RESEARCH ARTICLE

The Biophysicist

A Torsion-Based Rheometer for Measuring Viscoelastic Material Properties

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ABSTRACT Rheology and the study of viscoelastic materials are an integral part of engineering and the study of biophysical systems. Tissue rheology is even used in the study of cancer and other diseases. However, the cost of a rheometer is feasible only for colleges, universities, and research laboratories. Even if a rheometer can be purchased, it is bulky and delicately calibrated, limiting its usefulness to the laboratory itself. The design presented here is less than a tenth of the cost of a professional rheometer. The design is also portable, making it the ideal solution to introduce viscoelasticity to high school students as well as for use in the field for obtaining rheological data.

KEY WORDS rheology; mechanics; viscoelasticity; lab activities; take-home; high school; undergraduate; inexpensive; DIY; portable

I. INTRODUCTION

K–12 science instruction is currently experiencing a revolution. Instruction is shifting from a view of standards-based instruction as a checklist of items to be covered to a three-dimensional approach wherein subject specific performance expectations are accomplished by the integration of three key components or dimensions (1). These dimensions are disciplinary core ideas (DCIs), crosscutting concepts (CCCs), and science and engineering practices (SEPs). These performance expectations are a part of the Next Generation Science Standards (NGSS) adopted by a majority of the United States as well as a number of other countries. As a part of a physics unit on waves, for example, students are expected to use mathematical equations to understand the relationship between wave characteristics, such as amplitude, wavelength, and frequency. This performance expectation targets a DCI of wave properties with the knowledge that wavelength and frequency are related to wave speed, which depends on the medium through which the wave is traveling. Supporting this DCI are ideas about cause and effect within CCCs and using mathematics and computational thinking within SEPs. Furthermore, these three dimensions are to be taught in an authentic and cohesive fashion.

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As classroom teachers work to achieve this shift, 1 problem remains: the existence of a disconnect between what high school students and college researchers do. One reason for this disconnect is the immense cost that surrounds the highly technical equipment used in college and professional labs. The solution to this issue is the design and creation of an affordable and portable version of such materials that can be used by students to study advanced lab practices before graduating from high school. Students can observe phenomena relevant to engineering and even biomedical applications in the classroom. Here, we present a low-cost portable rheometer that can be used to measure the mechanical properties of many different materials. We characterize the stiffness of agar and other common classroom materials at frequencies that range from approximately 1 to 50 rad/s. This rheometer operates on the principles of damped harmonic motion, and we present a step-by-step guide for high school and undergraduate teachers interested in introducing mechanical concepts in the classroom.

II. BACKGROUND

In introductory-level physics and engineering courses, the mechanical properties of materials are often framed by 2 distinct categories: solids and fluids. In reality, however, most soft condensed materials, such as foams, gels, and biological fluids, exhibit a combination of both solid and fluid mechanical properties. These types of materials are called viscoelastic. The study of viscoelastic materials is an integral part of understanding structural stability in engineering, the importance of texture in food science, and the wear on joints in the body.

Whether a material is solid, fluid, or some combination thereof is often assessed by applying an external force on the material and measuring its resulting deformation. Purely elastic solids behave similarly to Hookean springs: the force F to stretch or compress the elastic solid is proportional to the amount of stretch or compression x,

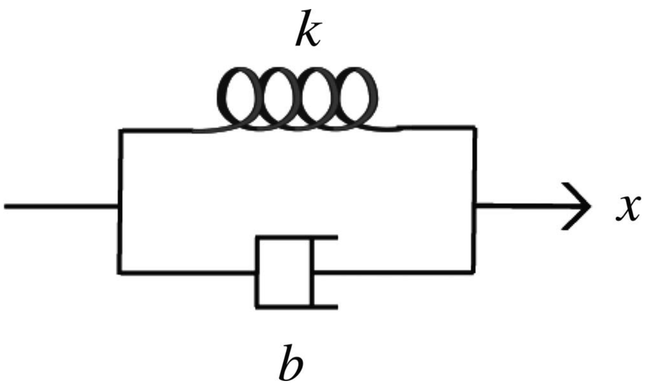


Fig 1. Kelvin–Voigt model of a viscoelastic material. The spring (k) represents the elastic components of the material, and the dashpot (b) represents the viscous component.

$$F = -kx \tag{1}$$

where k is the spring constant and the minus sign represents the restoring force opposing the displacement of the spring. The behavior of liquids can be modeled by Newton's law of viscosity,

$$F = -b\,dx/dt \tag{2}$$

where b is a linear damping coefficient arising from the fluid viscosity and the damping effect is represented by the minus sign.

Viscoelastic materials can be described in part like solids and in part like fluids in relation to how they move in response to applied forces (2, 3). One such description is the Kelvin–Voigt model (Fig 1). The Kelvin–Voigt model captures viscoelastic materials as a combination of an elastic spring and a "dashpot," a movable plunger immersed in a viscous fluid. In this model, the two elements are combined in parallel, as shown in Figure 1. That is, the two elements have the same displacement x, and the overall force on the material is the sum of the forces from each element,

$$F = -kx - b\,dx/dt \tag{3}$$

Rotational oscillatory shear is one of the most common methods to quantify the viscous and the elastic components of a material (3) (Fig 2). When a strain is imposed on the sample, the sample resists the deformation by developing a restoring torque. Using the Kelvin–Voigt model, we have that the torque τ that the sample exerts on the upper plate is directly propor-

