How stiff is a French fry? – Teaching biomechanics to biology students

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Mechanical investigations of biological materials are becoming increasingly important in the study of organismic and evolutionary ecology. Such studies help to explain how and why organisms evolve and exist today, and address some questions of scale (e.g., how big can a tree or mammal grow?). These ideas and questions often intrigue biology students, but rarely are they exposed to the measurements and principles underlying the mechanics of biological structures. We present a simple technique to measure an important biomechanical feature of tissues, namely tissue stiffness or elastic modulus, that is used to determine the strength and durability of biological structures. Using this technique on tubers of Russet Burbank poataoes (*Solanum tuberosum*), the elastic (or Young's) modulus (E) ranged from 1.08 to 14.15 MPa. This was well within the range reported for this plant material. We suggest several experimental manipulations and provide results for one of these which can be easily conducted in an A-level or early university 3-hour teaching practical (or laboratory).
Key words: Biomechanics, Elastic modulus, Mechanical measurement.

Introduction

Biomechanical investigations have become increasingly relevant to the study of the ecology and evolution of organisms. Vogel (1988) provides an excellent review of this material, which is suitable for students, but the following texts may also be consulted: Wainwright *et al.*, 1982; Fung, 1990; Vincent, 1990; Rayner and Wootton, 1991; Niklas, 1992; Vincent, 1992; Lyall and El Haj, 1994. This is especially true in plant systems where plant evolutionary history is related to their ability to conquer terrestrial habitats, and hence support themselves against gravity (Niklas, 1992). The study of plant biomechanics has been traditionally associated with studies of plant anatomy and morphology, rather than direct mechanical testing and related engineering approaches. Lack of familiarity with physical principles and lack of instrumentation are often provided as reasons for an inferential, rather than a direct, measuring approach to plant biomechanics. This is not the case at the University of Northern British Columbia, where the basic properties of materials and a simple mechanical testing device are used in a Physical Ecology Course. We believe that this approach could also be aimed at the A-level or early university classroom, providing a valuable opportunity to use biomechanical measurements as a cross-curricular exercise combining physics and biology. In this report, we present a brief review of the properties of plant biomaterials, as well as suggestions for an experiment to measure these within a 3-hour laboratory practical.

Seven properties of materials

The seven basic properties of materials can be presented in a lecture preceding the plant biomechanics practical. The presentation begins with the idea of subjecting a mass of material (or tissue) to a load or force measured in newtons (N) as illustrated in Figure 1. The material reacts to the applied stress (σ) measured in pascals (Pa; i.e., Nm^{-2}) according to the Equation $\sigma = F/A$, where F is the force measured in N and A is the cross-sectional area measured in m^2. It does so by changing its length (L in m) in the direction of the applied load. When F is applied in compression (Figure 1(a)), the material shrinks by ΔL, and when F is applied in tension (Figure 1(b)), the material stretches by ΔL. The ratio of the change in length (ΔL) to the original length (L) provides a measure of the response or strain ($\epsilon = \Delta L/L$ in percentages) of the material. The distinction between stress and strain can be confusing because of the near-interchangeable use of the terms in common parlance. Therefore, it is important to reinforce the distinction between stress and strain as is illustrated in Figure 1. The stress is the force per unit

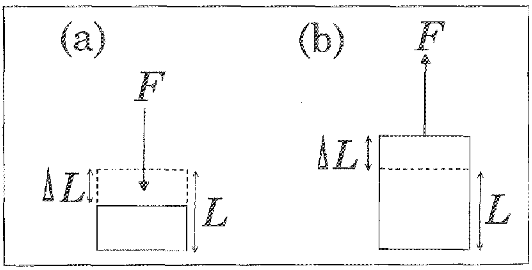

Figure 1 A schematic of the response (strain) of a material to an applied load (F). (a) In compression, the original length of the material (L) is compressed by ΔL. (b) In tension, the original length of the material (L) is stretched by ΔL.

area acting to compress or stretch the material (Figures 1(a) and 1(b), respectively), while the strain is the extent to which the material is compressed or is stretched. Engineers typically use a load cell, which is a mechanical testing device, to increase the load continuously and record the strain of the material via strain gauges. Typical load cell results for viscoelastic materials, like many biological materials are presented in Figure 2.

