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# 생체 연조직의 기계적성질 규명을 위한 양축인장실험

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# BIAXIAL TESTING METHODS FOR THE MECHANICAL CHARACTERIZATION OF SOFT TISSUES

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## 1. INTRODUCTION

Soft tissue may be considered in several basic categories: soft connective tissue (lung tissue, skin, blood vessels, ligaments, tendon, mesentery, pericardium, and other membranes), muscle, organs, and the brain. Thus mechanics of soft tissues covers a vast area.

The tissue's capacity to withstand and transmit the loads through deforming appropriately can be characterized in health and disease. Knowledge of such 'load-deformation' relations of the tissue can serve a basis for diagnosis. Therefore, identification of the mechanical properties of living tissues has been a major activity in recent years.

Generally, soft biological tissues are regarded as nonhomogeneous, anisotropic viscoelastic materials, and they are usually subjected to large deformations. Unfortunately, these anisotropic, nonlinear, history-dependent characteristics and geometrical complexity of the tissue make it difficult to perform experiments and data analysis. Therefore, the majority of soft tissue studies were limited to the one-dimensional structures such as ligaments and tendons. In order to completely determine the mechanical properties of two-dimensional membranes such as skin and pericardium, biaxial data in which the extensional and shear strains are varied independently are needed. However, in most of previous biaxial studies [1,2,3], this generalized biaxial testing has not been performed because of the experimental difficulties and somewhat misleading understanding.

In the present study, a more promising approach is suggested to overcome experimental difficulties and to avoid the misleading interpretation of biaxial data. An advanced biaxial testing machine, consistent experimental protocols and data analysis methods are introduced. In addition, the application of the present approach to studying the mechanical properties of pericardium [4] is described as an example.

## 2. EXPERIMENTAL SYSTEM

The computer-controlled biaxial test system, shown in Figure (1), is used to investigate the mechanical properties of soft tissues. The key features of this system are the independent control of two stretching axes and the noncontacting strain measurement in the central portion of the tissue sample. The main components of the system are the tissue bath, stretching arms, force measurement system and dimension measurement system.

Tissue bath is a jacketed plexiglass chamber containing a physiological solution. The bath can be maintained at constant temperature by using a heater-pump and refrigeration unit to circulate ethylene glycol through a manifold.

The stretching mechanism consists of two identical, orthogonally positioned axes, each driven by a digital DC servo motor. Each axis consists of two coupled, double-nut, preloaded ball screws, one with a left and one with a right hand thread; an arrangement that keeps the center of the specimen fixed. The servo system accepts velocity and position information through controller units and sixteen bit parallel interfaces connected to the computer. The velocity range of the servos is 0.000127 to 4.16 cm/s, and the position accuracy is 5.08 microns.

The resultant force on each axis is measured using a strain gauge type force transducer; a Statham gould cell with a tension-to- compression converter. The load-voltage relationship for the load cell is linear in the range of 0 to 200 grams. The load cell signal is conditioned with a strain gage amplifier and filtered by a 10 Hz low pass filter. Force data are digitized with a twelve bit A/D converter interfaced to the PDP-11/34. The load cell is connected to the force plate which rides in an air slide to eliminate frictional forces.

The dimension measurement system consists of a video camera, a video image digitizer and a controller unit. This system is completely controlled by the software. A picture frame can be digitized into a 640 column by 480 row pixel grid. Each pixel is identified by an x-y position and a light intensity value. Using this system, the four particles placed on the the central region of specimen may be continuously tracked and their locations determined. The resolution of the system is 0.03 mm and the accuracy of displacement measurement is +0.06 mm.

## 3. METHODS & ANALYSIS

In order to quantify the pseudoelastic properties of the membrane-type biological tissues, the following procedures are recommended.

(a) Tissue acquisition. After marking the anatomical orientation of tissue, an appropriate size of specimen is excised and stored in the physiological solution.

(b) Determination of material symmetry axes. By imposing uniform stress field on the excised tissue, the direction of maximum stiffness may be determined.

(c) Preparation of a square specimen. Cutting along the material symmetry axes gives a square specimen for biaxial testing. Small tracking particles are placed on the central region of the specimen, one at the center and one at each of four corners.

(d) Determination of an initial reference state. After mounting the specimen in the experimental device, care should be taken to obtain the stress-free state as an initial reference state. The position of tracking particles and the dimension of specimen at this state should be determined.