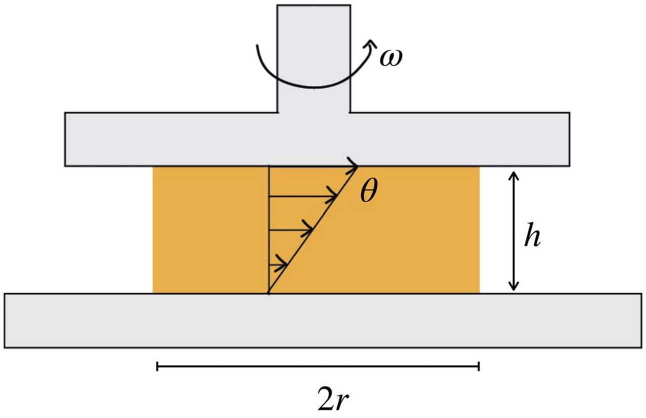


Fig 2. Schematic of a parallel-plate rheometer. The sample consists of a material in a circular disc of diameter $2r$, wedged between 2 plates, spaced a distance h apart. The bottom plate is fixed, and the top plate rotates at a frequency ω, allowing the application of strain $r\theta/h$, where θ is the amplitude of the angular displacement.

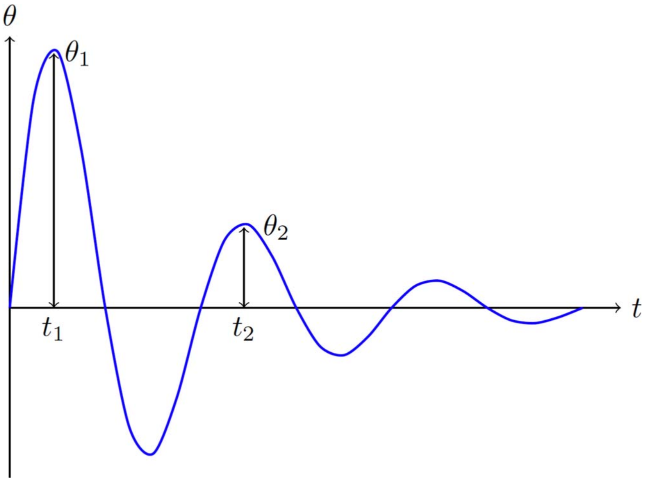


Fig 3. The damped harmonic motion of a viscoelastic sample after being disturbed.

tional to the twist angle θ and the twisting rate $d\theta/dt$ such that

$$\tau = -\kappa\theta - \beta d\theta/dt \tag{4}$$

where κ and β are angular analogs of and b and the minus sign again represents the forces opposing the angular displacement of the plate. Setting $\tau = Id^2\theta/dt^2$, where I is the moment of inertia of the plate, yields the equation

$$Id^2\theta/dt^2 + \beta d\theta/dt + \kappa\theta = 0. \tag{5}$$

This is the equation of a damped harmonic oscillator. If the plate is given a twist at time $t = 0$, then the family of solutions that starts with $\theta(0) = 0$ is given by

$$\theta(t) = \theta_0 e^{-\beta t/2I} \sin \omega t \tag{6}$$

where θ_0 is an amplitude that depends on the initial angular velocity of the disturbance. This describes the motion of the top plate (Fig 3), which dies off while oscillating at an angular frequency ω given by

$$\omega = \sqrt{\frac{\kappa}{I} - (\frac{\beta}{2I})^2} \tag{7}$$

In this test, the elastic solid component of the material acts to oscillate the sample back and forth, while the fluid viscosity of the sample acts to dampen its motion. This motion is described by a slightly damped harmonic oscillator due to the spring and dashpot components, which represent the material's response (Kelvin–Voigt model).

Most commercial rheometers operate by applying a constant oscillatory stress or strain on the sample over time. As the sample is driven by the oscillations, the sample exerts against the upper plate a restoring torque that oscillates at the same frequency of the driven motion but at a phase lag depending on the amount of viscous damping in the sample. The resulting torque values and phase lag can be used to compute the sample's oscillatory elastic storage modulus G' and viscous loss modulus G'' (see Supplemental Material).

Commercial rheometers rely on sensitive force transducers to measure the restoring torque the sample exerts on the plate as it is sheared and can cost between \$40,000 and \$200,000. Here, we present a low-cost portable torsion rheometer that can quantitatively measure G' and G'' of soft gels and that can be assembled for less than \$400. The torsion rheometer operates on the principles of damped harmonic motion, making it practical for educational purposes.

III. MATERIALS AND METHODS

A. Torsion rheometer assembly

Our torsion-based rheometer stems from an adopted version of the oscillatory test and is

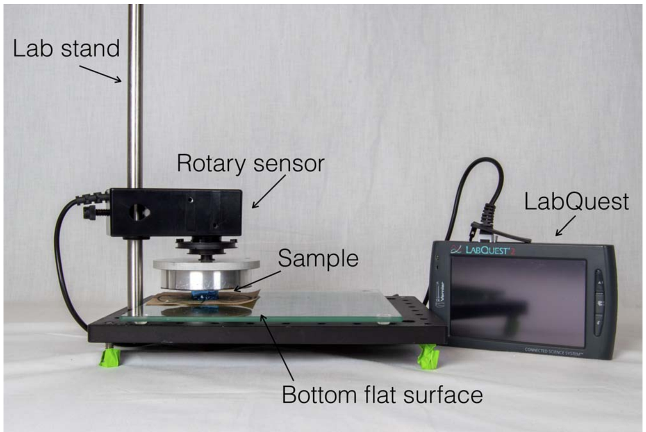


Fig 4. Design of the torsion rheometer. A photograph of the torsion rheometer device. The sample is cut into a circular disc and then placed on a flat surface. The rotary sensor is mounted on a lab stand and brought down in contact with the sample. LabQuest is connected to the rotary sensor to provide live angular displacement data over time.

related to the torsion pendulum developed previously (4, 5). The design is shown in Figure 4. The torsion rheometer itself consists of a flat circular plate connected to a rotary motion sensor and a few hardware accessories to properly mount the plate above a sample. To allow precise real-time feedback of the plate motion, we designed the device around a rotary motion sensor (Vernier, Beaverton, OR) (Fig 4 and Table 1). The LabQuest 2 digital interface (Vernier) connects with the rotary sensor to display a graph of the rotary motion data while the data are being collected, but a computer may also be connected to the LabQuest to collect the angular position θ and angular displacement rate $d\theta/dt$ of the plate over time *t* from the Vernier rotary sensor.