The seven basic properties of materials are: stiffness; strength; extensibility; dilation and shearing resistance; stored energy; resilience; and toughness.

Stiffness

Initially, the slope of the stress-strain curve is straight, indicating that the material is undergoing an elastic deformation, meaning that it will return to its original length when released from the load. The slope of this portion of the curve (a in Figure 2) provides a measure of the **stiffness** of the material, called the elastic or Young's modulus ($E = \Delta\sigma/\Delta\epsilon$ in Pa). To put it in perspective, a mollusc (clam) shell has a stiffness that is three times that of pine wood (measured with the grain), and 15 times that of a tendon, which is composed of collagen fibres.

Strength

As the stress is increased, the material begins to yield or undergo a plastic deformation (b in Figure 2), which means that it will not return to its original length when released from the load. Further increases in the stress lead to the breaking or failure of the material (c in Figure 2). The stress at which failure occurs (σ_f in Pa) provides a measure of the **strength** of the material. For example, your tendons have a strength that is 50 times that of the walls of your arteries, hence the hazard of aneurysms (dilation of a section of an artery that may result in haemorrhage). Some materials may have different strengths in compression, tension, and even in direction (see ***Dilation and Shearing Resistance***). For example, pine wood has a strength when measured in tension with the grain that is three times that of the same wood measured in compression. In contrast, pine measured in tension cross grain has only 1/25 the strength of the same wood measured with the grain.

Extensibility

The strain at which the material fails (c in Figure 2) is the failure strain (ϵ_f in percentages). It provides a measure of the **extensibility** of the material. In this case, tendons have an extensibility that is 100 times that of mollusc shell. The stress-strain relation can be demonstrated in the lecture using an extensible gelatine-based sweet (e.g., Gummy, or Gummi, Bears originally developed by Haribo, Bonn, and now produced by a variety of manufacturers). The sweet can be stretched a short distance and released to illustrate an elastic deformation (i.e., it returns to the original length and shape). If it is stretched farther apart to illustrate yield deformation (i.e., plastic deformation) and released, it will not return to the original length and shape. Further stretching will ultimately lead to failure (breakage) of the sweet.

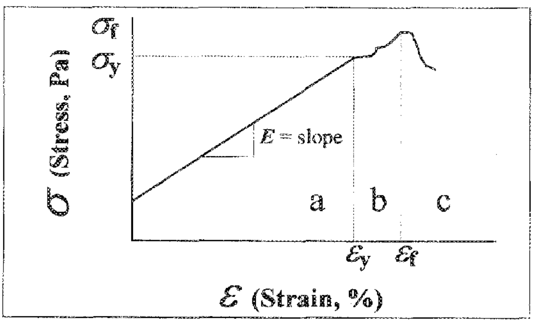

Figure 2 A stress-strain curve for a material undergoing (a) elastic deformation, (b) plastic deformation following yield, and (c) failure. The slope of the elastic portion of the curve is used to determine the elastic modulus (E). The strength and extensibility of the material are determined from failure stress (σ_f) and failure strain (ϵ_f), respectively. The subscripts y and f correspond to mechanical yield and failure, respectively.

Dilation and shearing resistance

Stretching the gummy bear also reveals the fourth property of materials, namely that as materials are strained parallel to the applied stress, they may also become strained normal to the stress (i.e., the gummy bear gets thinner as it is pulled apart; see Figure 3). The ratio of the induced strain (normal or y-direction) to the applied strain (parallel or x-direction) is called the Poisson's Ratio ($\nu_{xy} = -\epsilon_y/\epsilon_x$, the negative sign accounts for the shrinkage in the y-direction), which provides a measure of the **dilation and shearing resistance** (i.e., resistance to change in volume and shape, respectively). The Poisson's Ratio ranges from 0.1 for tissues like bone, which do not change shape or volume easily, to 0.5 for potato tubers and gels that act as if they were incompressible fluids (i.e., change shape easily but not volume).

