shown in Figure 2.

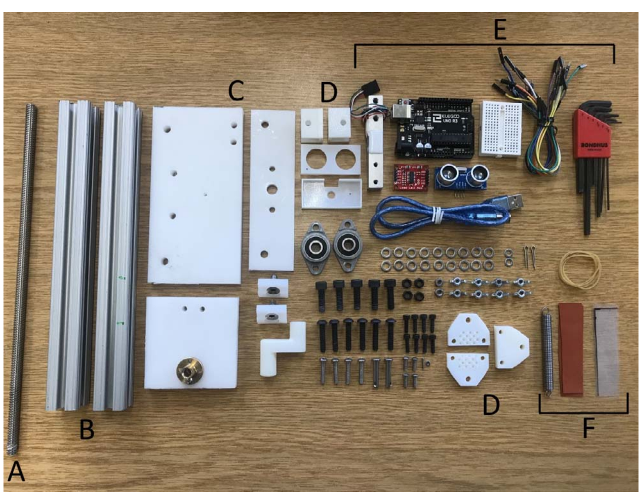

Fig 2. The lab kits are given to students disassembled. Each kit consists of the (A) leadscrew, (B) frame and hardware, (C) custom end blocks, (D) 3D printed parts, (E) electronics and sensors, and (F) test specimens to conduct a series of 3 separate lab activities exploring concepts pertaining to elasticity and viscoelasticity.

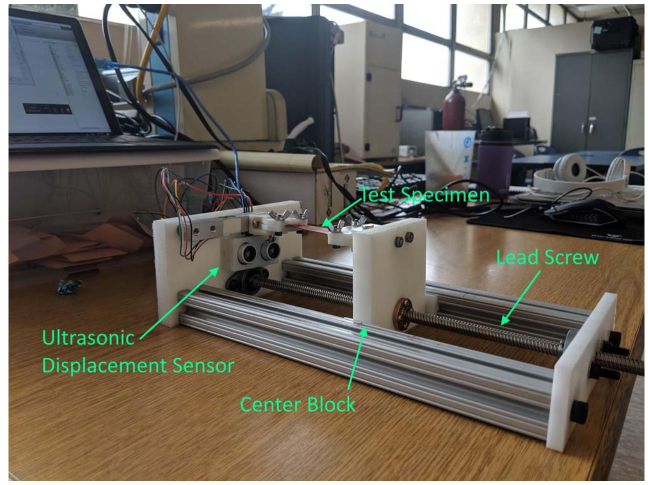

Fig 3. The fully assembled desktop tensile testing system connects to a laptop or desktop computer through the Arduino USB interface. A MATLAB script is used to record the measurement data collected by Arduino. When the leadscrew is turned, the center block travels horizontally.

B. Hardware

The hardware required to construct the tensile testing system is a combination of off-the-shelf components and custom parts. The custom parts can be fabricated by using a combination of standard machine shop tools (end mill and drill press) and 3-dimensional (3D) printing. The support frame for the tensile tester consists of T-slot aluminum framing rails connected to custom Delrin plates. A T8 leadscrew (8 mm pitch) is supported by this frame and is threaded through a Delrin center block, as shown in Figure 3. Rotation of this leadscrew causes the center block to travel linearly inside the frame. The sides of the center block are supported by the T-slot framing by using a linear slide, which reduces the friction during its travel. The leadscrew was manually turned by using a hand crank fixed to one end. The hand-crank design was selected as a simple and low-cost mechanism for driving the lead-screw. Alternative drive mechanisms, such as a stepper motor, could produce more consistent displacement of the travel block but increase the cost and complexity of the system. A complete list of materials, SolidWorks (Dassault Systèmes, Waltham, MA) part files, engineering drawings, and stereolithography (STL) files can be accessed at https://drive.google.com/drive/folders/18PynClGD8ul6S6UKH5Afd-Lre80FCfob.