A building plan and a full list of the parts to assemble the torsion pendulum are provided in the Supplemental Material. The torsion rheometer requires a smooth top plate attached to the rotary sensor. While nearly all the hardware to assemble the torsional rheometer is commercially available, the top plate should be customized to interface with the rotary sensor (Supplemental Material). The Vernier sensor is then attached to a vertical pole mounted on an optical breadboard and then lowered to sandwich the test sample between the sensor's rotating plate and a flat surface, such as a glass plate.

Table 1. Main parts for torsion rheometer.

Manufacturer	Item	Item ID	Price
Vernier	Rotary motion sensor	RMV-BTD	$169
Vernier	Rotation motion accessory kit	AK-RMV	$112
Vernier	LabQuest 2 (optional; see Supplemental Material)	LABQ2	$339

For use with soft, slippy samples like agar, sandpaper can be added to the top and bottom plates with double-sided tape to grip the material and suppress slip between the material and the plates during oscillations.

B. Test materials and sample preparation

The benchtop rheometer was tested on 4 soft materials: polydimethylsiloxane (PDMS; Dow Corning, Midland, MI), JELL-O Jigglers (Kraft Foods, Chicago, IL), agar (BD Bacto, Fisher Scientific, Waltham, MA), super firm tofu (Trader Joe's, Monrovia, CA), and polyacrylamide (PAA) gels (Fisher Scientific, Waltham, MA). PDMS samples were prepared by mixing the 2-component dielectric gel at a ratio of 1:1, degassing the sample, and curing the sample at 65° for 1 h. The JELL-O Jigglers are a stiffer gelatin recipe with a higher gelatin-to-water ratio compared with conventional JELL-O recipes. JELL-O Jigglers were prepared by mixing 1 3-ounce package of JELL-O gelatin with 1.5 cups of boiling water as per the manufacturer's instructions. Agar was prepared by dissolving 2% agar by weight in water and bringing to a boil; 15 mL of agar was then poured into 100-mm Petri dishes and allowed to cool. The PAA gels were prepared at 13% PAA and 0.33% bis-acrylamide cross-linker. Polymerization was initiated by addition of 2 μL of tetramethylenediamine and 4 μL of ammonium persulfate.

Before loading the samples into the torsion rheometer, test samples were cut into circular disks. We recommend 5- to 10-mm tall and approximately 20 mm in diameter. A cork borer or tissue punch works well to punch a circular disc from a sample (Fig 5a).

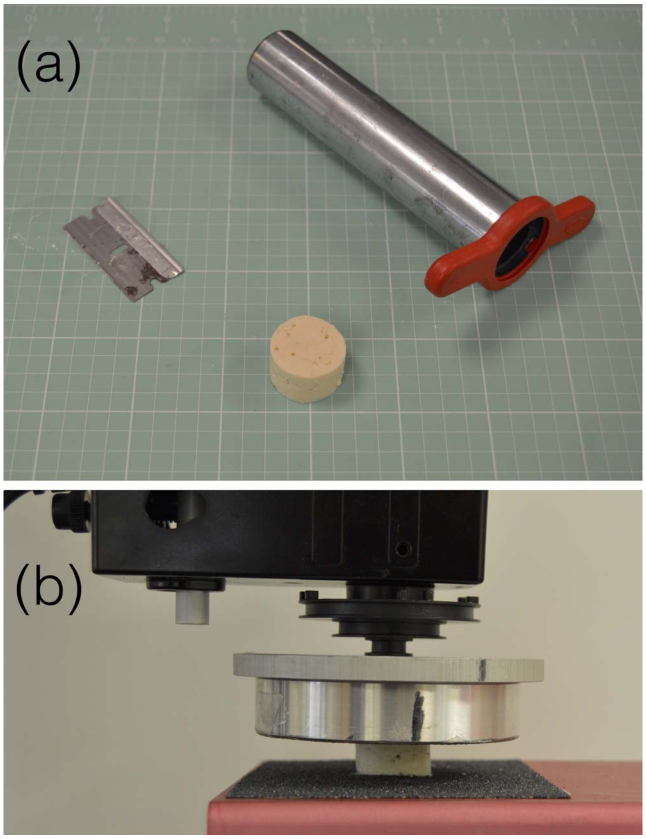


Fig 5. Sample preparation. (a) Samples should be cut into a circular disk. An easy way to do this is with a cork borer, as shown in the photograph of a tofu sample punched by a 20-mm cork borer. The top and bottom of the disc should be made as flat as possible. The sample can be cut or trimmed with a knife or razor blade. (b) To properly position the sample for measurement, the sample should be placed in the center of the gap between the plates and the entire top and bottom of the disc flush with the surfaces.

The soft samples tested here adhered well to the plates of the torsion rheometer, but solids that are too firm may slip against the plates and will not work as well. We also note that this design does not work well for Newtonian fluids or Maxwell viscoelastic fluids, which will creep without retaining their shape between the plates.