This discussion leads to an important concept of directionality in the properties of materials. Those materials with similar mechanical properties, regardless of the direction at which they are measured, are referred to as isotropic. Most biological materials are anisotropic, in that they are generally of composite construction and the mechanical properties vary according to the direction of measurement. As a consequence of anisotropy, it may be possible to define six Poisson's Ratios for most biological materials since a force can be applied to each of the six faces of the material prepared as a cube.

Stored energy or work of extension

Returning to the stress-strain relationship, it is possible to integrate the areas under the stress-strain curve (Figure 2) to measure the work needed to deform the material, which is called the **stored energy** or **work of extension** (Work = $\sigma\epsilon$ in Jm^{-3}). Both bone and collagen have stored energies that are about six times that of wood, and thus have a greater area under their stress-strain curves.

Resilience

Experiments with load cells have shown that the work of extension of a material is not necessarily equal when applying (load-

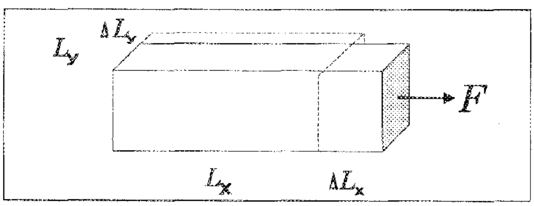

Figure 3 Material strain in parallel and normal to the applied force. The Poisson's Ratio ($\nu_{xy} = -\epsilon_y/\epsilon_x$) provides a measure of the dilation and shearing resistance (i.e., resistance to changes in volume and shape).

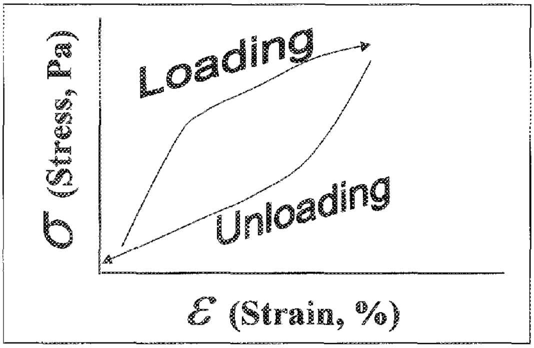

Figure 4 The area under a stress-strain curve is equal to the stored energy or work of extension of the material. In this case, the work in loading was greater than unloading indicating a not very resilient material.

ing) or releasing the force (unloading), even though the materials return to the same shape (Figure 4). The ratio of the work in unloading to that of loading the material (i.e., the capacity to release the strain energy that was absorbed) is called the **resilience** ($Work_{out}$ / $Work_{in}$ in percentages). For example, tendon (collagen) is almost three times as resilient as silk, even though they both appear to have a high resilience. This is because the $Work_{out}$ component in silk is released as heat not mechanical energy (Vogel, 1988).

Toughness

The **toughness** or **work of fracture** of the material, is the work per unit area (Jm^{-2}) required to cause the material to fail. Wood has a toughness seven times that of a mollusc shell when both are tested cross grain or normal to the shell. They have lower toughness (1/80 and 1/11, respectively) when compared with the grain or parallel to the shell.

Putting it together: materials to structures

In summary, the seven properties of materials are stiffness, strength, extensibility, dilation and shearing resistance, stored energy, resilience, and toughness. Some of these can be of importance in determining the strength of plant structures (e.g., trees) and their constituent elements (e.g., upright stems and branches). So, for example, the maximum load (W in N) that an upright solid stem can bear before it fails in buckling, is given by,

$$W = \frac{n\pi^2 EI}{L^2} \qquad (1)$$

where n is a constant, E is the elastic modulus in MPa, I is the moment of inertia in m^4 (see Equation 3), and L is the length of the stem in m. It is important to note that buckling, bending, and other important failures to plant structures depend only on the stiffness (E) of the material (along with the geometry given by I and L of the structure). As such, stiffness is an important mechanical property to determine for plant materials.

Many of these properties, with the possible exception of dilation and shearing resistance, may be measured directly and simply. Unfortunately, the stiffness (or elastic modulus E), which is important when determining the resistance to breaking, buckling, and torsion, requires information from a stress-strain curve, or alternatively, requires sophisticated equipment that would not be available for an undergraduate biology laboratory (Niklas and Moon, 1988; Pang and Scanlon, 1996). We present a simple and inexpensive experimental technique for determining the elastic modulus of biological materials and their response to differing water content.

