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Measuring the elastic parameters of samples without anchoring

A. Rusz [a], Z. Kocsis [b], S. Bokor [c], P. Hantz [d,*]

[a] *Semmelweis, Department of Urology, Budapest, Hungary*

[b] *Budapest University of Technology and Economics, Department of Polymer Engineering, Budapest, Hungary*

[c] *SCAAN Ltd., Cluj/Kolozsvár, Romania*

[d] *Sapientia University, Faculty of Technical and Natural Sciences, RO-530104 Miercurea-Ciuc/Csíkszereda, Szabadság tér 1, Romania*

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Abstract

Conventional methods for the measurement of elastic parameters demand the anchoring of the investigated specimen. In order to determine the elastic modulus, one needs to measure the force acting on the specimen, as well as the deformation caused by the force. If the investigated object is not anchored, it does not only deform, but will also shift due to the applied force, and the measurement cannot be performed. Several medical and robotic applications require the investigation of tissues and objects that cannot be fixed. In order to overcome this problem, an alternative method for the measurement of the elastic parameters has been elaborated. A device with offsetting and indenting regions was constructed. Force sensors are built into the offsetting, and distance measuring sensors built into the indenting regions of the device. If the instrument is pressed to the sample, the sample will deform according to its elastic parameters. A soft sample will fold with greater extent into the indenting regions as a hard one. Knowing the geometric characteristics of the device, and the values of the signals supplied by the force and distance sensors, it is possible to determine the elastic properties of the sample.

Keywords: Palpation sensor; Haptic sensor; Elastic modulus

1. Introduction

Methods of medical diagnostics have been remarkably improved in the last decades. However, there is a lack of devices that could substantially improve or replace the examination through palpation [1–4]. Elaboration of haptic sensors, that could quantify the ‘‘hardness’’ or ‘‘softness’’ of the investigated samples, would be of great importance also for the perfection of artificial human limbs and the fingers of robots [5–7].

One of the main difficulties of the measurements of elastic parameters in the above mentioned applications lies in the circumstance that most of the samples cannot be anchored. Therefore, they do not only deform, but may also shift due to a force acting on them. If the deformation component cannot be measured independently, there is no way to calculate the elastic parameters. However, it is still possible to perform relative measurements on inhomogeneous specimens [9]. In this paper we describe the conception and the realization of a device that can perform measurements even on non-anchored samples in such a way that the data supplied enable the approximate calculation of some elastic parameters of the investigated region of the specimen [10].

The elasticity of a specimen is usually characterized with an elastic modulus. In the deformation regime where the response of the specimen is linear, this is referred to as the Young modulus E [8]. Surprisingly, our investigations revealed that the Young modulus of various sponges does not correlate with their ‘‘softness’’ in the common sense. More adequate characteristics turned to be the general elastic moduli GE, defined as the ratio of the stress and the strain at deformations where the response of the specimen does not follow a linear law any more. Note that the GE

* Corresponding author. Fax: +40 264 593648.
E-mail address: hantz@general.elte.hu (P. Hantz).

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defined above is not related to the derivative of the compression-force curve, but to the angle of the straight line directed from the origin to a certain point of the curve. The device presented in this paper enables the approximate determination of the general elastic moduli. Results of measurements on regular sponge prisms of various softnesses in the conventional and the novel way will also be presented.

2. Conception and realization of the device

In order to be able to find the elastic parameters of samples that are not anchored, we were looking for characteristics that correlate with the elastic parameters, and can easily be measured even if the investigated sample is free to move. Such a characteristic turned to be the deformation of the samples pressed with a certain force to a rigid surface having outstanding and indenting regions. A ‘‘soft’’ sample folds into the indenting regions of the surface, while a ‘‘hard’’ will deform only in a much smaller extent. In the vast majority of the cases, an object that is in common sense ‘‘harder’’, has higher general elastic moduli than a ‘‘softer’’ one.

This conception can be scheduled as follows (Fig. 1). The body of the device is a rigid surface with outstanding and indenting regions. The force (pressure) sensors are fixed on the top of the outstanding regions. The body is covered by a thin, easily deformable membrane. Distance sensors are located in such a way to be able to measure the alternation of the interval between the membrane portions and the bottom of the indenting regions. If the device is pressed to the sample, the sample will deform according to its elastic parameters. A soft sample folds into the indenting regions, and the distance alternation sensors will show a strong signal. By pressing the device to a hard sample, the distance alternation sensors will only show a weak signal. Knowing the geometric characteristics of the device, and the values of the signals supplied by the force and distance alternation sensors, it is possible to calibrate the device and to calculate a set of the sample’s (general) elastic moduli.