C. Work flow for torsion rheometer

1. Performing the test

The sample to be measured should be placed on a flat surface below the upper rotational plate of the torsion rheometer. The user then lowers the upper rotational plate to make contact with the sample. Care should be taken to align the center of the upper plate with the center of the sample. For best results, the entire surface of the sample should be in contact with the upper plate (Fig 5b). The position of the upper plate with respect to the sample can be readjusted by lowering and raising on the stand as needed. A permanent marker can be useful for marking the center of placement for the sample on the top and bottom plates.

Once the sample is in contact with the upper plate, data collection is started, zeroing the sensor at its current position. The test is then initiated by twisting the top plate, which applies a small initial angular displacement. This twist should be made very quickly and should be small enough that the sample does not slip, usually through an angle of 30 degrees or less. For soft viscoelastic solids, the applied displacement causes the plate to oscillate back and forth over time. The amplitude of the oscillations decays over time at a rate proportional to the viscous damping of the sample. The resulting motion of the plate is measured by the rotary sensor, which reads the angle of the plate, θ, over time. Sample data are shown in Figure 6. The data are well described by damped harmonic motion. Typically, 2 to 20 peaks can be observed before the oscillations completely die out, with more oscillations for stiffer, less damped materials. If you cannot observe 2 peaks, apply a twist with a larger amplitude, as a minimum of 2 peaks is needed for the measurement.

The readout from the test is used to calculate G′ and G″ through 2 main parameters: (a) the angular frequency ω of the oscillations in rad/s and (b) the ratio of amplitudes between subsequent peaks. The frequency of the oscillations is given by $\omega = 2\pi/T$, where T is the time interval between subsequent peaks. The rate of amplitude decay is given by the ratio of the amplitude of the first peak and the amplitude of the second peak, θ_1/θ_2. If the motion is strongly damped, an alternative calculation can use the time t_m and the amplitude θ_m of the first minimum, where T is given by $2(t_m - t_1)$ and the ratio θ_1/θ_2 is given by $(\theta_1/\theta_m)^2$. These data can be read directly off the graph by selecting points in the LabQuest

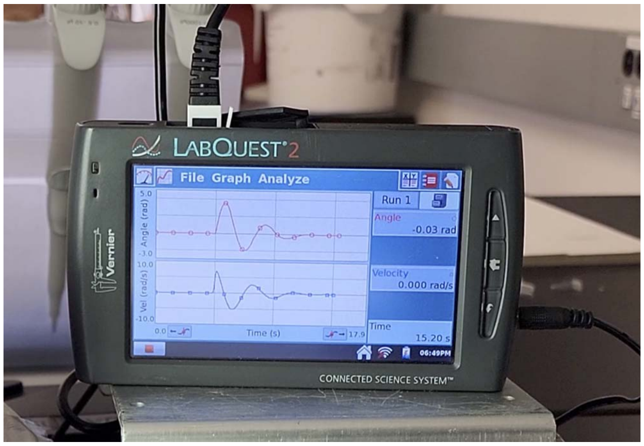


Fig 6. Sample snapshot of a completed data readout on LabQuest. The 2 displayed curves are (top) angular position in radians and (bottom) angular velocity in rad/s, both shown with time on the *x*-axis. A small, brief twist was made on the top plate at the moment both quantities deviate from zero, and the sample displayed the decaying oscillations shown in response. The red and blue circles guide the eye to equally spaced moments in time but were not used for analysis. The time and magnitude of the peaks in angular position can be found with the LabQuest by using the left arrow and right arrow buttons seen toward the bottom of the screen to move the crosshairs from point to point, or the data can be read in software on a connected computer.

display or read by the user from a data table provided by the Vernier device or software. With LabQuest, the data can also be saved to analyze later.

2. Calculating the moment of inertia of the torsion plate

The moment of inertia I of the rotating plate is given by $I = \frac{1}{2}mr^2$, where m is the mass of the plate and r is its radius. If the top plate has more than 1 assembly piece, then the total moment of inertia is given by the sum of each piece, with each point mass m adding $I = md^2$ for d, the distance of the mass from the axis of rotation.

3. Calculating sample shape factor

The strain on a sample depends not only on how it is displaced but also its size and shape. To account for these variations, we defined the sample shape factor s as

$$s = \frac{\pi R^4}{2h} \tag{8}$$

where R is the radius of the sample and h is the height of the sample.

4. Calculating shear and loss modulus

The mechanical properties of the test samples can be calculated based on the results of the torsion test. The shear modulus G′ and the loss modulus G″ can be computed from the frequency (ω) and the logarithmic decrement of the amplitude Δ, defined here as $\Delta = \ln(\theta_1/\theta_2)$. The logarithmic decrement (Δ) is a metric of the amplitude decay quantifying how damped the system is. The shear modulus G′ and loss modulus G″ are then given by

$$G^{'} = (\omega^2 I/s)(1 + \Delta^2/4\pi^2) \tag{9}$$

and

$$G^{'} = (\omega^2 I/s)(\Delta^{\pi}) \tag{10}$$

where I is the moment of inertia of the rotating plate and s is the shape factor (Eq. 8), a quantity measured in units of volume. This can also be used to show that G′ and G″ are measured in units of pressure, Pa or kPa.

We provide a full derivation of these equations from the experimental variables T, θ_1, and θ_2 in the Supplemental Material, in which the Kelvin–Voigt model parameters κ and β appear as intermediate quantities.

D. Commercial rheology tests

Here, we compared the results from the benchtop rheometer with the results of parallel-plate oscillatory shear tests performed with a commercial Malvern Kinexus rheometer (Malvern Panalytical Ltd, Worcestershire, United Kingdom). The Malvern rheometer was equipped with a 20-mm plate, and the oscillatory tests were performed at 2% strains and a frequency of 1 rad/s.

