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Teaching Tips

Teaching Material Testing and Characterization with an Open, Accessible, and Affordable Mechanical Test Device

GABRIELLA P. SUGERMAN[1] and MANUEL K. RAUSCH[1,2,3]

[1]Department of Biomedical Engineering, University of Texas at Austin, 107 W Dean Keeton, Austin, TX 78712, USA; [2]Department of Aerospace Engineering & Engineering Mechanics, University of Texas at Austin, Austin, TX, USA [3]Oden Institute for Computational Engineering & Sciences, University of Texas at Austin, Austin, TX, USA

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Abstract—Hands-on experiences in biomechanics and biomaterials courses are an important part of biomedical engineering education. Curricula of those courses often include laboratory modules on material testing and characterization. Unfortunately, large and expensive mechanical testing equipment may not be available to all students, thus limiting students' access to actual hands-on experience. Here, we introduce an open, accessible, and affordable mechanical test device that ensures that every student gets their hands on test equipment and a test specimen. In fact, the device has a small form factor, is inexpensive, and can therefore be taken home. The device is built with low-cost components and 3D-printed parts for a total cost of less than $45. The device also makes use of each student's cell phone camera for optical strain measurements, thereby avoiding the need for expensive imaging equipment. In addition to the device, we also introduce a rich set of supplementary materials that make adoption and application by educators and students as easy as possible. A first experience in a 20-student biomedical engineering technical elective class has demonstrated ease of use and anecdotally confirms the device and material's usefulness in practical teaching. However, more formal evaluation is needed to demonstrate that our test device and materials enhance laboratory teaching.

Keywords—Uniaxial, Constitutive, Soft material, Learning, Hands-on, Load-controlled, Digital image correlation, Smart phone, Biomechanics.

Address correspondence to Manuel K. Rausch, Department of Biomedical Engineering, University of Texas at Austin, 107 W Dean Keeton, Austin, TX 78712, USA. Electronic mail: manuel.rausch@utexas.edu

CHALLENGE STATEMENT

Hands-on experiences are an important part of biomedical engineering education.[1] In biomechanics and biomaterials instruction specifically, such hands-on experiences include material testing and characterization in laboratory courses.[2,3] Unfortunately, laboratory courses may fail in providing each student with a meaningful experience. That is, not every single student may get the opportunity to prepare, mount, and test a specimen for example. The reasons are multi-fold, but may include the unavailability of enough test equipment for medium to large course sizes. Additionally, the high cost of sensitive load cells and high-resolution cameras may prohibit use by untrained personnel. As teachers of two laboratory courses at the University of Texas at Austin we have struggled with this reality. In this teaching tip, we introduce a teaching module that overcomes this gap and guarantees hands-on learning of material testing for every single student with an open, accessible, and affordable mechanical test device. We focus in this teaching module on the testing of soft materials akin to soft tissues such as skin, heart valves, and others[4,5] with moduli ranging from approximately 1kPa to 10MPa. To this end, we introduce a novel mechanical test device, testing and imaging protocols, and data analysis tools. To maximize adoptability, this teaching tip is also accompanied by supplementary videos that show how to build and assemble the device and conduct each element of this module.

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NOVEL INITIATIVE

Material testing and characterization is an important element of biomechanics and biomaterials research. The classic material testing pipeline comprises sample preparation, device assembly (where necessary), experimentation including imaging, and data analysis as well as material model parameter identification. Our novel initiative encompasses all five of these elements and ensures that every single student has a meaningful, hands-on experience with each element of this pipeline. Figure 1 illustrates this pipeline for the reader and lists the supporting materials provided with this teaching tip.

OPEN AND AFFORDABLE TEST DEVICE

Generally speaking, the purpose of mechanical testing lies in either comparing measures of mechanical behavior between groups of samples, e.g., before and after treatment, or in identifying the mechanical properties of a material for later use in finite element simulations for example. Either way, the outputs of a mechanical test are force/displacement data and ultimately stress/strain data. While mechanical test devices usually require expensive actuators and load cells to measure force and displacement, we designed this device to require neither. Instead, our teaching module is centered around an open and affordable mechanical test device that is built on i) gravity providing a highly reliable and repeatable load source, and ii) the omnipresence of high-resolution optical measurement devices, i.e., cell phone cameras. Thus, the device is an inherently load-controlled device in which we measure kinematic quantities, such as strain or stretch, optically using cell-phone based digital image correlation (DIC). Note, the device and pipeline could also be easily adapted to replace the use of DIC with consecutive, ruler-based distance measurements between drawn points on the sample. This modification could accommodate students without access to a cell phone with a camera.

