All-electrical indentation shear modulus and elastic modulus measurement using a piezoelectric cantilever with a tip

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We have investigated an all-electrical indentation shear modulus and elastic modulus measurement technique using piezoelectric cantilever sensors with a tip for potential in vivo applications. A piezoelectric cantilever with a tip was capable of carrying out compression, shear, indentation, and indentation shear tests, where compression and shear tests refer to those where the sample is not confined by a container and the contact area of the cantilever is the same as or larger than the sample surface area and the indentation and indentation shear tests are those where the contact area of the cantilever is smaller than the sample surface area. Because the cantilever could measure both the elastic modulus and the shear modulus, Poisson’s ratio of a sample could be determined from the ratio of the shear modulus to the elastic modulus with no presumption. We showed that the experimental elastic moduli and shear moduli obtained from the indentation and indentation shear tests agree with those obtained from the compression and shear tests. Furthermore, we showed that the same elastic moduli and the same shear moduli could be obtained either by using the displacement measurements or by the induced voltage measurements across the sensing piezoelectric layer. With a model tissue consisting of modeling clay embedded in gelatin, we demonstrated that the indentation compression and indentation shear tests could produce two-dimensional elastic and shear moduli maps or images that accurately showed the size and location of the modeling clay inclusion. © 2007 American Institute of Physics.

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I. INTRODUCTION

The elastic modulus of soft tissues can vary in orders of magnitude.1 The elastic modulus of abnormal tissue, including breast tumors, may differ from surrounding tissues by a factor of 90-fold.2 It is also known that the shear modulus of many tissues can vary in response to changes in physiological state.3 Studies showed that the elasticity of muscles in the relaxed and contracted state can differ by more than 100-fold. These differences in the elastic properties of tissue provided the incentives to seek measurement technologies that can estimate or assess the mechanical properties of tissues. A typical soft-tissue or soft-material mechanical property tester measures the elastic modulus (or Young’s modulus) using the compression tests.4–11 The mechanical testers typically require an external force (displacement) applicator and an external displacement (force) gauge.4,7 They also require specimens cut to a disk shape to fit in the tester and thus are unfit for in vivo measurements. Another method for measuring the elastic properties of soft tissues in vivo involves using an indenter to depress the tissue and measuring the depth of the indentation using linear variable differential transformer12 or ultrasound transducer.13–15 As for shear modulus measurements, few existing mechanical testers measure the shear moduli of tissue or soft-material samples let alone in vivo measurements.

Recently, Markidou et al. demonstrated that piezoelectric cantilever (PEC) sensors consisted of a piezoelectric layer, e.g., lead zirconate titanate (PZT) bonded to a nonpiezoelectric layer and an L-shaped tip could measure both the elastic modulus and shear modulus of soft materials directly using the same sensor.16 Applying a voltage across the piezoelectric layer generates an axial displacement or force at the cantilever tip, which can be measured with a laser displacement meter. Using such techniques, the elastic modulus and shear modulus of small samples of soft materials, e.g., gelatin and rubber, were measured with the free end of the piezoelectric cantilever contacting samples with surface areas equal to or less than that of the cantilever’s probe surface.16 In the following, we refer to elastic and shear modulus measurements where the sample is not confined by a container and the sample area is smaller than or equal to the contact area as compression (N) and shear (S) tests, as schematically shown in Fig. 1(a). Szewczyk et al.17,18 have developed a piezoelectric cantilever that had both a driving piezoelectric layer for applying forces and a separate sensing piezoelectric layer for measuring the corresponding displacement. With both electrical driving and electrical sensing in one fingerlike
Using piezoelectric cantilevers with a tip, we demonstrated that the same sensors could perform all four measurements: compression (N), shear (S), indentation (I), and indentation shear (M) tests. Poisson’s ratios of the tested rubber samples were determined from the ratio of the measured shear modulus to the measured compressive elastic modulus to be 0.47±0.20, as expected of isotropic rubber materials. With the experimentally obtained Poisson’s ratios, we deduced the indentation elastic moduli from the force-displacement curves using Sneddon’s analysis\cite{19} and showed that they closely agreed with the measured compressive elastic moduli. Although the indentation elastic modulus could be deduced without experimentally obtaining Poisson’s ratio by using the plane strain modulus, it is advantageous that the present technique can resolve both the elastic moduli and Poisson’s ratio. For the indentation shear modulus, we showed that an expression analogous to that relating the indentation elastic modulus to the force-displacement curve of an indentation test could also be applied to relate the shear modulus and the force-displacement curve of an indentation shear test by including an empirical preconstant $\alpha$. Experimentally, we found that $\alpha=1±0.2$. Finally, the feasibility of tissue imaging using indentation shear modulus map will be presented and compared with the elastic modulus map of the same sample.