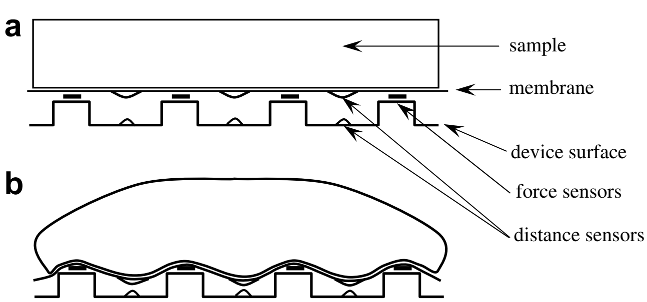

Fig. 1. Schedule of a device for measuring elastic parameters, having force and distance alternation sensors. When the device just touches the investigated sample, the sensors do not show signals (a). If the device is pressed to the specimen, the signals of the force and that of the distance alternation sensors enable the calculation of the generalized elastic moduli of the sample (b).

An alternative solution is presented in Fig. 2. According to this conception, force sensors should be placed both on the outstanding, and on the indenting regions of the device’s body. During the measurement, the device is pressed to the sample, and a soft sample will fold in a greater extent into the indenting regions, than a hard one. Therefore, the force sensors located in the indenting regions of the device, will show a relatively stronger signal when investigating a soft sample, than in the case of a hard one. Having the values of the signals supplied by the force sensors located on the outstanding and the indenting regions, it is also possible to determine the elastic properties of the sample.

Our device has been realized according to the first conception. The body of the device is a plastic cylinder, having 25 mm inner, and 35 mm outer diameter. The edge of this cylinder serves as the outstanding, while its interior as the indenting region. The body of the device is placed in a cylindrical shell, where the body can perform movements parallel to the common axis (Fig. 3). The bottom of the

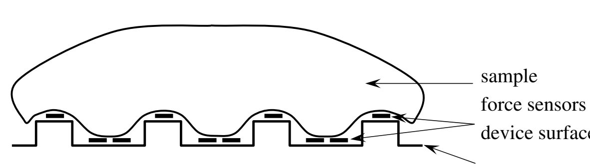

Fig. 2. Schedule of a device for measuring the elastic parameters, with force sensors in its outstanding and indenting regions. The device is pressed to the investigated sample, that folds into the indenting regions. Signals of the force sensors enable the calculation of the elastic moduli of the sample.

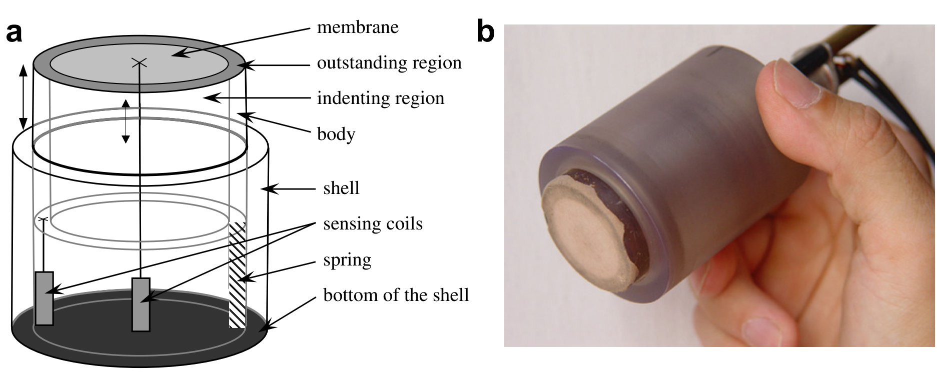

Fig. 3. Sketch (a) and the photo (b) of the built device. For explanation, see the text.

body is attached to a spring, that leans on the bottom of the shell. The spring serves as a force sensor: when the device is pressed to the investigated sample, the compression of the spring, that is, the diminishing of the distance between the bottom of the body and that of the shell, is proportional to the acting force. This movement is monitored by inductivity measurements, with an accuracy of 0.1 mm: a coil is attached to the bottom of the shell, while its movable core to the body. The cylindrical body is covered by a thin membrane. The folding of the membrane is also measured inductively, with an accuracy of 0.1 mm. The center of the membrane is attached to the core of a coil, that is also built in the shell.