Materials and methods

Students are asked to test the null hypothesis that the stiffness of potato tuber parenchyma is equal for potatoes of differing water content (other comparisons are also possible, see **Discussion**). They are informed that the deflection of a horizontal beam in the vertical direction due to an applied load is related to the applied load, the length and moment of inertia of the beam, and the stiffness (elastic modulus) of the beam. This is modelled using the following relationship,

$$\delta = \frac{WL^3}{kEI} \qquad (2)$$

where δ is the deflection in m, W is the applied load in N, L is the length of the beam in m, k is a constant equal to 48, E is the elastic modulus in MPa, and I is the moment of inertia in m^4. The moment of inertia for a beam is determined using the following relationship,

$$I = \frac{\pi r^4}{4} \qquad (3)$$

where r is the radius of the beam in m.

The beams are produced from large (> 15 cm long) potato tubers (*Solanum tuberosum*; we used the cultivar Russet Burbank, but this could be replaced with any suitably long potato such as the Pentland Dell cultivar) of similar shelf age from a grocery store. Students are directed to cut the end off each side of the potato and core approximately ten 10–15 cm long cylinders along the long axis of the potato using a stainless steel #2 or #3 cork bore (i.e., < 5 mm diameter). Each cylinder is carefully weighed on an electronic balance to the nearest tenth of a gram, and measured for length to the nearest mm using a ruler. The diameter of the cylinder is measured to the nearest tenth of a mm, using a thin cross section viewed under a dissecting microscope and a calibrated ocular micrometer. The cylinders are set aside on a paper towel and re-measured at the beginning and end of each measurement.

The potato cylinders are inserted into 5 mm (¼") holes drilled between two blocks of wood as presented in Figure 5. The blocks can be braced or free-standing provided that they do not move apart. The cylinders should fit snugly (the ends may need to be wrapped with parafilm), but not tightly. Approximately 1–2 cm of the cylinder should extend into each block, which ideally should be 8–10 cm apart (L). A thin metal fishing leader is wound around the cylinder several times and attached to a barbless three-prong fishing hook. Pre-weighed steel washers of various sizes (3–13 mm diameter; we used, not as yet being metric, ⅛", 3/16", ¼", 5/16", ⅜", and ½" diameter), are added sequentially to the fishing hook, and the vertical deflection is measured with a ruler after each loading (Figure 5(b)). New washers are added until the cylinder either slips out from the block of wood or breaks (the leader should not cut through the potato). At least five or six loads should be added to determine the mean stiffness (E) of each sample. The cylinders can be kept and allowed to air dry for approximately 2 days to determine their

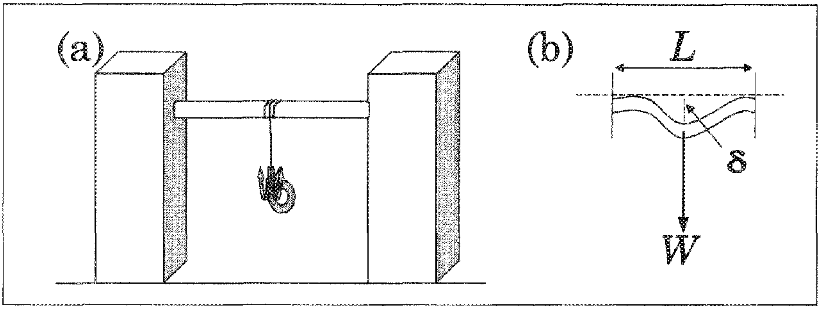

Figure 5 *The experimental technique for measuring the stiffness of plant tissues. (a) A cylinder of potato tuber is inserted into 5 mm (¼") holes drilled into wood blocks. Pre-weighed washers are added sequentially to a barbless three-prong fish hook to load the beam. (b) Schematic of (a). The vertical deflection (δ) of the beam (L = length between blocks) from the horizontal is measured each time a new load (W) is applied.*

dry weight if required. The experiment can be repeated at 15–20 minute intervals using the remaining cylinders to complete the practical.