SAMPLE PREPARATION

In our class, we used silicone rubber as a sanitary and safe soft tissue mimic, but have also successfully tested the device against research materials (including murine skin). Note: Latex and nitrile gloves also make for an excellent low-cost test material. The sample preparation begins by cutting the material to size. To this end, we point the reader to an excellent, 3D-printable stencil as published by others.[6] Once the sample is cut to shape, we speckle the sample with water-soluble ink using a simple toothbrush-based technique (see *Supplementary Table 1* for a parts list, parts cost, and order information, and *Supplementary Video 1* for instructions). Note, all supplementary materials are accessible through a link provided at the end of the manuscript.

DEVICE MANUFACTURING AND ASSEMBLY

The device was designed specifically for low-cost and easy assembly. Figure 2 shows the assembled device in a front (right) and rear view (left). The device frame consists of an aluminum plate (6'' × 6'' × 0.25'') and two aluminum rods (12'' × Ø 0.5''). While both components are available as stock materials on McMASTER-CARR (www.mcmaster.com), this frame assembly requires threading the rod ends (1/2''-20 for example) as well as drilling two holes and adding internal threading in the bottom plate. Our

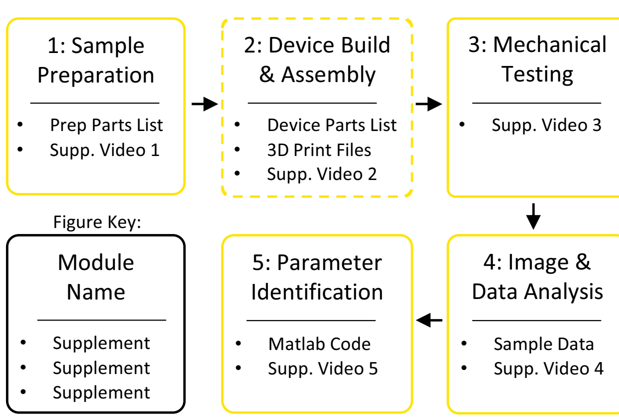

FIGURE 1. Material testing and characterization pipeline. This teaching module will cover steps 1–5 of this pipeline and will provide supplementary materials to maximize adoptability of our initiative. Such materials include materials and parts lists, technical drawings and 3D printing files, as well as sample data, Matlab scripts, and instructional videos.