C. Sensors and electronics

Force and displacement were measured by using a 10-kg bar-style load cell (TAL 220, SparkFun Electronics, Niwot, CO) and ultrasonic displacement sensor (HC-SRO4, SparkFun Electronics), respectively. Both sensors were standard off-the-shelf units and were selected for the combination of small size and low cost. The bar-style load cell used a 4-wire Wheatstone bridge configuration and required an external amplifier (HX711 breakout board, SparkFun Electronics) to produce a measurable voltage. The ultrasonic sensor was connected directly to the microcontroller and used an internal clock to estimate the time of flight of ultrasonic pulse echoes to estimate distance. The sensor had a range of 2 to 400 cm, with a resolution of approximately 0.3 cm.

Data were collected by using an Arduino Uno microcontroller connected to a personal computer through a Universal Serial Bus (USB) connection. Both sensors were connected to the microcontroller 5-V power supply with jumper wires connected to a miniature breadboard. The wiring connection diagram for the sensors and microcontroller is shown in Figure 4.

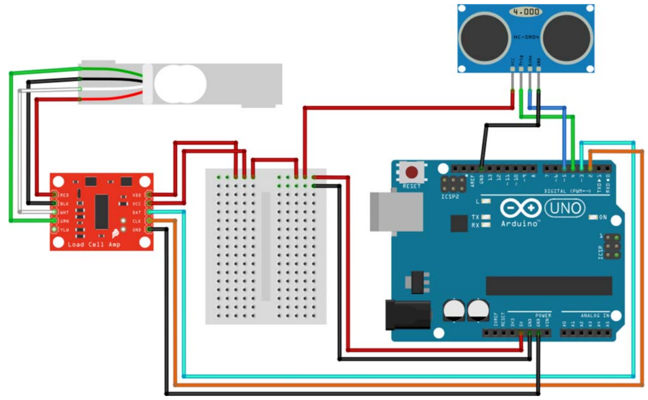

Fig 4. Wiring diagram for the load cell (top left), ultrasound displacement sensor (top right), and Arduino Uno microcontroller. The load cell requires the use of a signal amplifier (left) to increase the output voltage prior to being recorded by the microcontroller. Both sensors run off the Arduino Uno onboard 5-V power supply.

D. Software

A custom Arduino script was uploaded to each microcontroller to interface with the sensors and transmit the measurements to a personal computer through a serial connection. Customized MATLAB (The MathWorks, Natick, MA) scripts were also created to read the data from the serial port and plot it in real time. Separate scripts were created for MATLAB releases newer than R2017a and older than R2017a. When the MATLAB plot window was closed by the user, the data were automatically saved to a delimited text file of the user's choosing. A similar script was also created for data acquisition by using Python (Python Software, Beaverton, OR) so that students and institutions without access to MATLAB can also use the system. Similar to MATLAB scripts, the Python code plots the data in real time and outputs it to a comma-separated value text file.

E. Test materials

Four different material types were originally included in each lab kit: (a) a linear spring, (b) latex rubber bands, (c) silicone rubber sheet, and (d) polyethylene sheets. The linear spring had a known stiffness of 3.8651 ± 0.1933 N/cm and was used to calibrate the load cell. The remaining 3 materials were chosen to exhibit varying degrees of elasticity and viscoelasticity.

Video of the tensile testing system being used to conduct a single loading cycle on a sheet of silicone elastomer is shown in Supplemental Videos S1 and S3 in the Supplemental Material. As the user turns the crank handle, the center block travels along the leadscrew and stretches the test material. The resulting force and deformation data are plotted by using the MATLAB interface in real time (Supplemental Videos S2 and S4).