We used spreadsheet software (Microsoft Excel) to enter, manipulate (i.e., calculate WL^3 and $k\delta I$), and plot the data, and to determine the slope through linear regression. The stiffness (E in Pa) can be determined by isolating for E in Equation 2. This is equivalent to finding the slope of a scatter plot of WL^3 versus $k\delta I$ (i.e., $E = WL^3/k\delta I$). The units of E should be in Pa (Nm^{-2}) given the units of the slope (Nm^3m^{-5}).

Results

Results for a typical experimental run in which the potato was loaded with six washers are presented in Figure 6. Since the relationship between WL^3 and $k\delta I$ is linear, it is possible to use linear regression analysis to estimate the elastic modulus (E). In this case, the regression was meaningful ($r^2 = 0.99$) and statistically significant ($P < 0.05$), and provides an estimate of E equal to 10.4 MPa. Other measurements of E were consistent when measured within the same time period (e.g., within 5 minutes of coring, $E = 10.50 \pm 0.58$ MPa, n = 9; mean ± standard error, sample size). However, E declined monotonically over the duration of the laboratory period as presented in Figure 7. A total of 88 potato cores were tested over 97 minutes post coring, providing a mean value of 6.89 ± 0.29 MPa. The decline in E corresponds well to the percent water loss measured on the potatoes at the time of testing versus the time of coring (dotted regression line in Figure 7).

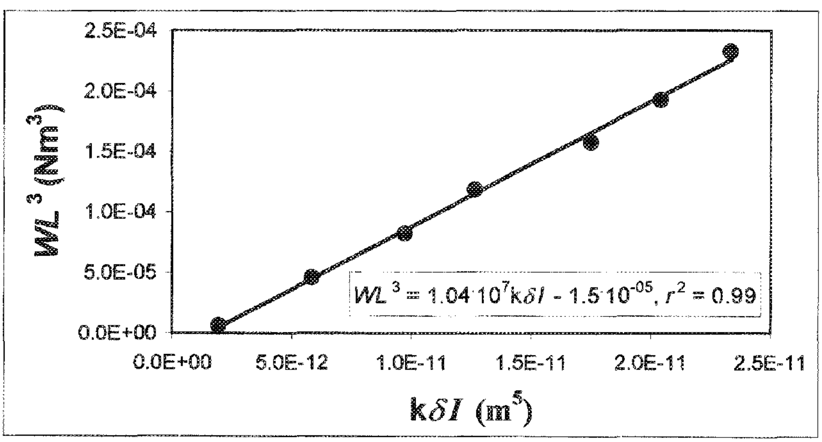

Figure 6 *Typical results for a single sample of potato tuber in which the product of the applied load (W) and length cubed (L^3) are plotted against the product of a constant (k = 48), the vertical deflection (δ), and the moment of inertia (I). Linear regression can be used to estimate the stiffness of the material when it is plotted in this way (see Equation 2). The slope of the regression provides an estimate of 10.4 MPa for the elastic modulus of this potato.*

Discussion

Potato tuber is an excellent tissue for mechanical measurement as its parenchyma cells are generally uniform in shape, and thus the tissue is considered to be relatively isotropic. This was confirmed by Niklas (1992), who was not able to detect directional bias in his results. However, new techniques indicate that there is some level of anisotropy in potato tuber parenchyma (Pang and Scanlon, 1996), although it is doubtful that this level of directional bias would be of significance in this application. Further confirmation of the validity of the technique can be found in our measurements of potato tuber stiffness (E = 1–14 MPa). These estimates are consistent with values determined under a variety of measurement techniques (e.g., E = 1.2–19 MPa (Niklas, 1988); E = 0.3–8.1 MPa (Pang and Scanlon, 1996)). This indicates that our technique is robust and appropriate for application in a student laboratory setting.

The decline in tuber stiffness with water loss provides a valuable experimental factor in the practical. Our results are consistent with previous studies that demonstrated a reduction of stiffness with drying of potato tubers (Niklas, 1988; Pang and Scanlon, 1996). Drying was estimated from the water loss, measured as the difference in the mass of the tuber cylinders at the time of measurement compared to the time of coring. The elastic modulus was directly, and significantly, related to the water loss using data for the cores in Figure 7 in a regression analysis (e.g., the regression equation is $E = 11.5 - 0.343 \times$ Water loss; $r^2 = 0.78$; $P < 0.001$; n = 88). Water content of potato tubers may also be manipulated using different storage intervals, osmotic manipulations, or drying. We prefer the air drying approach for its simplicity and ease of completion within a single 3-hour practical.