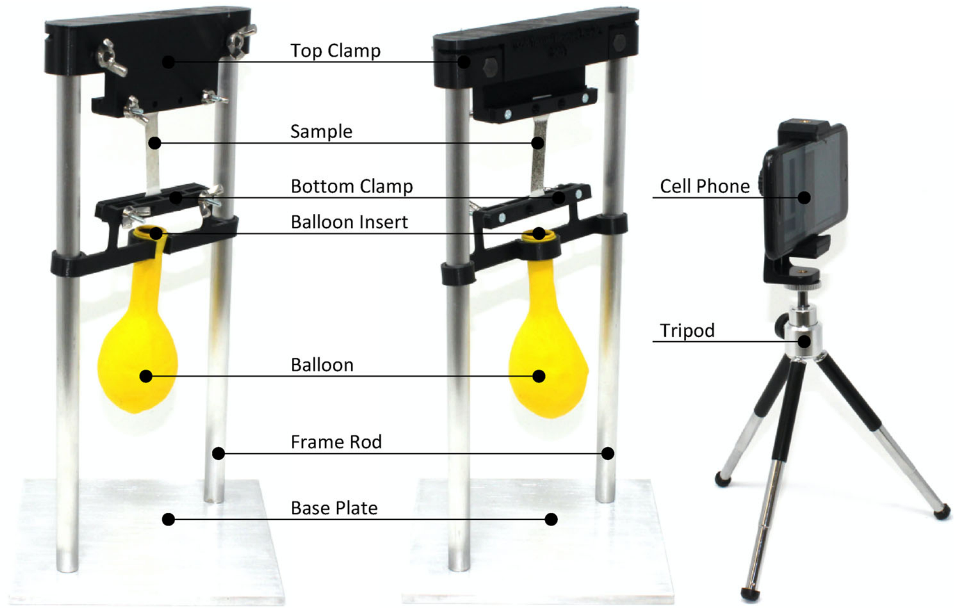

FIGURE 2. Hands-on mechanical test device. Rear view (left) and front view (right) with part labels and cell phone with tripod.

campus machine shop charged $22.50 for 30 minutes of labor on this frame, which constitutes 50% of the total device cost (see *Supplementary Table 2* for a parts list, parts cost, and order information. We also included the design drawings for plate and rods in Supplementary File 1). The remainder of the device consists of 3D-printed material and low-cost components (such as screws and nuts). We included the Solid Works files and the 3D-printable *.stl files in the supplement (see Supplementary Files 2–3). We envision that the device components would be manufactured/printed by the teacher or learning institution and given or shipped to the student in a disassembled state. For easy assembly at-home, we used only wing nuts, thus not requiring for students to own screwdrivers or hex wrenches. Specifically, the device contains a 3D printed top portion that functions as the stationary sample clamp, as well as a bottom portion that functions as the moving sample clamp. The sample is loaded *via* addition of weights to the bottom portion that are collected in a 12'' balloon. The balloon is attached to the bottom portion through a wedge-type interface that prevents balloon slip through the self-tightening interaction between a 3D-printed insert piece and the bottom portion. As weights, we use ½'' Ball Bearings that each weigh ~ 8 g (order information included in Supplementary Table 2). We designed the bottom piece to be of minimal weight to reduce the prestretch of the sample before weights are added (see Supplementary Video 2 for assembly instructions).

EXPERIMENTAL AND IMAGING PROTOCOL

During the experimental testing, ball bearings are added to the bottom portion of the device, one at a time. After each addition of a ball bearing an image of the sample's speckle pattern is taken with the students' cell phone camera (see Supplementary Video 3 for experimental instructions), see Figure 3. In our class, we provided low-cost cell phone tripods with the devices (product details are also included in Supplementary Table 2). While DIC imaging can be an art form in that optimal imaging conditions require adjustment of camera resolution, focus, aperture, and lighting, we have found our pipeline to be remarkably robust. That is, we tested our setup and pipeline under ''real-world'' conditions that reflect a students' home or a classroom environment. We found that our chosen freeware DIC algorithm (NCorr, www.ncorr.com) performed successfully on unprocessed images that were taken under suboptimal conditions. Note, we did crop the images to reduce memory and computational resources (this cropping step is included in Supplementary Video 3). The outcome of the experimentation is a table of ball counts and a corresponding image of the sample's DIC pattern. We are providing an example set of data (unprocessed and processed images) in the supplement (see Supplementary File 4). Note, the images of this example data set were collected with a conventional smart phone (iPhone 5) under real-world conditions.

FIGURE 3. Testing sequence with addition of 0 to 14 ball bearings each weighing approximately 8 g.