IV. RESULTS AND DISCUSSION

Table 2 shows the average shear modulus G′ and loss modulus G″ for our 4 experimental samples. Also in Table 2, we compare the values of G′ and G″ obtained using the benchtop torsion device to results obtained using a commercially available rheometer. Overall, we find strong agreement between the benchtop torsion and commercial rheometer for a range of shear storage moduli G′

Table 2. Results from the classroom rheometer design as well as the laboratory rheometer. G′ and G″ were determined on a commercial Malvern Kinexus rheometer with an oscillatory shear test at 2% strain and frequency 1 rad/s. Error denotes standard deviation of 3 independent samples.

Material	Specifications	Torsion rheometer G′ (kPa)	Commercial rheometer G′ (kPa)	Torsion rheometer G″ (kPa)	Commercial rheometer G″ (kPa)	Frequency of torsion rheometer (rad/s)
PDMS	Sylgard 527 1:1	0.8 ± 0.3	1.1	0.3 ± 0.1	0.5	1.6 ± 0.3
JELL-O Jigglers	According to manufacturer's package	1.6 ± 0.2	1.1	0.2 ± 0.07	0.2	1.7 ± 0.2
Tofu	Trader Joe's Super Firm	29.0 ± 5.8	26.4	6.0 ± 0.15	5.4	21.4 ± 0.2
Agar	2% water	30.1 ± 1.7	18.0	4.2 ± 0.4	1.5	22 ± 0.2
PAA	13% PAA	34.4 ± 0.9	17.0	7.5 ± 0.2	0.5	4.9 ± 0.7

PAA, polyacrylamide; PDMS, polydimethylsiloxane.

ranging from 0.8 to 30 kPa. We note that there are discrepancies in the experimental data between the torsion rheometer and the commercial rheometer. This is likely caused by the limitations of controlling strain and frequency in the benchtop torsion rheometer, which cannot be as sensitively controlled compared to the commercial rheometer. In the benchtop rheometer, the strain is dependent on how hard the user pushes the plate, whereas the frequency is set by the moment of inertia of the top plate and viscoelastic properties of the sample. Nonetheless, the data presented in Table 2 are close to the values obtained with the commercial rheometer. These results indicate that the torsion rheometer can be reliably used to obtain viscoelastic data of complex, viscoelastic solids.

In many materials, the shear modulus G′ and storage modulus G″ depend on the frequency of oscillation. For our torsion rheometer, the frequency of oscillations is an emergent dependent parameter of the torsion rheometer's design, being a complex function of the material properties, sample shape, and moment of inertia of the top plate (Supplemental Material). Stiffer material increases the torque on the plate and the restoring force, increasing the frequency. Likewise, a larger sample radius increases torque on the plate and increases the frequency. In contrast, the moment of inertia of the top plate is inversely related to the frequency: a smaller top plate is easier to move, thus having a higher frequency than a large top plate with a larger moment of inertia.

Here, a systematic way to vary the frequency of oscillation is to alter the moment of inertia of the top plate. Figure 7 shows such a design. A simple outrigger (e.g., a ruler) is added to the top plate, and weights are added to the ends of the outrigger to alter the moment of inertia. More mass increases the moment of inertia of the upper plate and decreases the frequency of oscillations.

Figure 7 shows frequency sweeps using our torsion rheometer for 3 different samples: tofu, agar, and a linear PAA gel. The range of frequencies we obtain from this design with these samples is 0.5 to 5 Hz. As shown in the data, tofu and agar exhibit a frequency-dependent result in which G′ increases with oscillation frequency. In contrast, the PAA sample exhibits a nearly constant G′. These trends are consistent with results obtained from a commercial rheometer (Fig 7c). The range of frequencies of the torsion rheometer and its manual nature are much more limited compared to the commercial rheometer, which can easily apply frequencies from 0.1 to 10 to the sample via a force transducer. Nonetheless, the torsion rheometer is able to reliably vary oscillation frequencies and detect frequency-dependent changes in shear modulus for such materials.

We note that our analysis (Eqs. 9 and 10) has assumed that shear and loss modulus of the sample is independent of the strain amplitude or frequency at which the material is probed. This is not always a justified assumption. Commercial rheometers face the same challenge for highly nonlinear complex materials (3,