II. EXPERIMENT

The cantilever used in this study was 3.2 mm wide that had two 127 $\mu$m thick PZT layers (T105-H4E-602, Piezo Systems Inc., Cambridge, MA) bonded to a 50 $\mu$m thick stainless steel layer (Alfa Aesar, Ward Hill, MA), one on the top side of the stainless steel for driving and the other on the bottom side of the stainless steel for sensing, using a non-conductive epoxy (Henkel Loctite Corporation, Industry, CA) followed by curing at room temperature for one day and sanding of the edges for uniformity. The top and bottom PZT layers were 22.5 and 9.4 mm long, respectively. The stainless steel formed a square loop at the free end as the probe [see Fig. 1(b)] to facilitate both compression and shear measurements using one single cantilever. The contact area of the stainless steel square probe was 16 mm$^2$ for both the compression and shear measurements. The cantilever was clamped with a fixture made of 7.5 mm thick acrylic (McMaster-Carr, New Brunswick, NJ). The PZT layers have a piezoelectric coefficient, $d_{31}=-320$ pC/N. Young’s modulus of the stainless steel and that of the PZT layers were 200 and 62 GPa, respectively. The capacitance and the dissipation ($D$) factor of the driving and sensing PZT layers were measured using an HP 4192A LF impedance analyzer (Hewlett-Packard, Palo Alto, CA). The axial displacements at the tip of the cantilever were measured using a laser displacement meter (LDK), Keyence model LC-2450 (Keyence Corporation, Osaka, Japan), with a resolution of 0.5 $\mu$m (see Fig. 2). HP E3631A (Hewlett-Packard) was used as the programmable dc voltage source. The measurements were conducted on a Newport optical table (RS1000, Newport Corporation, Irvine, CA) to minimize low-frequency background vibrations. The applied voltage at the driving electrode, the
induced voltage at the sensing electrode, and the output of the displacement meter were recorded on an Agilent Infinium S4832D digital oscilloscope (Agilent, Palo Alto, CA). The dc power source and the oscilloscope were connected to a personal computer (PC). All measurements and data acquisition were controlled from the PC by LABVIEW (National Instrument, Austin, TX) programing. Three commercial soft rubber materials, Versaflex CL2003X, CL2000X, and CL30 (courtesy of GLS Corporation, McHenry, IL), of known Young’s moduli of about 50, 100, and 500 kPa, respectively, were used to validate the measurement methods developed in this study. In what follows, we will denote Versaflex CL2003X, CL2000X, and CL30 as R50, R100, and R500, respectively. Unless otherwise mentioned, all reported data were the average of three to four samples.

III. THEORY

A. Compression

In Ref. 16, the elastic modulus $E_N$ of a soft material was measured with a piezoelectric cantilever by what was called “regular compression tests” in Ref. 16 or “compression (N) tests” in this study, where the soft material was cut to a size such that the sample surface area was the same as or smaller than the cantilever tip area. In what follows, we will use the letter “N” to represent compression and a subscript $I$ of any quantity represents the “indentation test” conditions. As schematically shown Fig. 2(d), the contact area, $A_I$, is defined by gluing a thin, square plastic sheet of a known area on the underside of the cantilever tip. When a voltage is applied to the cantilever, it generates a force causing indentation on the sample. Sneddon’s analysis for an indenter of a circular contact area relates the indentation elastic modulus $E_I$ of the sample to the applied force $F$, Poisson’s ratio $\nu$ of the sample, the radius $a$, and the normal displacement $d_I$ of the probe as