F. Take-home labs

A series of 3 take-home lab assignments was created to accompany the lab kits. The first lab provided instructions on how to construct the system, calibrate the load cell, and perform basic tensile testing to quantify elasticity. The second lab used the silicone, rubber band, and polyethylene test samples to explore viscoelastic behavior and plastic deformation. The third

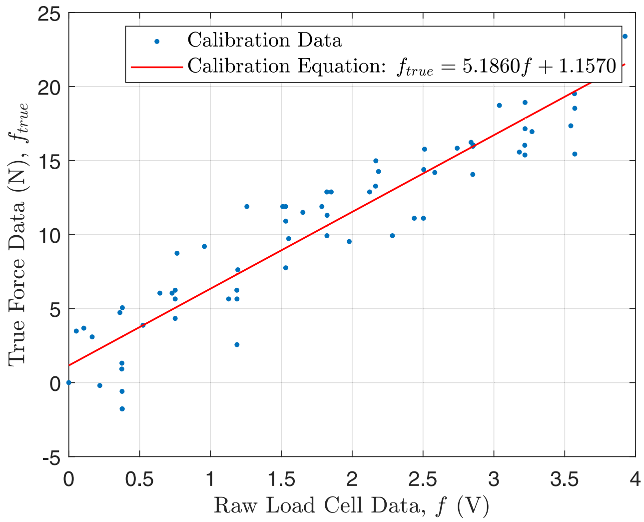

Fig 5. The load cell was calibrated by fitting the linear relationship to the raw voltage from the load cell to the expected force produced by stretching a spring with a known rate constant. The noise in the "true force data" is a result of the low resolution of the ultrasonic displacement sensor.

lab required students to perform cyclic loading on the rubber band, silicone, and spring materials to quantify hysteresis.

For each lab, groups of 3 students worked together to build the test system and then collect force and deformation measurements for each required test. Written and pictorial step-by-step instructions were provided for how to assemble the testing platform, and the lab handouts provided step-by-step instructions for how to perform each test. Because each lab kit was self-contained, the student was able to perform all experiments on his or her own time, outside of the traditional classroom and laboratory settings. However, open lab hours were offered twice a week for the instructional staff to answer questions and troubleshoot problems with the test platforms, as needed.

G. Load cell calibration

To calibrate the load cell, a linear spring of known stiffness was placed in the testing apparatus and stretched a fixed distance, as measured by the ultrasonic displacement sensor. The displacement data were used to estimate the nominal "true" force applied from the spring by using Hooke law. Linear regression was then used to establish a mathematic relationship between the nominal force and the voltage signal output by the load cell, as shown in Figure 5. Note that the uncertainty in the spring stiffness and noise in the ultrasonic sensor output do degrade the accuracy of this calibration relationship. Although alternative methods of calibration, such as hanging high-precision lab weights, could be used, the spring-based method was chosen due to its low cost and light weight.

H. Lab activities

Because the data acquisition system provided the student with raw data, the student had to perform all preprocessing of the data for all lab activities. This preprocessing includes zeroing both the force and deformation data and performing any filtering necessary to reduce the noise. For each of the 3 labs, students were asked to fit the preprocessed data to material models representing elastic behavior (Hooke law) or viscoelastic behavior (SLS model) or a combination of both to quantify the material constants for each material.

In ideal stress and relaxation tests, an instantaneous strain is applied to the material, and the resulting stresses produced in the material are recorded. The solution to Eq. 2 for this instantaneous input is provided in Eq. 3.

$$\sigma(t) = \varepsilon_0\left(E_1 + E_2 e^{-t/\tau}\right) \tag{3}$$

Sample data from a stress and relaxation test on silicone are shown in Figure 6. Because the dimensions of the thin silicone specimen were not recorded, force and deformation were used in place of stress and strain. Similarly, the initial displacement ($\varepsilon_0 \approx 5.9$ cm) cannot be instantaneously applied, so students were instructed to rapidly turn the crank to approximate this idealized behavior. The calibrated force data (blue dots) were then fit against the SLS model solution (Eq. 3) by using exponential regression to determine the E_1, E_2, and τ parameters.

