MEASUREMENT OF STRAIN IN SOFT BIOLOGICAL TISSUES

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ABSTRACT

This paper describes the application of particle tracking to the measurement of strains in soft tissues under in-vitro and in-vivo conditions. The methodology is outlined and application to two problems is discussed. Specifically, the biaxial mechanical testing of the pericardium and the measurement of strains in the vicinity of an anastomosis.

INTRODUCTION

In biomechanics, it is important to know how soft tissues react to mechanical loading under both in-vivo and in-vitro conditions. Since soft tissues are very compliant, non-homogeneous and anisotropic, accurate strain measurement requires special considerations.

This paper describes the development and application of particle tracking as a method for the non-contacting measurement of strain in soft tissues. Some advantages of the method are the redundant measurement of uniform strain - including shear strain -, quantification of the non-uniformity of deformation and little or no trauma to the tissue. Because the method is "digital", strains may be used for on-line control of experiments and large amounts of data may be analyzed facilitating a statistical approach to data analysis.

Our basic approach is to "track" the displacements of small markers placed on the unloaded tissue. Displacements at known particle positions or nodes are then used to construct interpolation functions approximating the displacement field over the measurement region. Strains follow directly from the strain displacement equations and these functions.

The strain measurement system consists of video cameras, video image digitizers and a high speed recorder. Factors such as strain rate, desired resolution, and the state of strain (plane vs. three-dimensional) determine the exact configuration of the system. Two setups are described for measuring strains in separate applications and results illustrative of the method are given.

METHODS

Small particles (50 - 200 microns) are used to mark at least three points on the tissue. Choice of particle size varies with the size of the region in which the strains are being measured and the expected magnitude of the deformation. The particles are attached to
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the tissue using cyano-acrylate adhesive or, if sufficiently rough (e.g., silicon carbide), simply placed on the tissue surface. The centroids of the particles are used for tracking. Centroids are determined from a digital image of the particle using gray level information. Two different software based approaches have been developed. In one, simply adding rows and columns of the matrix of gray levels which constitutes the digital image of the particle and searching for extreme values yields a good approximation to the location of the particle centroid \[1, 2, 3\]. More recently, images have been processed to increase contrast and the picture histograms used to set a threshold gray level. The result is a binary image of the particle and its centroid is easily found from its definition. The latter approach has the advantage of being closely tied to the image processing literature.

Measurements consist of particle displacements \( u \) and \( v \) in each of two orthogonal directions \( x \) and \( y \) measured from a reference state in which the tissue is unloaded. For \( n \) particles, \( u_i \) and \( v_i \), the displacements at points \((x_i,y_i)\) are known for \( i = 1...n \) and a given state of loading. The displacements \( u(x,y) \) and \( v(x,y) \) may be approximated at interior points by

\[
\begin{align*}
  u(x,y) &= f(\alpha_1...\alpha_n x, y) \\
  v(x,y) &= g(\beta_1...\beta_n x, y)
\end{align*}
\]  
\[
(1)
\]

where \( f \) and \( g \) are polynomials in \((x,y)\) and \( \alpha_j \) (\( j = 1...n \)) and \( \beta_j \) (\( j = 1...n \)) are determined, for a given load, by matching expressions \( (1) \) to the known displacements of the particles.

The problem posed by \( (1) \) is comparable to the problem of developing a finite element stiffness matrix using the displacement method \[4\]. Thus we may write

\[
\begin{align*}
  u(s,t) &= \sum h_i(s,t)u_i \\
  v(s,t) &= \sum h_i(s,t)v_i
\end{align*}
\]  
\[
(2)
\]

where \( h_i \) (\( i = 1...n \)) are the interpolation functions which map both the particle positions \((x,y)\) and displacements \((u,v)\) into the \((s,t)\) plane. This is analogous to the isoparametric finite element. Thus

\[
\begin{align*}
  x(s,t) &= \sum h_i(s,t)x_i \\
  y(s,t) &= \sum h_i(s,t)y_i
\end{align*}
\]  
\[
(3)
\]

The strains follow from equations \( (2) \) and \( (3) \) by application of the chain rule to the derivatives associated with the strain measure employed (e.g., Green strain or engineering strain).