$$E_I = \frac{F(1-\nu^2)}{2ad_I},$$

provided that the elastic modulus of the indenter is much larger than $E_I$. With the piezoelectric cantilever of a known spring constant $K$, the force applied to the sample by the cantilever is therefore $F=K(d_0-d_I)$, where $d_0$ and $d_I$ are the cantilever tip displacements without and with the sample, respectively, when a voltage is applied across the driving PZT layer, as schematically depicted in Figs. 2(b) and 2(d). For a circular probe surface, the contact area $A_I=\pi a^2$ and the indentation elastic modulus $E_I$ can be related to $A_I$, $K$, $\nu$, $d_0$, and $d_I$ as

$$E_I = \frac{1}{2} \left( \frac{\pi}{A_I} \right)^{1/2} (1-\nu^2) F = \frac{T_I}{d_I},$$

where

$$T_I = \frac{1}{2} \left( \frac{\pi}{A_I} \right)^{1/2} (1-\nu^2) K(d_0-d_I).$$

Note that $T_I$ has the dimension of force per unit length (N/m) and that the $T_I/d_I$ in Eq. (3) represents the slope of the $d_I$-reducing branch of the $T_I$ vs $d_I$ loop near the maximum, as discussed in Ref. 18. Although Eq. (3) was originally derived for a cylindrical probe, when applied to a square probe, the
error in the deduced elastic modulus was only 1.2%,\(^{19}\) which is within the present experimental errors. Thus, effectively, Eq. (3) can also be used to deduce elastic moduli when a square probe is used as in the present experiments.

### C. Shear

In Ref. 16, the shear modulus \(G_S\) of a soft material was measured with a piezoelectric cantilever by what was called the “regular shear tests” or the “shear (S) tests” in this study, where the soft material was cut to a size such that the sample surface area was the same as or smaller than the cantilever tip area. Figures 3(a) and 3(b) depict the cantilever tip without and with an applied voltage \(V_{app}=V\), respectively. In what follows, we will use the letter "S" to represent shear tests and a subscript \(S\) in any quantity denotes the “shear test” conditions. The applied voltage generates a displacement, \(d_0\), at the cantilever tip and an induced voltage, \(V_{in,0}\), at the sensing electrode. Figure 3(c) shows a schematic of a shear test on a sample using a piezoelectric cantilever with an applied voltage \(V_{app}=V\), where the cantilever tip is in contact with the sample surface area, \(A_S\). Note that in Fig. 3(c), in a shear test, the sample area is equal to or less than the probe area of the cantilever tip. When in contact with the sample, the same applied voltage \(V_{app}\) generates a displacement, \(d_S\), at the cantilever tip and an induced voltage, \(V_{in,S}\), at the sensing electrode and the soft-material shear modulus can be obtained using the following formula:

\[
G_S = \frac{(F/A_S)}{(d_S/h_0)} = \frac{K(d_0 - d_S)h_0}{d_S A_S},
\]

where \(G_S\) is the shear modulus as obtained by the shear test, and \(h_0\) and \(A_S\) are the height and the surface area of the soft material, respectively.

### D. Indentation shear

A schematic of the indentation shear (M) test on a sample is shown in Fig. 3(d). In what follows, a letter “M” stands for indentation shear tests and a subscript \(M\) of any quantity denotes the “indentation shear test” conditions. As shown in Fig. 3(d), the contact area, \(A_{MP}\), is defined by gluing a thin, square plastic sheet of a known area on the underside the tip of the cantilever. As mentioned above, presently, there is no known analytical expression to relate the shear modulus to the force-displacement curve of an indentation shear test, where the normal force is negligible compared to the shear force as in the present experimental conditions. However, there is an expression for the indentation shear modulus for a circular probe with appreciable known normal force,\(^{21}\) which has a similar expression as that of the indentation elastic modulus except for a numerical preconstant. For indentation shear modulus analysis, we will simply use an empirical expression similar to that depicted in Eqs. (3) and (4) for the indentation shear modulus, except that we will allow a numerical preconstant \(\alpha\), which will be determined empirically. The indentation shear modulus \(G_M\) is therefore expressed in terms \(A_M, K, d_0, d_M\) and \(n\) as

\[
G_M = \alpha \left[ \frac{1}{2} \left( \frac{\pi}{A_M} \right)^{1/2} (1 - \nu^2) \right] F \frac{d_M}{d_M - d_M},
\]

where

\[
T_M = \alpha \left[ \frac{1}{2} \left( \frac{\pi}{A_M} \right)^{1/2} (1 - \nu^2) \right] K(d_0 - d_S),
\]