To facilitate these improvements and to encourage adoption of take-home lab technology for STEM education, the parts lists, assembly instructions, part designs, code, and laboratory activities have been made available

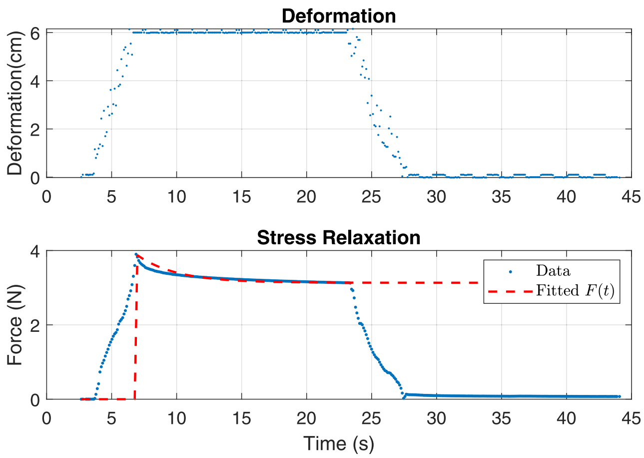

Fig 6. Sample deformation and force plots for the stress and relaxation testing of the silicone rubber specimen. The sample was quickly stretched to a 5.9-cm deformation, held at a constant length for approximately 16 s, and then returned to the original length. The SLS material constants were then determined by performing an exponential linear regression on the decaying force versus time data. This analysis returned parameters $E_1 = 57.9$ N/m, $E_2 = 14.4$ N/m, and $\tau = 2.0\ s^{-1}$.

online at https://drive.google.com/drive/folders/18PynClGD8ul6S6UKH5Afd-Lre80FCfob.

I. Assessment

All of the underlying course concepts required for the labs were taught prior to the labs being assigned. Student understanding of these core concepts was assessed with a 10-question multiple choice "concept quiz" immediately prior to the lab kits being distributed. The same quiz was administered approximately 3 weeks later, after the completion of all 3 labs and postlab questions. Students were not provided with the correct answer to the concept quiz prior to the follow-up quiz. A pairwise Student *t* test determined whether the labs increased quiz scores by using $\alpha = 0.05$. To provide a baseline comparison from which to compare the students' performance, the same quiz was also administered on a volunteer basis to students who took the course 1 year earlier. These previous students had not had the opportunity to participate in the take-home labs, nor had they participated in any similar activities in a traditional lab, so the responses were meant to represent what a student remembers approximately 12 months after completing the course

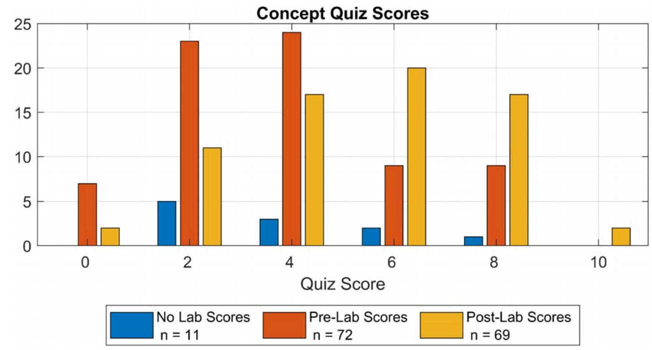

Fig 7. Pre- and postlab quiz scores show a significant improvement after completion of the labs. The small cohort of students representing the 1-year follow-up quiz for students who did not have access to any lab activities performed similarly to the prelab scores.

without any hands-on experiments. The mean of the no-lab group was compared against both of the pre- and postlab scores by using standard Student *t* tests with significance at $\alpha = 0.05$. All assessment activities were conducted as part of the normal educational practices for the purpose of curriculum improvement and were exempt from full institutional review board review.

IV. RESULTS AND DISCUSSION

The score distributions for all three sets of quiz results are shown in Figure 7. Of 72 students who took the prelab quiz, only 69 participated in the postlab quiz. The pre- and postlab mean ± standard deviation scores were 4.3 ± 2.3 and 5.8 ± 2.5, respectively, of a possible 10 points. The scores from the 3 students who did not participate in both tests were discarded from the pairwise comparison, and the results show a statistically significant increase of 1.49 ± 2.34 points in the postlab quiz ($P < 0.001$). The 1-year follow-up quiz only received responses from 11 students and resulted in a mean of 4.4 ± 1.9, which was not significantly different from the prelab quiz scores but was significantly lower than the postlab scores ($P < 0.001$). Overall, these preliminary results suggest that the labs did increase student understanding of the underlying concepts behind elasticity, viscoelasticity, and uniaxial tensile testing. However, note that the small sample size and different student cohort used for the no-lab group makes direct comparison of the efficacy of take-home labs at improving concept retention difficult. Additional data are needed from subsequent years to confirm these findings. Of particular interest will be the 1-year follow-up quiz from the students who participated in the labs, which will evaluate how well the core concepts were retained compared with the no-lab group.