Calibration of the device consists of the registering of two curves, namely one representing the force acting on the body as a function of the signal of the first coil, as well as the indention of the membrane as a function of the signal of the second coil. The range of the device is [0...2 N] for the force sensing spring, and [0...5.9 mm] for the deformation sensing membrane.

3. Experimental

The device outlined above was designed for performing quantitative investigations on samples, that are "soft" in the common sense. The instrument has been tested by comparative measurements of general compression–elastic moduli of 15 sponge prisms of $80 \times 80 \times 30\ mm^3$. The sponge samples were selected such as to cover, as far as possible, a large range of elastic parameters.

In order to obtain the compression–elastic modulus of the sponge samples with a high accuracy, a series of classical compression tests were conducted according to ISO 3386 international standard. The measurements were carried out with a Zwick Z005 type mechanical testing machine at room temperature as follows. The sponge prisms were placed between two parallel steel interfaces, and compressed perpendicular to their 80×80 mm surface with a loading speed of 50 mm/min. In order to eliminate the very beginning of the compression curves, where minor disturbances may cause deviations from the linear law, a pre-load force of 1–1.5 N was applied. Typical compression–resistance force diagrams are shown in Fig. 4. Note that even the sample "n" is considered, by palpation, to be "softer" that sample "f", the steepness of the linear sequence of its diagram, that is proportional to its Young modulus, is surprisingly slightly higher.

The compression-Young moduli are calculated making use only of that compression interval where the sponges show a linear response. These intervals vary from sample to sample, and were determined visually, by the compression–resistance force diagrams. As generalized elastic modulus, we took the ratio of the stress and the strain when the deformation of the sample was of 5.5 mm. The reason for this choice was motivated by the geometry of our new device: this is close to the maximal depth in which the outstanding region can penetrate. The error of the measurements were smaller than 0.01 mm and 0.01 N, respectively. Due to the non-negligible hysteresis of the sponge samples, we were making use only of the data collected during the compression, and not also of those that could be collected during the relaxation.

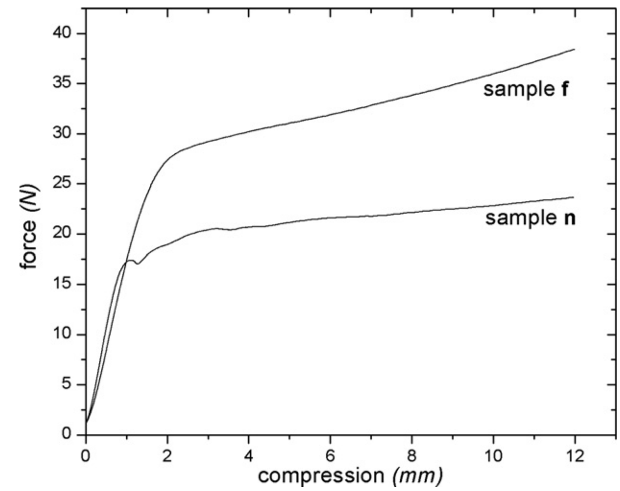

Fig. 4. Compression–force diagram of samples "*f*" and "*n*".

The results are summarized in Fig. 5, representing the generalized elastic modulus of the samples at 5.5 mm deformation, as a function of their Young modulus. Note that no correlation can be observed between the linear and non-linear elastic moduli.

Having obtained the above compression elastic moduli of the sponge samples, we turned on investigating their elastic properties with our new device. The measurements were conducted as follows. The device was fixed vertically, such as its sensing surface, that is, the outstanding region and membrane was looking downstairs. Below the device, a liftable horizontal plate was mounted, where the investigated

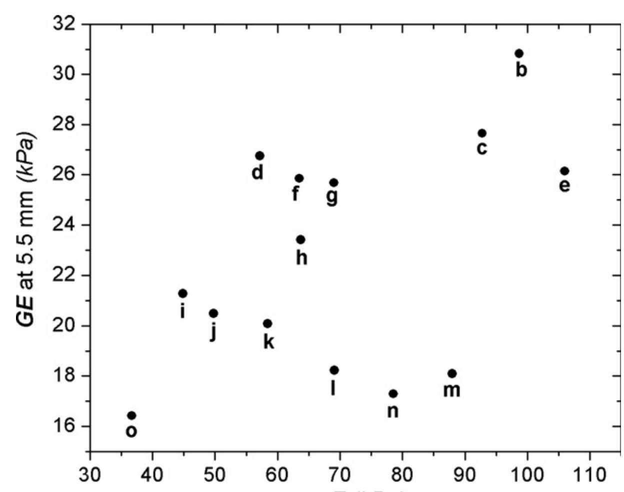

Fig. 5. General compression elastic moduli (GE) measured at 5.5 mm vs. compression-Young moduli (E) of the investigated sponge samples. There is no correlation between these elastic parameters. The point representing sample "a" ($E = 222.74$ kPa, GE = 163.68 kPa) is out of the range of the figure.