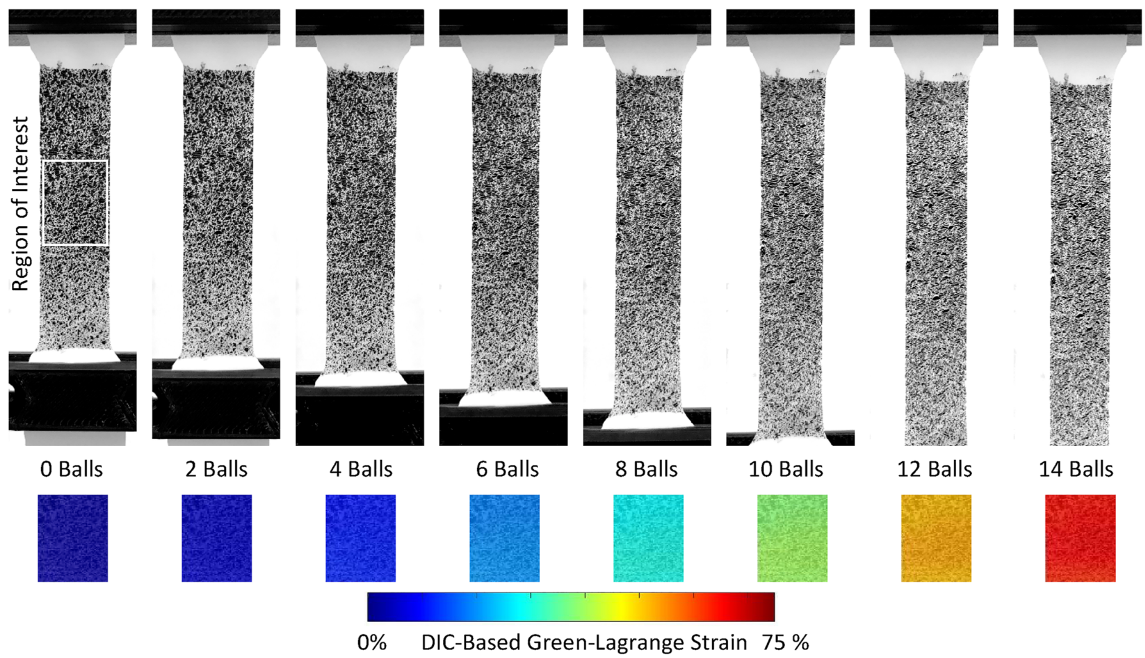

FIGURE 4. Images of speckle pattern in response to mechanical loading. Regions of interest are color coded with digital image correlation-based Green-Lagrange strain. Homogeneity of strains illustrate the homogeneity of the uniaxial tensile state created in our test sample. *Undeformed sample width = 10mm.

DATA ANALYSIS AND MATERIAL PARAMETER IDENTIFICATION

The last step in the mechanical testing pipeline is the data analysis and material parameter identification. The analysis step includes conversion of ball weights into stresses and the DIC-based analysis of the speckle images to identify the material strains in response to the mechanical loading. Figure 4 shows the DIC analysis as conducted with NCorr for the experiment illustrated in Figure 3. Note, as part of the teaching tip, we are also providing a simple Matlab code that conducts a least-squares based identification of material parameters to popular material laws for rubber-like materials and soft tissues. We include the Neo-Hookean, Ogden, Mooney-Rivlin, and Yeoh[7] models (see Supplementary File 5). See Figure 5 (left) for the result of a least-squares curve fit to the Ogden material model using our provided Matlab script. We provide instructions for data analysis and parameter identification in Supplementary Video 4 (instructions on the DIC analysis) and Supplementary Video 5 (parameter identification of hyperelastic materials laws *via* Matlab least-squares optimization), respectively. Additionally, we tested the entire pipeline against measurements of rat skin's uniaxial tensile properties, see Figure 5 (right) where we used the same sample geometry as for the silicone rubber.

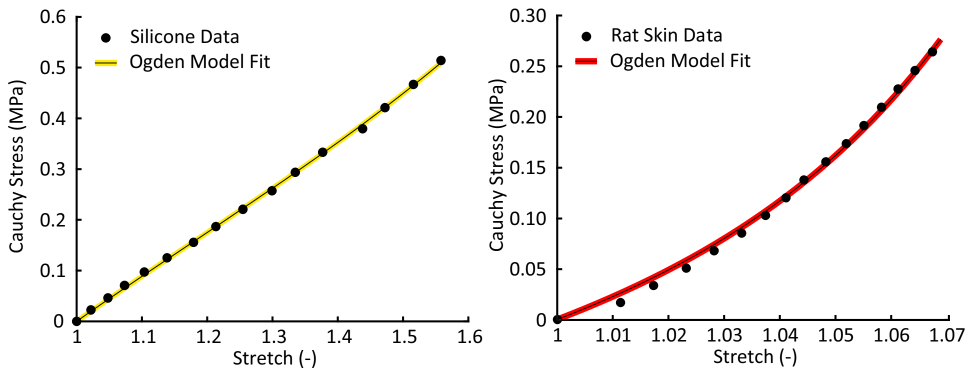

FIGURE 5. Stress-strain data based on the experiment illustrated in Fig. 3 and strain analysis illustrated in Fig. 4. Both Cauchy stress of silicone (left) and rat skin (right) are shown and demonstrate the relatively low noise in our test set-up.