where \(T_M\) has the dimension of force per unit length, \(\nu\) is Poisson’s ratio of the sample, \(A_M\) the contact area of the piezoelectric cantilever with the soft material, \(K(d_0 - d_M)\) the applied shear force, and \(d_0\) and \(d_M\) the cantilever tip displacements without and with the sample, respectively, as depicted in Figs. 3(b) and 3(d). The \(T_M/d_M\) in Eq. (6) should also represent the slope of the \(d_M\)-reducing branch of the \(T_M\) vs \(d_M\) loop near the maximum as similar analysis for the indentation elastic modulus discussed in Sec. III B. The empirical factor \(\alpha\) accounts for any numerical factor associated with the contact area geometry and the control of the normal force during an indentation shear test.

### IV. RESULTS AND DISCUSSIONS

The effective spring constant \(K\) of the PEC was determined by applying a force at the cantilever tip and measuring the corresponding axial displacement at the cantilever tip. Since the stainless steel tip is not very small, a force applied at the top of the stainless steel tip (which may affect the shear tests more) and that applied at the bottom of the stainless steel tip (which may affect the compression test more) may be different. To better calibrate the force-displacement relationship for both the compression tests and the shear tests, forces were applied both at the free end of the driving PZT [point A in Fig. 1(b)] and at the bottom of the stainless steel tip [point B in Fig. 1(b)] using a PEC load cell with a known spring constant \(K_S=213\) N/m as calibrated by the
weight loading experiments described in Refs. 16 and 18. The PEC load cell had a known response of free tip displacement, \(d_0\), at a given applied voltage. When the PEC load cell was in contact with a cantilever to be calibrated, the displacement at the given applied voltage was reduced from \(d_0\) to \(d\). Therefore, the force exerted by the PEC load cell on the cantilever to be calibrated was \(F = K(d_0 - d)\). By varying the voltage applied to the PEC load cell an \(F \text{ vs } d\) curve was generated, as shown in Fig. 4. The open squares represent measurements with forces applied at the free end of the driving PZT (point A) and the solid circles represent measurements with the forces applied at the bottom side of the stainless steel tip (point B), while the displacements were measured at the free end of the driving PZT. As can be seen, the curves of force versus axial displacement for both cases were essentially the same within the experimental error. This indicates that the same effective spring constant, \(K = 120 \text{ N/m}\), as determined by the slope of force versus displacement in Fig. 4, could be used for both the contact on the driving PZT side and that on the stainless steel side.

### A. Compression and shear

In Figs. 5(a) and 5(b) we plot \(d_N\) vs \(V_{\text{app}}\) obtained from the compression tests and \(d_S\) vs \(V_{\text{app}}\) from the shear tests, respectively. Also included in Figs. 5(a) and 5(b) is \(d_0\) vs \(V_{\text{app}}\), where \(d_0\) (open squares) was the displacement of the free cantilever. To obtain the elastic modulus and shear modulus, we plot the compressive stress (\(\sigma_N\)) versus the compressive strain (\(e_N\)) in Fig. 6(a), where \(\sigma_N = K(d_0 - d_N)/A_N\) and \(e_N = d_N/h_0\), and the shear stress (\(\sigma_S\)) versus the shear strain (\(e_S\)) in Fig. 6(b) with \(\sigma_S = K(d_0 - d_S)/A_S\) and \(e_S = d_S/h_0\). The slopes in Fig. 6(a) and those in Fig. 6(b) gave the elastic moduli, \(E_N\), and shear moduli, \(G_S\), of the samples, respectively. The resultant \(E_N\) and \(G_S\) are listed in Table I. Meanwhile, the resultant \(G_S\) is plotted versus \(E_N\) in Fig. 7. The slope of \(G_S\) vs \(E_N\) gave a ratio of \(G_S/E_N = 0.34 \pm 0.05\). Given that \((G_S/E_N) = 1/(1 + \nu)^2\), we obtained \(\nu = 0.47 \pm 0.20\), close to that of the isotropic soft materials, 0.5. In what follows, \(\nu = 0.47 \pm 0.20\) will be used in all computations involving Poisson’s ratio.