The choice of interpolation functions depends on the number of particles. Hoffman and Grigg \[6\], Humphrey et al. \[5\] and Choi and Vito \[3\] chose bilinear interpolation with four particles for which the \( h_i \) are

\[
\begin{align*}
  h_1 &= (1-s)(1-t)/4 \\
  h_2 &= (1+s)(1-t)/4 \\
  h_3 &= (1+s)(1+t)/4 \\
  h_4 &= (1-s)(1+t)/4
\end{align*}
\]  
\[
(4)
\]
This is illustrated schematically in Figure (1). Note that since the interpolation is bilinear, the extensional strains vary quadratically in one direction and linearly in the other.

**FIGURE (1)** Schematic diagram showing mapping of \((x,y)\) to the \((s,t)\) plane.

**FIGURE (2)** The deformation of four particles affixed to a sample of canine pericardium undergoing biaxial testing. The dashed lines represent the undeformed state. Strain fields for each of the four states shown are given in Table (1).

**FIGURE (3)** Shear angle in pericardium undergoing biaxial loading.

**FIGURE (4)** Anastomosis geometry indicating sites at which strains were measured.
APPLICATION

Biaxial Testing of Pericardium

In previously published works on biaxial mechanical testing of soft tissues, the tissue was assumed orthotropic with the stretching and the material symmetry axis aligned. However, the material symmetry axis were usually unknown implying that shear strains were present in the tissue, even under equibiaxial loading. Video equipment has been used by others (e.g., [7]) to measure extensional strains in biaxial tests by tracking the edges of a marked rectangular region placed on a central part of the specimen. However, this method cannot be used to measure shear strains nor can it determine the degree of non-uniformity of the strain - both of which influence the choice of the mechanical model used to interpret the data.

Particle tracking has been used effectively to study the biaxial mechanical properties of the pericardium [3], the membrane which surrounds the heart. Interest in the pericardium stems from its role in coupling the left and right heart, its use in making heart valves and its constrictive function in pathologies such as pericardial effusion and pericarditis [8].

Figure (2) shows actual particle histories indicating the presence of shear strains. The system used could resolve 0.03 mm and the accuracy of displacement measurement is +/- 0.06 mm. For finite deformation, the angle $\theta_{12}$ between the deformed differential line elements which were initially orthogonal to each other depends on both the shear and extensional strains. The cosine of $\theta_{12}$ is given by

$$\cos \theta_{12} = \frac{\varepsilon_{12}}{\sqrt{(1 + 2\varepsilon_{11})(1 + 2\varepsilon_{22})}}$$  \hspace{1cm} (5)

where $\varepsilon_{ij}$ are Green strains. Representative results are plotted in Figure (3).

Biaxial mechanical tests are analyzed using the theory of large elastic deformation [9] which assumes homogeneous deformation. Table (1) gives strains at the nodes as well as the center points for four values of loading. Note that the deviation of the nodal extensional strains from the strain at the center point ranges from 3 to 17%. The small shear strains also exhibit considerable variation across the 1 cm square measurement region. This suggests that perhaps a finite element method ought to be used to analyze the data.

Strains in the Vicinity of an Anastomosis

Speculation in the literature (e.g.,[10]) indicate that graft compliance is a factor in determining the ultimate success of peripheral by-pass surgery. Since the strains in the arterial wall in the vicinity of an anastomosis are influenced by the elasticity of graft material used, studies are under way to measure the strain field in the arterial wall in the vicinity of an anastomosis. In experiments conducted in collaboration with the University of
Chicago, both PTFE and autogenous saphenous veins are used to produce end to side anastomoses in the femoral arteries of dog. Strains are measured using particle tracking. Particle tracking accommodates the expected rigid body motions of the arterial wall, geometric complexity, non-uniformity of strain and results in minimal disturbance to the measurement sites. Three particles (silicone carbide, approx. 50 μ) are placed at each of 7 measurement sites as shown in Figure 4. Although the deformation is three dimensional, the particles are placed close enough together (1 - 2 mm) so that out of plane displacements are negligible. For the lens used, the field of view was 2x2 mm and the depth of field about 100 μ at a working distance of 71 mm. Hence the strain resolution was 0.41 - 0.52% per pixel.