TABLE 1. Outcomes of anonymous Qualtrics student survey with 13 responses

Question	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The device was easy to use	7.7% (1)	0% (0)	7.7% (1)	15.4% (2)	69.2% (9)
The project was valuable to my learning	7.7% (1)	0% (0)	0% (0)	7.7% (1)	84.6% (11)
I enjoyed completing the project	7.7% (1)	0% (0)	0% (0)	7.7% (1)	84.6% (11)

REFLECTION

We have tested this learning module in a technical elective undergraduate/graduate course we teach at University of Texas at Austin, "Soft Tissue Biomechanics". The course had 20 students with a heterogeneous academic background, but was primarily comprised of senior biomedical engineering undergraduate students. The module functioned as the students' problem-based final project and active learning element in which they, as a group of four, executed the entire pipeline and produced a final report[3,8]. In evaluating the success of this module, we feel there were two fundamental questions to answer: (1) Is this learning module practical, i.e., can students easily follow the instructions and conduct the experiments, (2) Is the learning module useful, i.e., does it support student learning. As to the first question, the students found the videos easy to follow and did not experience any challenges with device assembly, execution of the experimental protocol, use of the DIC software, or use of the Matlab script for data analysis and parameter identification. As to the second question, the students' informal response has been almost universally positive with the opinion being that the project successfully enabled hands-on training within the home setting and reinforced learned materials. Please see also Table 1 for a brief summary of an anonymous student survey conducted after the conclusion of the class.

Given the small student number in this current course and the lack of a formal assessment, we consider the current evidence for the success of this module anecdotal. Therefore, we are planning to expand our effort and test its effectiveness through more formal assessments. To overcome the limited class size of "Soft Tissue Biomechanics", we will test our module in our other laboratory course, "Aerospace Materials Laboratory", with student numbers as large as 100. Specifically, for our laboratory module on uniaxial tensile testing of soft materials, we will divide students in two groups. The first group will attend our traditional laboratory class during which 8-12 students watch a teaching assistant conduct the experiments. In contrast, the second group will conduct the same experiments within the comfort of their home using our novel device. After the laboratory module, we will qualitatively survey students from both groups and compare their responses in regard to their learning experience. Additionally, we will include a test question on uniaxial tensile testing in the class's midterm and/or final exam and compare each student group's scores for this specific problem. If we find that students have a better learning experience and/or perform better in the formal test setting, we will adopt this device and similar devices in our future laboratory courses.

Finally and importantly, while this teaching module may function as a replacement for in-person laboratory courses during the COVID pandemic, as pointed out by other helpful teaching tips in this journal, our vision was for it to supplement in-person laboratory courses even after the end of this pandemic[9–12]. In this regard, we can envision our project providing many learning opportunities in areas as diverse as experimentation, image analysis, and constitutive modeling. For example, students could test samples before and after "treatment", where treatments of soft tissue mimicking materials could include differential cross-linking. Students could also explore the sensitivity of DIC to lighting conditions, speckle pattern density, or DIC parameters. Finally, students could expand our provided Matlab code to include other hyperelastic material models. In conclusion, we believe that our device bridges a gap between rudimentary at-home protocols for material testing (for example: https://www.youtube.com/watch?v=c6e7Sa_ITew) and high-end material testing equipment in the laboratory setting. Thereby, it provides an opportunity for students to learn about material testing and characterization with an open, accessible, and affordable mechanical test device.

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at https://doi.org/10.1007/s43683-021-00056-x.

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DECLARATIONS

CONFLICT OF INTEREST

Neither author has conflicts of interest to declare.

DATA AVAILABILITY

All Supplementary Videos and Supplementary Files are available through the Texas Data Repository https://dataverse.tdl.org/dataverse/OAAMTD.

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