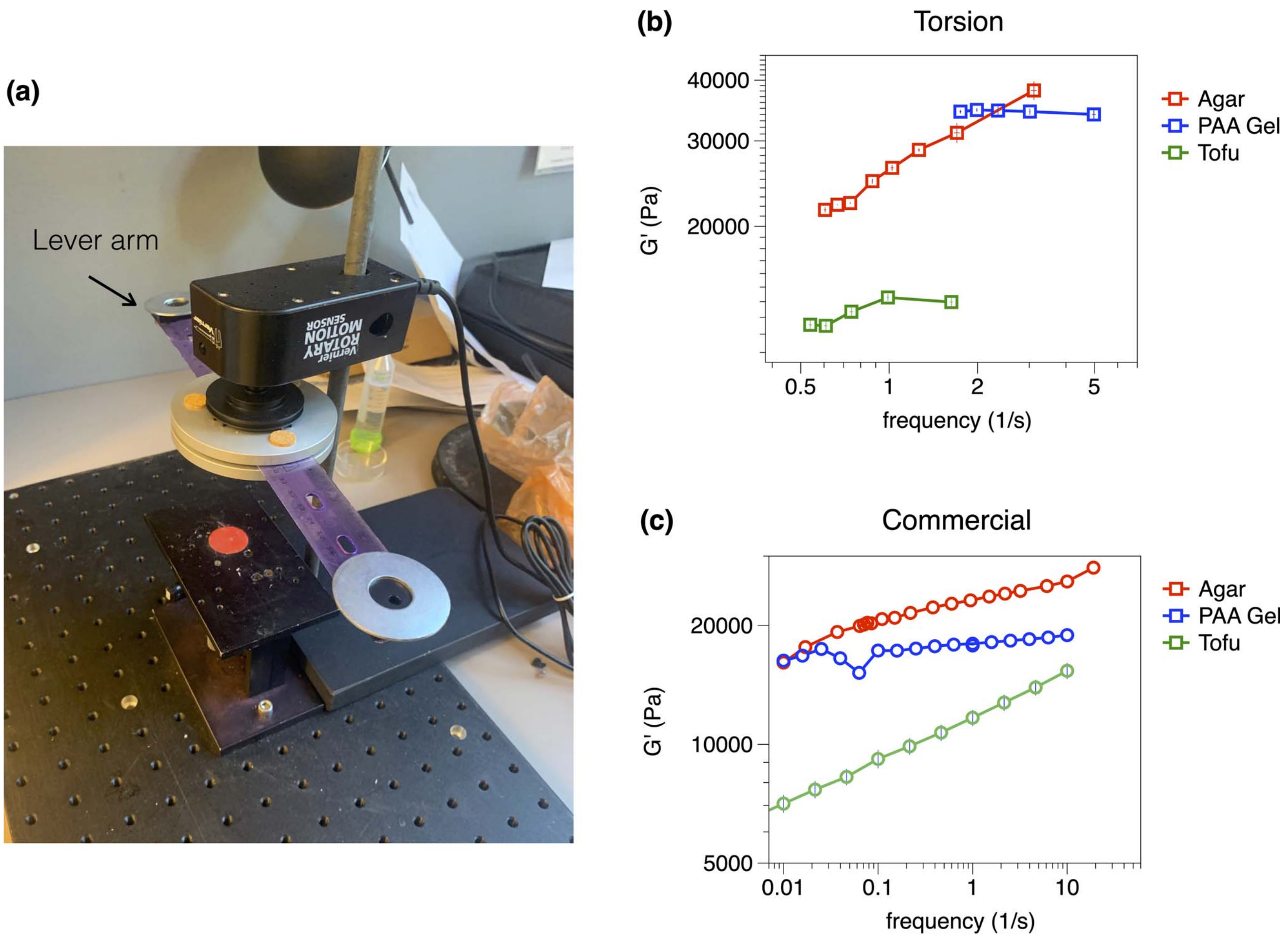


Fig 7. Frequency control. (a) A straightforward way to modulate the angular rotation frequency is by altering the moment of inertia of the top plate by addition of an outrigger. Weights can be added to both ends to systemically vary the natural response frequency. Sample results of frequency sweeps using (b) the benchtop torsion rheometer versus (c) the commercial rheometer are shown for 3 materials: agar, polyacrylamide (PAA), and tofu samples. While the frequency range of the torsion rheometer is much more limited than the commercial rheometer, the torsion rheometer is able to capture the frequency-independent shear modulus G′ of PAA as well as the frequency-dependent behavior of agar and tofu.

6) for which G′ and G″ are not strictly defined. The storage and loss modulus reported by a commercial rheometer is often the best-fit value from the collected stress–strain data over the course of an oscillation. An alternative approach often used for nonlinear materials and for large-amplitude oscillations is to analyze the stress–strain curves directly and choose the appropriate model (6, 7). One limitation of the basic design we have presented is that the torsion rheometer does not have a torque sensor to directly obtain the stress–strain data over the course of an oscillation. Given the modular nature of the torsion device, a force transducer could be incorporated for studies of nonlinear materials.

A. Use in educational settings and example experiments

The motivation for this design was to create an affordable rheometer to conduct simple rheology tests, that is portable for classroom demonstrations or laboratory work where access to commercial rheometers is not available. Because many undergraduate and high school classrooms have Vernier and LabQuest products to use at their disposal (8–10), the design of the torsion rheometer presented here is just 1 configuration, and the torsion rheometer can be easily adapted and customized for other applications or made for even cheaper. For example, alternatives to the Vernier rotary sensor setup are listed in the Supplemental Material.

This design works well with soft samples, such as tofu, agar, or JELL-O, which are ideal samples for introducing viscoelastic properties to students. Students can use the sensor to determine the moduli for a particular material, such as JELL-O Jigglers or agar, as an isolated lab experiment, or they can use the equipment throughout the course of the school year as part of a larger research assignment. While studying rotational motion, they can calculate the moment of inertia for the different plates and then experimentally determine them using the sensor. During a unit on waves, students can interpret displacement versus time data to determine the frequency and logarithmic decrement. While this tool works best for solid-like Kelvin–Voigt materials, other viscoelastic models, such as the Maxwell model, in which the spring and dashpot are assembled in series, can be introduced and compared. A sample lesson aligned with the NGSS can be found in the Supplemental Material.

As part of an outreach program funded by the New York State Section of the American Physical Society, a team of graduate and undergraduate students took the portable rheometer to high school classrooms in the Syracuse, New York, area as part of a lesson on viscoelasticity. These outreach visits were across 7 classes in 3 schools, reaching more than 100 students in physics, biology, and earth science. Students were shown the response of 3 different materials—PAA hydrogel (purely elastic), water (purely viscous), and Jell-O or agar (viscoelastic)—in the form of the angular displacement curve versus time after perturbing the samples. The response curve was shown in real time, and students were led in group discussions predicting the response curves of hypothetical materials that were more or less viscous or elastic than the sample they had seen.