Although the tensile testing systems performed well overall and were able to complete the desired tests (simple tension, stress and relaxation, and cyclic loading), several key areas for improvement of the system remain. The primary limitations are introduced by the hardware itself, namely, the low spatial resolution of the ultrasonic displacement sensor and the manual crank mechanisms for driving the center block displacement. Both limitations contribute to noise in the force and deformation measurements and are compounded by errors introduced by the assumptions and simplifications inherent in the material models (e.g., SLS model), leading to errors in the material parameters estimates calculated in the lab activities. However, although this measurement noise makes the test system inadequate for research or commercial testing, it provides students with the opportunity to practice working with noisy data and interpreting their results in the context of these errors. Future iterations of these systems will introduce add-ons, such as stepper motors, to automate the testing process and reduce the detrimental effects of the current limitations. Work to develop these tests is ongoing, and subsequent improvements will be added to the open-source online repository.

Despite these limitations, the take-home tensile testing labs were well received by students and show promise for adoption in mechanics courses at the high school, community college, and undergraduate level. The portability of these testing systems enables a student to take them home and work to complete them in his or her own time, thereby reducing the need for them to rush through lab activities during set class hours. Similarly, this testing system is particularly promising for low-resource settings, when access to traditional laboratory space and equipment is limited.

Finally, the proposed testing platform provides excellent opportunities for students to see the difference between the idealized and empirical behavior of biologically relevant materials. By obtaining hands-on experience constructing this system, performing the experiments, and analyzing the data, students learn that our understanding of material behavior is influenced by the technology and procedures used to conduct the experiments and the models selected to represent the material behavior. Furthermore, this platform gives instructors the flexibility to customize the take-home lab activities and course discussions to meet the level of complexity appropriate for the students and to teach material characterization concepts beyond the simple viscoelastic applications presented in this article. For example, latex rubber bands can be used with appropriate models to represent nonlinear and hyperelastic load–deformation behavior, and polyethylene sheets can be used to represent materials undergoing the transition between elastic and plastic deformation. Although neither of these materials are direct analogs to biologic tissues, each can be used to illustrate one or more types of material behavior exhibited by physiologic systems. Conducting the experiments exposes students to the types of tests used to characterize material behavior, and the results provide context interpreting the published load–deformation relationships and material constants for actual tissues (e.g., tendons, ligaments, and muscle).

V. CONCLUSION

This article presents a low-cost and portable desktop tensile testing system for characterization of linear elastic, nonlinear elastic, and viscoelastic materials. Using these tensile testing systems, students complete a series of take-home labs that do not require them to complete the activities in a traditional, structured laboratory environment. The initial evaluation of these take-home labs suggest that they are effective at reinforcing the underlying theoretic course concepts of elasticity and viscoelasticity applied to biomedical polymers. The existing labs target undergraduate biomechanics courses, but the technology is applicable to a range of topics, including statics, mechanics, material engineering, and mechanobiology.

SUPPLEMENTAL MATERIAL

Supplemental videos of the tensile testing system and the MATLAB interface recording the raw data from the load cell and displacement sensor in real time are available at: https://doi.org/10.35459/tbp.2020.000149.S1, https://doi.org/10.35459/tbp.2020.000149.S2, https://doi.org/10.35459/tbp.2020.000149.S3, and https://doi.org/10.35459/tbp.2020.000149.S4.

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AUTHOR CONTRIBUTIONS

ML contributed to the system design and was the sole contributor to the assessment, analysis, and manuscript preparation.

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