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sponge sample was laid. By lifting the plate, the middle region of the sponge's 80×80 mm surface could be pressed to the sensing surface of the device. The lifting speed of the investigated sponge prism was roughly 50 mm/min, being interrupted for short times in order to record the signs shown by the sensing coils. Since the sponge samples have a non-negligible hysteresis, we were making use only of the data collected during the compression. Moreover, the sponge samples were let to relax at least 30 min between repeated investigations. Note that the results of the first 1–2 investigations were not considered.

According to the expectations, the indention of the membrane, at a given pressing force acting on the outstanding region, is as greater as the sample is more "soft". Although there are several possibilities to find a relation between the measured data and the elastic properties of the samples, the simplest way turned to look for the indention Δh of the membrane at certain pressing forces of the outstanding region. Since the device allowed as the maximal value of this force 2 N, we were looking, among others, for the indention Δh at the middle of this domain, namely at 1.3 N. Note that the force excreted by the membrane was less than 0.2 N. In order to average the deviations due to the imperfections of the measurements (condition of the sample, friction of the device) repeated measurements have been performed on the same specimen. The typical deviation of the measurements from their average value was less than $\pm 20\%$.

The average membrane indentions $\overline{\Delta h}$ vs. the GE measured at 5.5 mm deformation of the samples are represented in Fig. 6. It can be observed, that there is a clear correlation between the general elastic moduli and the indention $\overline{\Delta h}$: at smaller values of GE, that is, in the case of the samples that are "soft" in common sense, the average membrane indention $\overline{\Delta h}$ is greater. Thus the device is able for the approximate determination of a generalized elastic parameter, and to distinguish between "hard" and "soft" samples.

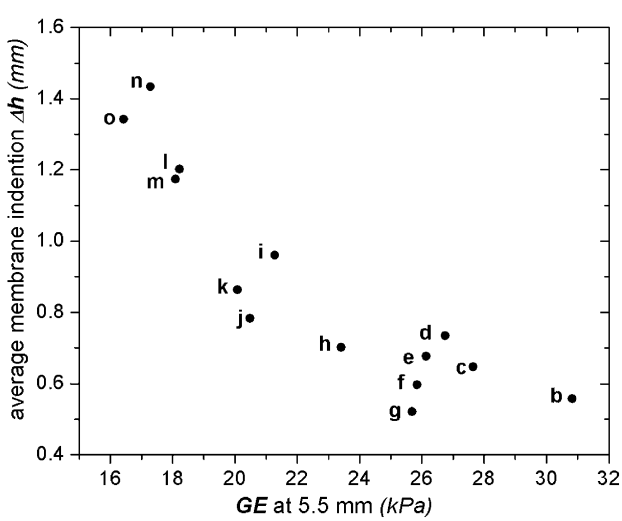

Fig. 6. Averaged membrane indention values ($\overline{\Delta h}$) when the outstanding region was pressed by a force of 1.3 N, vs. the generalized elastic modulus GE measured at 5.5 mm deformation of the samples. Note the correlation between $\overline{\Delta h}$ and GE. Again, the point representing sample "a" ($\overline{\Delta h} = 0.22$ mm, GE = 163.68 kPa) is not figured.

4. Conclusions

In this paper, we presented conceptions and a realization of a device that is able to perform approximate measurements of the elastic moduli on soft samples, even if the samples are not anchored. The device has been tested with sponge prism samples. The measurements revealed that the generalized elastic moduli, that are, the ratio of the stress and strain in the non-linear regime are better characteristics of the "softness/hardness" in common sense, than the Young modulus of the linear regime. Although the hysteresis of the specimens diminished the accuracy of the measurements, we concluded that our device is able to examine generalized elastic moduli of various samples.

The idea underlying this mechatronic device (having mechanic and electric/electronic components) can be used not only in medical instruments for examination through palpation, but also in sensors of artificial human limbs, fingers of domestic robots, and other real-time systems for measuring elastic parameters of samples that are not, or cannot be anchored. Moreover, such sensors can be used as parts of larger mechatronic systems involved in mechanic control processes.

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