Data is recorded using a high speed video camera (240x192) at 60 frames per second or about 30 samples per canine cardiac cycle. Particle tracking is currently done by hand using a cursor to locate the approximate centroid of the particles every 1/30 second. Data reduction uses linear interpolation of the particle positions at each time step. From equation (1):

\[ u(x,y) = f(x_0, y_0, x, y) = a_x + a_y x + a_y y \]
\[ v(x,y) = g(x_0, y_0, x, y) = b_x x + b_y y \]  (6)

At each time, the six constants \(a_1, a_2, a_3, b_1, b_2, b_3\) are determined by writing equations (6) for each particle. Thus, for each time step and for \(i = 1, 3\)

\[ u_i = u(x_i, y_i) = a_1 + a_2 x_i + a_3 y_i \]
\[ v_i = v(x_i, y_i) = b_1 + b_2 x_i + b_3 y_i \]  (7)

represent six equations in six unknowns. Linear strain-displacement equations are used since the strains, though superposed on large strains, are not too large.

Figure (5) shows the area dilatation at site #1 on the PTFE side vs time. Approximately 2 cardiac cycles are shown. Since the presence of shears in the vicinity of the sutures is a potential consequence of the compliance mismatch, Figure (6) shows the shear strain at site #2 on the venous side.

To assess site to site and PTFE vs saphenous vein differences, data were reduced using three schemes for eliminating time. In the first, the maximum peak to peak strain was measured for a cardiac cycle. Secondly, the average strain over the 60 frames of data was computed. Finally, the amplitude of the first term of a Fourier series was computed. Figure (7) compares the amplitude of the first harmonic of the area dilatation on the PTFE side vs the saphenous vein side for various sites along the artery for subject #1.
FIGURE (5) Plot of the area dilatation vs time at site #1 for roughly two cardiac cycles.

FIGURE (6) Shear strain for axis oriented along and perpendicular to the vessel centerline vs time for site #2, which is near the suture line.

FIGURE (7) The amplitude of the first harmonic for various sites and for PVE vs saphenous sides.
**TABLE 1**

Green strain values at nodal points (particle positions) and the center point. The 0.2 mm markers were placed on the central region (1 cm x 1 cm) of the specimen. The strains were calculated from the displacements of four particles using bilinear interpolation functions as described in the text.

<table>
<thead>
<tr>
<th>Green Strains</th>
<th></th>
<th></th>
<th></th>
<th>Center point</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[E_{11}]</td>
<td>0.082</td>
<td>0.082</td>
<td>0.098</td>
<td>0.098</td>
<td>0.090</td>
</tr>
<tr>
<td>[E_{22}]</td>
<td>0.073</td>
<td>0.070</td>
<td>0.070</td>
<td>0.073</td>
<td>0.072</td>
</tr>
<tr>
<td>[E_{12}]</td>
<td>-0.005</td>
<td>0.003</td>
<td>-0.005</td>
<td>-0.013</td>
<td>-0.005</td>
</tr>
<tr>
<td>[E_{11}]</td>
<td>0.171</td>
<td>0.171</td>
<td>0.201</td>
<td>0.201</td>
<td>0.186</td>
</tr>
<tr>
<td>[E_{22}]</td>
<td>0.158</td>
<td>0.169</td>
<td>0.169</td>
<td>0.156</td>
<td>0.163</td>
</tr>
<tr>
<td>[E_{12}]</td>
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<td>-0.003</td>
<td>0.000</td>
<td>-0.015</td>
<td>-0.009</td>
</tr>
<tr>
<td>[E_{11}]</td>
<td>0.293</td>
<td>0.293</td>
<td>0.312</td>
<td>0.312</td>
<td>0.302</td>
</tr>
<tr>
<td>[E_{22}]</td>
<td>0.259</td>
<td>0.279</td>
<td>0.279</td>
<td>0.259</td>
<td>0.269</td>
</tr>
<tr>
<td>[E_{12}]</td>
<td>-0.024</td>
<td>-0.015</td>
<td>0.010</td>
<td>0.000</td>
<td>-0.007</td>
</tr>
<tr>
<td>[E_{11}]</td>
<td>0.435</td>
<td>0.435</td>
<td>0.426</td>
<td>0.426</td>
<td>0.431</td>
</tr>
<tr>
<td>[E_{22}]</td>
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<td>0.431</td>
<td>0.431</td>
<td>0.438</td>
<td>0.434</td>
</tr>
<tr>
<td>[E_{12}]</td>
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<td>-0.029</td>
<td>0.025</td>
<td>0.031</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

**CONCLUSION**

Particle tracking is a powerful method for the measurement of strain in soft tissues. The method has been successfully applied to in-vitro and in-vivo problems in tissue mechanics. The connection with finite elements and application to three dimensional problems have yet to be exploited.

**REFERENCES**