### B. Indentation

In Fig. 8(a), we plotted \(d_I\) vs \(V_{\text{app}}\), where \(d_I\) is the displacement of the free cantilever which is represented by open squares. To obtain the elastic modulus, we plotted \(T_I\) vs \(d_I\) in Fig. 8(b), where \(T_I\) was as expressed in Eq. (4). The elastic moduli, \(E_I\), were obtained from the slopes in Fig. 8(b) and listed in Table I. As can be seen, the indentation elastic moduli \(E_I\) obtained using the indentation tests agreed with the normal elastic moduli \(E_N\) as obtained with the compression tests.

### C. Indentation shear

In Fig. 9(a), we plotted \(d_M\) vs \(V_{\text{app}}\), where \(d_M\) is the displacement of the free cantilever and represented by open squares. Since the expression for the indentation shear modulus \(G_M\), involved a preconstant \(\alpha\) yet to be determined, we first plot \(T_M\) vs \(d_M\) in Fig. 9(b), where
determined from the shear tests versus computed according to Eqs. listed in Table I. To check for self-consistency, the slopes in Fig. 9 determine the value of $\nu = 0.34 \pm 0.05$, consistent with that used from the slope of $0.54 \pm 10^{-6}$ Yegingil, Shih, and Shih J. Appl. Phys. 101, again, indicating the validity of Eqs. TM $S$ are as defined in the text. The slope of $S$, $R_{100}$ gave a slope of $0.34 \pm 0.05$ gave a Poisson ratio of $0.47 \pm 0.20$, close to $0.5$ of isotropic soft materials.

D. Induced voltage

Meanwhile, the axial displacement at the cantilever tip was accompanied by an induced voltage at the sensing PZT layer which increased sharply to a maximum and then decayed with time. The sharp increase was due to the bending stress and the exponential decay was due to the fact that the PZT layer was not perfectly insulating. Induced voltage versus time at various applied voltages is shown in Fig. 10. Denoting the maximum in the induced voltage as $V_{in}$ and $d$ the displacement of the cantilever, $V_{in}$ vs $d$ of the cantilever used in this study is shown in Fig. 11, which had a slope of

$$\frac{V_{in}}{d} = 0.014 \text{ V/\mu m.}$$  \hspace{1cm} (9)

Combining Eq. (9) with Eqs. (1)–(7), we can express $E_N$, $G_S$, $E_I$, and $G_M$ in terms of the maximum induced voltage as

$$E_N = \frac{X_N}{V_{in,N}},$$

where

$$X_N = \frac{K(V_{in,0} - V_{in,N})h_0}{A_N},$$

TABLE I. $E_N$, $E_I$, $G_S$, $G_M$ and Poisson’s ratio ($\nu$) of the three rubber samples measured by the displacement and induced voltage methods, where $E_N$, $E_I$, $G_S$, and $G_M$ are as defined in the text.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Method</th>
<th>$E_N$ (kPa)</th>
<th>$G_S$ (kPa)</th>
<th>$\nu$</th>
<th>$E_I$ (kPa)</th>
<th>$G_M$ (kPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R500</td>
<td>By displacement</td>
<td>482±20</td>
<td>163±5</td>
<td>0.48±0.1</td>
<td>480±10</td>
<td>160±30</td>
<td>0.47±0.1</td>
</tr>
<tr>
<td></td>
<td>By voltage</td>
<td>498±20</td>
<td>167±4</td>
<td>0.47±0.1</td>
<td>489±20</td>
<td>170±34</td>
<td>0.46±0.11</td>
</tr>
<tr>
<td>R100</td>
<td>By displacement</td>
<td>102±4</td>
<td>34±1</td>
<td>0.5±0.1</td>
<td>102±5</td>
<td>34±6</td>
<td>0.49±0.11</td>
</tr>
<tr>
<td></td>
<td>By voltage</td>
<td>105±3</td>
<td>35±1</td>
<td>0.5±0.1</td>
<td>101±5</td>
<td>34±6</td>
<td>0.47±0.14</td>
</tr>
<tr>
<td>R50</td>
<td>By displacement</td>
<td>55±2</td>
<td>19±1</td>
<td>0.45±0.13</td>
<td>56±2</td>
<td>19±4</td>
<td>0.4±0.12</td>
</tr>
<tr>
<td></td>
<td>By voltage</td>
<td>56±3</td>
<td>19±1</td>
<td>0.39±0.17</td>
<td>56±3</td>
<td>19±4</td>
<td>0.47±0.2</td>
</tr>
</tbody>
</table>
The quantities $X_N$, $X_S$, $X_I$, and $X_M$ have the dimension of Pa V. In Fig. 12, we plot $X_N$ vs $V_{in,N}$ (open symbols) and $X_I$ vs $V_{in,I}$ (solid symbols) for the compression and indentation tests, respectively. The slopes of $X_N$ vs $V_{in,N}$ yielded $E_N$, and those of $X_I$ vs $V_{in,I}$ yielded $E_I$. As can be seen, for each rubber material, the compression data and the indentation data fall on the same line, indicating that the two tests indeed yielded the same elastic modulus using the induced voltage methods. The elastic moduli and shear moduli obtained by the induced voltage measurements are also listed in Table I, which shows that they agreed well with those obtained from the displacement measurements. Meanwhile, the shear moduli versus...
Elastic moduli obtained from the induced voltage measurements are also plotted in Fig. 7. Clearly, the data obtained by the induced voltage measurements agreed with those obtained from the displacement measurements. They also fall on the same curve as the data obtained by the displacement measurements, validating the induced voltage measurements for elastic and shear moduli determination.

