Biology on the Rack: A Simple Device To Measure Tensile Strength

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The physical world around us presents many challenges to everyday existence. In fact, the distribution of many plants and animals is related to mechanical properties of their bodies and their response to mechanical stresses (Koehl 1982; Vogel 1988; Brewer & Parker 1990). As a result, all living organisms have interesting, and sometimes unusual, morphological and physiological adaptations to their environments.

Mechanical stress is defined as the force, or load, per cross sectional area on the material bearing the load. Organisms bear stress in a variety of ways. For example, rigidity, flexibility, and ability to bend, twist or compress are all related to how organisms deform or break in response to conditions in their physical environment. Despite adaptations to their environments, many plants and animals do suffer some kind of mechanical failure of one part or another during their lifetime. Tendons and ligaments in joints are subjected to a variety of mechanical stresses as a result of daily activities. For some organisms, such as gazelles, tearing a ligament or breaking a bone while fleeing from a predator may ultimately lead to death—either by predation or subsequent inability to forage for food. For others, such as football quarterbacks, basketball players or weekend skiers, blown ligaments may end sporting careers.

Mechanical stresses and tissue failure are common for plants, too. Imagine the response of a palm tree in a strong wind compared to a cottonwood tree. Branches of cottonwoods snap off a tree, but a palm tree bends with the flow of the wind.

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Aquatic plants rooted in a stream also must be adapted to forces from flowing water. Plants rooted in streams are pulled, or dragged, by the force of moving water (Figure 1) and as a result, their tissues are placed under tension. While gentle flows in late summer may not be strong enough to break plant stems, during periods of high discharge the force of moving water may rip plants from the stream bed or cause stem breakage. For some plants, especially many aquatic species, breaking is one mechanism for reproduction and population growth and dispersal (Brewer & Parker 1990).

One of the most straightforward abuses of any material is tugging at opposite ends to apply tensile stress (Vogel 1988). Using a simple tensometer, students can compare the tensile strength of plant stems from a variety of aquatic plant species. The amount of stress a biological tissue can withstand before it breaks is called the tensile strength. It is a function of the cross-sectional area of the stem as well as the kinds of materials used to build the stem (Koehl 1982; Vogel 1988; Niklas 1992). Tensile strength is calculated as

$$\delta = \mathbf{F}/\mathbf{A}$$

where δ is the tensile strength, **F** is the force (Mega-Newtons), and **A** is the stem cross-sectional area (m^2) (Koehl 1984).