In a format appropriate for the short time allotted to a single classroom visit, elasticity was explained in terms of the spacing between oscillations in the response curve and viscosity in terms of the shrinking of the oscillations' amplitude over time. The more detailed formula combining these quantities to arrive at G' and G'' is appropriate to a lab project spanning more time.

B. Example experiments

To improve student learning and allow student discovery of material properties and experimental design, we propose a series of simple tests and experiments.

1. Frictional calibration

One limitation of the torsion rheometer device is friction of the rotary plate. The friction of the rotatory plate itself can be computed by spinning the rotatory device in the absence of a material sample and then allowing it to rotate until it slowly comes to a stop due to friction. This takes several minutes, indicating a very small coefficient of friction. Students can be asked to measure the friction and interpret the limitations of the device in measuring G' and G''. For the setup used here, we computed a frictional torque of 6.2×10^{-5} N m.

2. Measuring axial normal force

In addition to oscillatory shear tests, the benchtop rheometer can be easily modified to measure axial normal force and apply uniaxial compression to samples. The axial normal force can be measured in newtons (N) by swapping out the bottom plate with a scale such that the force can be read off by converting the displayed mass to kilograms and multiplying by g, where g is acceleration due to gravity, 9.81 m/s^2 (Fig 8). Supplemental Movie S1 shows a torsion rheometer test in which oscillations in the normal force ($\sim$1 N) can be detected as the plate oscillates back and forth in shear.

Uniaxial compression can be applied to samples by manually lowering the top plate down via the stand or by placing a laboratory jack underneath the sample and raising it up toward the top plate. The axial compressive strain of the sample can be determined by measuring the gap height d with a ruler. The axial strain is then given by $d/h \times 100\%$, where h is the initial height of the sample. The value of G' and G'' can then be determined as described above for different values of axial strain.

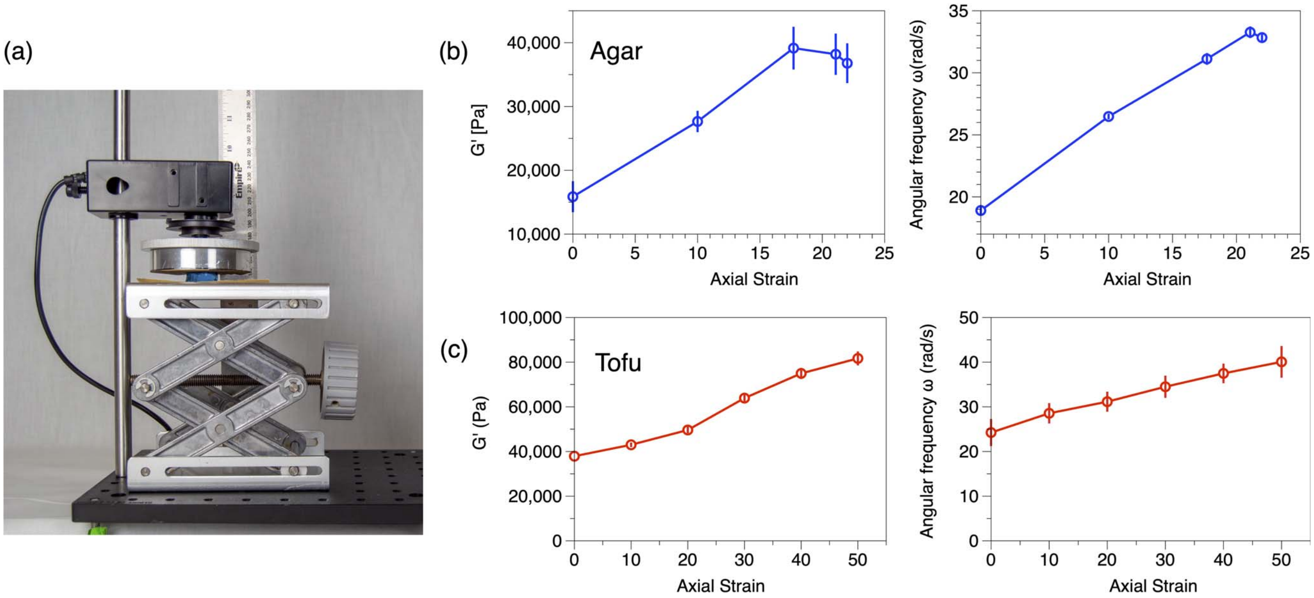


Fig 8. Application of uniaxial compressive strain. (a) Uniaxial compressive strain can be applied by systemically adjusting the height between the plates. A straightforward way to do this is by placing the sample on an adjustable lab stand and measuring the gap between the plates with a ruler. Sample shear moduli G′ versus axial strain curves from the torsion rheometer are plotted for (b) agar and (c) tofu samples. As the samples are compressed, they become stiffer, as indicated by the increase in G′. This also leads to a higher oscillation frequency (right).