E. Shear modulus imaging

Preliminary shear modulus imaging was carried out with a model tissue in which a green modeling clay (Modeling Clay, Crayola, Easton, PA) 12 mm in length, 9 mm in width, and 6.5 mm in height was embedded in gelatin as depicted in the photograph shown in Fig. 14(a). The modeling clay had an elastic modulus of 145±20 kPa as measured in a separate experiment, which was comparable to the Versaflex samples included in this study and those of breast tumors. The two-dimensional indentation shear modulus scan of the model tissue is shown in Fig. 14(b). Also shown in Fig. 14(c) is the indentation elastic modulus scan over the same area for comparison. As can be seen, both the indentation shear modulus scan and the indentation elastic modulus scan exhibited a higher modulus region consistent with the physical size and location of the modeling clay inclusion, indicating that like the indentation elastic modulus scan, the indentation shear modulus scan was also capable of locating and sizing a hard inclusion embedded in a soft material. At the peak of the high elastic modulus region, the highest elastic modulus value obtained was about 30 kPa, which was not as high as that of the modeling clay itself. The modeling clay had an elastic modulus of about 145 kPa. This is understandable as the high elastic modulus region was composed not only of the modeling clay but also the gelatin above it. The gelatin matrix had an elastic modulus of about 8±1 kPa as measured in a separate experiment. The gelatin and the modeling clay inclusion were chosen for their similarity to breast tissues and breast tumors. The preliminary results in Figs. 14(b) and 14(c) indicated that the present indentation and indentation shear tests were capable of identifying the high elastic and high shear modulus regions. A more detailed study that examines how the sensitivity of a piezoelectric cantilever depends on the inclusion’s depth and width, how to determine the inclusion’s elastic and shear moduli and its depth, as well as the application of piezoelectric cantilevers on real breast tissues will be described in future publications.
V. CONCLUSIONS

We have investigated an all-electrical indentation shear modulus and indentation elastic modulus measurement technique using piezoelectric cantilever sensors with a tip for potential in vivo applications. We showed that a piezoelectric cantilever with a tip could perform all four measurements including compression (N), shear (S), indentation (I), and indentation shear (M) tests. With Poisson’s ratio deduced from the ratio of shear modulus obtained from the shear tests to the elastic modulus obtained from the compression tests, we showed that the elastic moduli and shear moduli obtained from the indentation and indentation shear tests agreed with those obtained from the compression and shear tests. We also showed that the same elastic moduli and shear moduli could be obtained by using the induced voltage measurements. With a model tissue consisting of modeling clay embedded in gelatin, we demonstrated that the indentation shear or indentation tests could produce a two-dimensional shear or elastic modulus maps that accurately showed the size and location of the modeling clay inclusion. The advantages of

FIG. 14. (Color online) (a) Photograph of the model tissue with a modeling clay inclusion embedded in gelatin, (b) two-dimensional shear modulus plot of the model tissue shown in (a) by indentation shear measurements, and (c) two-dimensional elastic modulus plot of the model tissue shown in (a) by indentation measurements for comparison.
the present piezoelectric cantilever include (1) all-electrical, easily portable measurements, (2) high sensitivities, and (3) minimally intrusive, low-strain (less than 1%) operations.

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