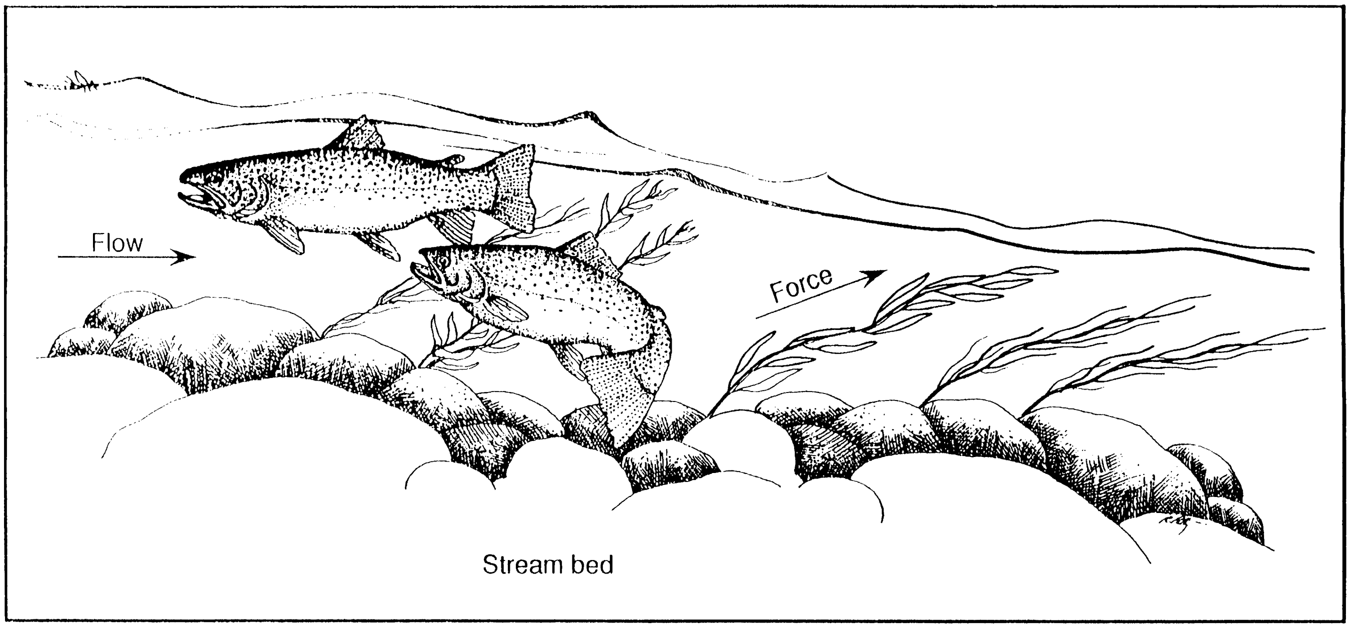
Procedure

Using a Tensometer

A simple tensometer is used to put plant stems under tension. The tensometer can be easily constructed using 1 × 10 boards, a fly-fishing reel, fish weighing scale, steel fishing leader, and alligator clips as shown in Figure 2. The fly-fishing reel is used to pull a steady tension on a plant stem, and the fish weighing scale is used to measure the load exerted on the stem. It is helpful to have a sliding marker or gauge affixed to the scale to indicate the maximum load reached during the measurements (Figure 2). The plant stem is held in place between the fly-fishing reel and scale with alligator clips. It is important to use a line, such as a steel leader material, that does not stretch when attaching the plant to the fly-fishing reel.

A variety of aquatic plants (with round stems) can be used in this activity. *Elodea canadensis* (frog-bit) is typically available from pet stores. Other species that can be used are *Ceratophyllum demursum* (hornwort), *Myriophylum exalbescens* (water-milfoil), *Potamogeton pectinatus* (common pondweed), *Potamogeton richardsonii* (Richardsons pondweed), *Ranunculus aquatilis* (water crowfoot), *Hippurus vulgaris* (mare's-tail), *Polygonum amphibium* (water smartweed) and *Sagittaria cuneata* (arrowhead plant). These plants may be available in local streams, ponds or lakes. Aquatic plants should be stored in an aquarium until they are used.

The most challenging part of the procedure is attaching the plant to the alligator clips. Vogel (1988) waxes poetic on the coarse oral tradition describing the design and use of grips for biomaterials. Biological materials present a particular challenge because they tend to be wet and slimy, small, and rapidly fall apart. I have found that small pieces of tygon tubing work well. A small, narrow piece of screen material wrapped around the stem ends prior to inserting the stems in the tygon tubing also reduces slippage out of the clips. There is ample opportunity for students to experiment with various grips to find the ones that cause the least damage to the plant



Stress on plants under tension from flowing water

Figure 1. Drag on aquatic plants in a stream environment. Force is experienced by plant tissues in the direction of flow of the stream.

stem, while at the same time, hold the stem firmly in place.

After selecting a plant and cutting it to the desired length to fit in the tensometer (approximately 25 cm), students use calipers to measure the stem diameter. Then the stem section is placed in the tensometer grips. A load is placed on the stem by steadily cranking the fly-fishing reel. It is important to crank the reel at the same steady speed for each test. Because data are often only roughly reproducible, it is very important to stress careful attention to the testing procedures to ensure consistent application of the load (Vogel 1988). Students record the maximum load (in pounds or kilograms) achieved before the stem breaks.

Where the stem breaks can be very interesting. Ideally, the plant will break somewhere along the stem length between the grips. Students