A number of other comparisons/experimental manipulations are possible for this practical including open-ended exploration for more advanced classes. An interesting and logical compari-

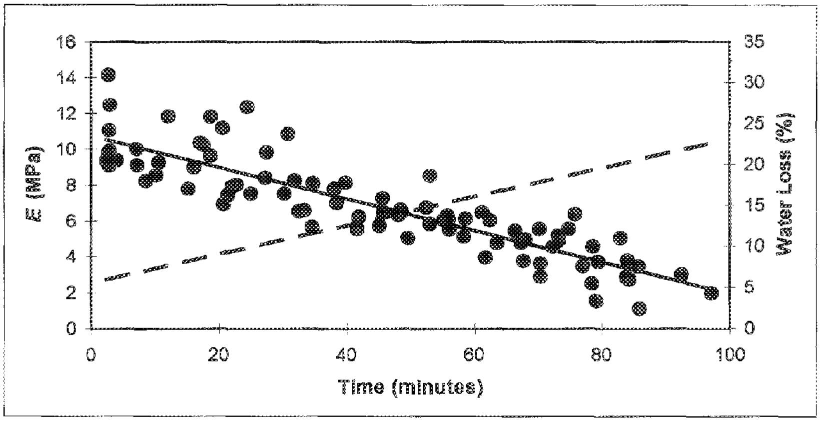

Figure 7 The effect of drying on the stiffness (E) of potato tubers. The solid line is the regression of E with time post coring. The dotted line is the regression of measured water loss with time post coring.

son would be between the parenchyma tissue of the potato tuber and the stem tissue of other plants. Asparagus spears or even horsetail stalks come to mind in this case, although twigs may also be of interest. The cross section of the stem should provide a means to estimate the amount of vascular and other supportive tissue, which could then be compared to the parenchyma tissue of the potato tuber.

There are a number of sources of potential error to be considered when preparing and conducting this experiment. These involve both experimental techniques and numerical analysis. The former difficulty pertains to the manner in which the potato cylinder is held in the wood blocks. Care must be taken to avoid premature slippage (i.e., slippage not due to loading; Equation 2) of the tuber from the blocks. This is especially important for measurements conducted later in the practical, as the diameters of the cylinders would be reduced due to water loss. This could lead to underestimates of the elastic modulus. The problem associated with the analysis of the data pertains to the number of data points used in the linear regression. In some cases, the number of points for a single tuber may be too small for a reliable estimate of the slope (E). We recommend that at least five or six washers are used to load each tuber cylinder to avoid this problem.

Finally, it is important to place these measurements of the elastic modulus in the context of other materials. Potato tuber parenchyma fall towards the lower end of the spectrum for the materials presented in Table 1, which range from $E = 1 \times 10^{-3}$ to nearly 10^5 MPa. This is not surprising given that tubers are storage organs rather than organs of mechanical support. It is important to recognize that most biological tissues are complex in that they are composed of composite materials. Rather than being simple engineering design solutions to single problems, biological materials and structures represent evolutionary solutions to a multitude of simultaneous and sometimes conflicting constraints. The examination of potato tuber parenchyma in an undergraduate practical may provide the first opportunity for a student to enter the interesting and exciting field of comparative biomechanics.

Table 1 Examples of Elastic Modulus for Selected Materials

Material	*E (MPa)*	*Source*
Sea Anemone Mesoglea	0.001	Vogel 1988
Parenchyma (*Solanum*)	1–14	Present Study
Algal Cell Wall (*Nitella*)	100	Wainright *et al.*, 1982
Bone (cancellous)	300	Wainright *et al.*, 1982
Tendon (collagen)	2000	Vogel, 1988
Silk	4000	Vogel, 1988
Wood (willow – *Salix nigra*)	5030	Niklas, 1992
Wood (pine – *Pinus resinosa*)	12 390	Niklas, 1992
Teeth (enamel)	78 000	Vogel, 1988

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