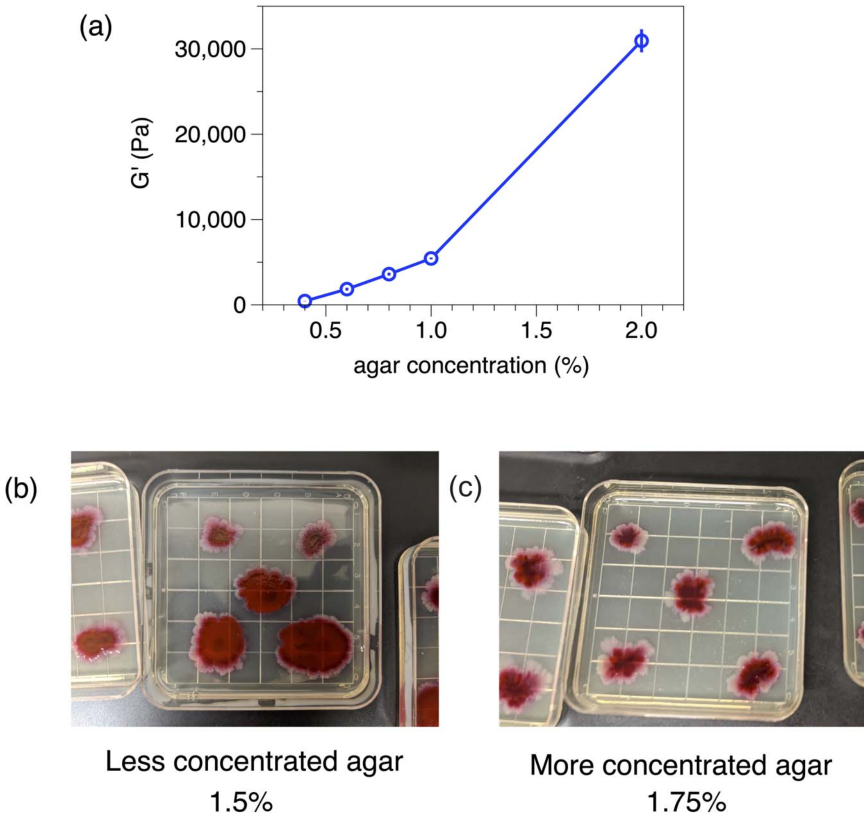
Figure 8 shows the shear modulus G′ of tofu and agar samples. For both samples, as they are compressed, G′ increases, indicating that the samples are stiffer compared to their uncompressed state. This is a feature common to many viscoelastic solids and biological materials, such as cells and tissues, and is called “compression stiffening” (11–13). This test can be used to connect concepts from physics and engineering to biology and medicine, as the onset of compressive stresses and dysregulation of physical stresses is associated with many different types of cancer (14–16) and tissue stiffness can be used as an early diagnostic marker for diseases, such as liver disease (17, 18).

3. Bacterial growth on substrates of varying mechanical properties

In recent years, the field of mechanobiology has emerged to study the effects of mechanical forces on biological systems (19–21). It is increasingly recognized, for example, that the mechanical properties of a cell’s environment can affect many cellular functions, including motility, differentiation, and proliferation (22–24). An example of this is the growth of bacterial colonies on agar substrates of varying stiffness. Most bacterial colonies tend to grow slower and smaller on more concentrated, stiffer agar (25, 26). A series of agar substrates of varying concentrations (0.4% to 2%) can be prepared and characterized by the torsion rheometer (Fig 9). Students can experiment with different types of bacteria, such as *E. coli* or other bacteria that they can isolate from soil (27, 28). Students can inoculate bacterial colonies on agar plates and then observe and document the colony growth. The growth rate can be computed by measuring the average size of colonies over multiple days. Students can note changes in colony morphology and use smartphones to document the colony growth (Fig 9).

V. CONCLUSIONS AND STUDENT FEEDBACK

We have demonstrated the feasibility of a low-cost, effective, and portable way to measure the mechanical properties of complex, viscoelastic materials. This tool can be used to



Less concentrated agar
1.5%

More concentrated agar
1.75%

Fig 9. Classroom experiment. Bacterial colony growth depends on the properties of their growth substrate. (a) The shear modulus of agar growth gels increases with increasing agar concentration. Data from torsion rheometer. The bacterial colonies grown on (b) 1.5% agar are larger than the bacterial colonies grown on (c) 1.75% agar. Bacteria: *Serratia marcescens*; growth duration: 1 week.

incorporate viscoelastic materials and biophysical concepts into high school–level classes. The skills obtained in these laboratory activities provide students with a foundation that can better prepare students for their college course work and future lab experiences.

Students' feedback on what part of our outreach lesson stood out to them often mentioned seeing and interpreting the rheometer output in real time. Overall, the rheometer was a very useful tool in showing how to quantify the intuitive properties of elasticity and viscosity. Using the rheometer stimulated discussion among the students and helped make concrete the concepts that were discussed. Some reflections from student feedback include the following:

> "I learned about scientific examples made out of everyday things."

> "It made me think of applications of elastic/viscous materials as shock absorbers."

> "I loved this lesson. I feel like I have a really great grasp on the concept now."

One teacher mentioned the demo sparking "conversations with students about the applications of viscoelasticity in other fields [food and engineering]. I will be sure to include related examples in the future." In an earth science classroom, 1 teacher remarked, "This gave me some great ideas on teaching fluid dynamics under the Earth's crust."

Overall, the classroom rheometer proved to be an engaging teaching device for students in biology, physics, and earth science.

SUPPLEMENTAL MATERIAL

Supplemental Material for the torsion-based rheometer and sample NGSS-aligned lesson is available at https://doi.org/10.

35459/tbp.2020.000172.s1 and for the torsion rheometer test movie at https://doi.org/10.35459/tbp.2020.000172.s2.

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AUTHOR CONTRIBUTIONS

EJ designed the torsion-based rheometer, performed and analyzed experiments, and wrote the lesson plan. MA and JK designed and analyzed experiments with agar. KK and DS designed and analyzed experiments with tofu and PAA. MA derived analytical results. BC assisted with commercial rheometry. MA and SG designed and implemented outreach efforts. EJ, MA, DS, and AP wrote the article.

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