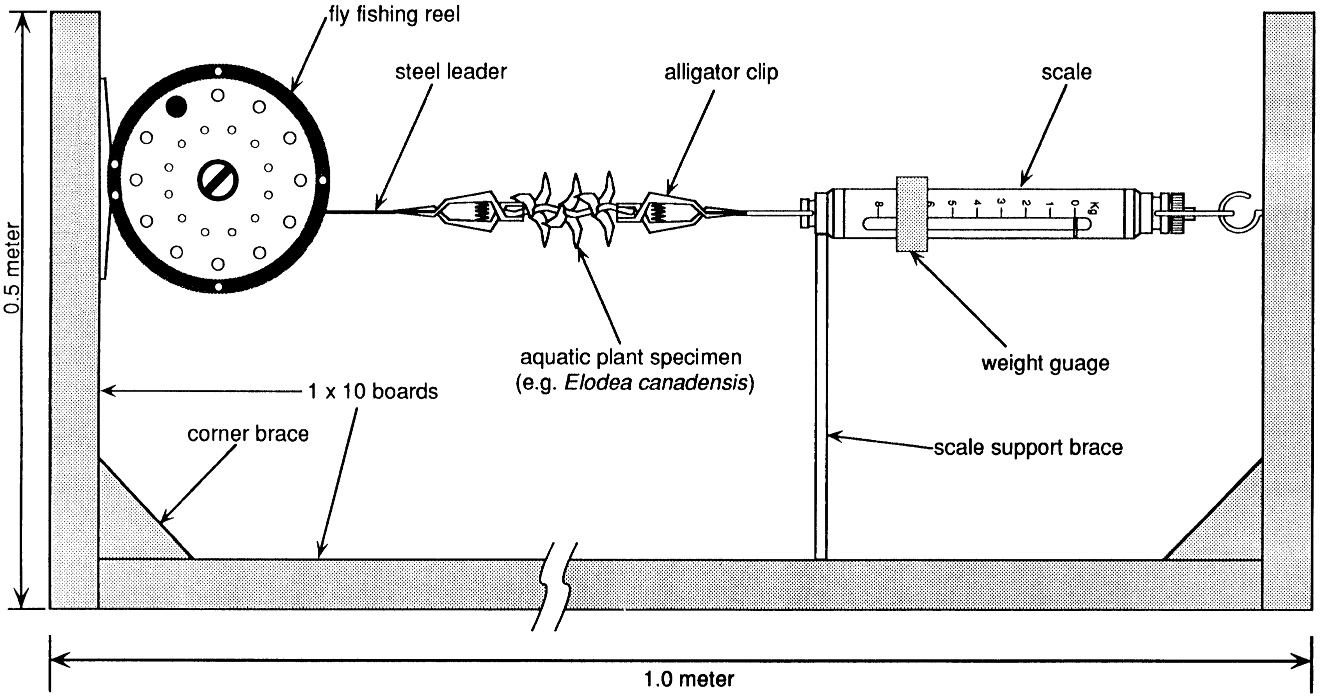


Figure 2. A simple tensometer for measuring tensile strength of biological materials.

Table 1. Example data sheet with equations and sample calculations.

Location of Break	Load (kg)	Stem Diameter (m)	Stem Radius (m)	Stem Area (m^2)	Force Newtons (kg ms^{-2})	Mega-Newtons	Tensile Strength (MN/m^2)
node or internode	direct measure	direct measure; convert to m	diam/2	πr^2	kg*9.81	convert using Table 2	$\delta = F/A$
node	0.11	0.075cm 7.5×10^{-4}m	3.75×10^{-4}	4.41×10^{-7}	1.079	1.079×10^{-6}	2.45

should note whether the breaks occurred at a node (joint where leaves or stems are attached) or internode (stem between nodes). If the plant break occurs at the grips, data from the run should not be used. It will take several iterations to find the best way to clamp the plant without weakening the stem sections near the clamps.

Calculating Tensile Strength

An example data sheet is shown in Table 1. Data on location of break, cross-sectional area and load are recorded. From data on stem cross-sectional area and load, students calculate tensile strength. This may involve conversion from English to metric units, depending on the type of fish scale and calipers used (Table 2).

Bar graphs conveniently illustrate differences in tensile strength among species. Students may also explore the relationship between stem tensile strength and stem cross-sectional area.

Data collected using this procedure can be analyzed using simple statistical tests. Means and standard deviations can be calculated to make generalizations about a particular species while T-tests or analysis of variance models can be used to compare several species.

Interpreting Data

One way to evaluate the cost of mechanical failure is to consider the effect on ecological fitness—the number of offspring left in the next generation. For species propagated mainly by producing seeds, fitness is greatly reduced when stems break and the season's reproductive effort floats downstream. Conversely, for species duplicating by fragmentation, fitness is increased when stems break and vegetative propagules are released into the environment.

Table 2. Useful conversion factors for calculating stem tensile strength.

Original Units	Multiply By	Desired Units
ounces	0.0625	pounds
pounds	0.454	kilograms
kilograms	9.81	Newtons
Newtons	0.000001	Mega-Newtons
inches	0.393	centimeters
centimeters	0.01	meters

In general, students can hypothesize about the cost of mechanical failure to ecological fitness as they learn more about how different species reproduce. For example, aquatic plant species propagated mainly by producing seeds (e.g. *Potamogeton pectinatus, Potamogeton richardsonii, Polygonum amphibium* and *Sagittaria cuneata*) typically have stronger stems than species that root easily after fragmenting (*Elodea canadensis, Ceratophyllum demursum, Myriophylum exalbescens, Ranunculus aquatilis, Hippurus vulgaris*) (Brewer & Parker 1990).

It is also important to consider the type of aquatic habitat from which the plants were collected. Plants rooted in fast-moving streams, shallow shores or intertidal zones would be expected to be much stronger than plants rooted in the deep water of a lake.

Extensions to Other Biomaterials

The tensometer can be used in a wide variety of open-ended exploratory investigations. Many different types of biological materials can be tested. For example, students can pose hypotheses about the cost of producing leaves on annual and perennial plants, as well as coniferous and deciduous plants. Then, they can determine how tightly leaf petioles are held to branches. Their data may be used to make generalizations about costs of retaining seasonal versus annual growth. Students may also wish to compare newly produced and older plant tissues. Interesting comparisons can be made between different kinds of animal tendons and ligaments as well.

Predicting the types of mechanical properties needed by plants and animals in different environments is a natural extension of this activity. Students may even design and test hypothetical organisms under different tension regimes and then discuss the costs and benefits of investment in strong versus weak tissues. Integrating concepts from biology, physics, mathematics, engineering and ecology make this extension a multidisciplinary activity. Books by Vogel (1988), Denny (1988) and Niklas (1992) are extremely useful for extending these concepts to a variety of organisms and habitats.

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