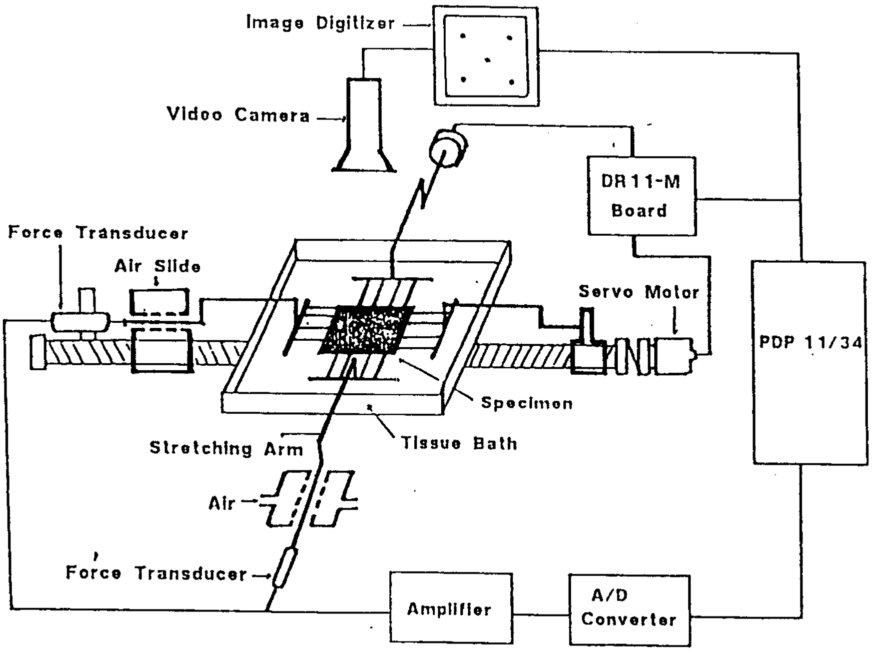

Figure (1). Schematic diagram of the biaxial testing system.

(e) Preconditioning. Imposing several cycles of loading and unloading, the variation in the stress-strain curves may be checked.

(f) Performing an equibiaxial stretching test. Two axes are stretched at the same rate, and the force-displacement data is recored.

(g) Performing several different modes of non-equibiaxial stretching tests. Both axes are stretched at various combinations of stretching rates, and the force-displacement data are recorded.

(h) Reduction of force-displacement data to stress-strain data. Using bilinear interpolation functions [5], the extensional and shear strains at any point within the central region can be calculated from the measured displacements of four tracking particles. The original data of stretching forces and particle positions can be converted to stress-strain data. For a large deformation, the Kirchhoff stresses ( $S_{ij}$ ) and Green strains ( $E_{ij}$ ) are recomended, because both are symmetric and directly related to the strain energy function.

(i) Construction of a complete data set. The data which are not properly collected or not representative may result in poor fits and erroneous conclusions. Therefore, the data-collection process and any limitations in the collected data should be investigated, and the inferential conclusions should be restricted accordingly. However, these basic considerations of data processing have sometimes been overlooked in biomechanics. Data base problems associated with collinearity [6] are commonly found, but ignored in most previous biaxial studies [1,2,3] on soft tissues. The data from a specific loading-unloading cycle cannot be used alone to determine the general two-dimensional stress-strain law, because a near linear relationship exists between two independent variables E and E . In this reason, a complete data set is constructed by accumulating all the stress-strain data from the various stretching tests in (f) and (g).

(j) Selection of the constitutive model. An appropriate form of strain energy function, such as the below [4], may be assumed:

$$W = B_0 \left\{ e^{1/2 b_1 E_{11}^2} + e^{1/2 b_2 E_{22}^2} + e^{b_3 E_{11} E_{22}} - 3 \right\}$$

where $B_0$, $b_1$, $b_2$, and $b_3$ are the material constants to be determined.

(k) Estimation of model parameters. A nonlinear least square method is used to determine the material constants in the assumed model.

## 4. RESULTS

The experimental system and methodology described above is used to quantify the mechanical properties of canine pericardium [7]. A representative pseudoelastic response of normal pericardium subjected to equibiaxial stretching is shown in Figure (2). This figure demonstrates several characteristic features. First, the stress-strain curves are highly nonlinear, showing a considerable tissue compliance at small strains but a rapid stiffening at large strains. Second, there exists some hysteresis as indicated by the difference between the loading and unloading curves. Third, the stress-strain curve in one direction is different from that in the orthogonal direction. This anisotropic behaviour is apparent at high strains.

The present approach significantly differs from the conventional approach used in previous studies. That is, the present methodogy yields the true material constants which are capable of describing mechanical responses over a wide range of strains [7], whereas the conventional methodology yields the arbitrary fitting constants which are capable of describing only a specific mechanical behavior [3]. Figure (3) shows

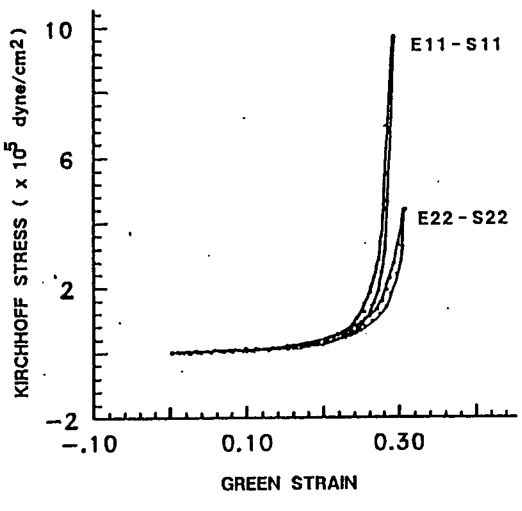

Figure (2). Stress-strain curves (equibiaxial stretching test).

strain trajectories used for the construction of a complete data set. The mechanical responses over these range of strains are shown in Figure (4). The predicted response, shown in Figure (5), are estimated using the material constants in our constitutive model. Similarity between both figures supports the superiority of our methodology over the conventional one.

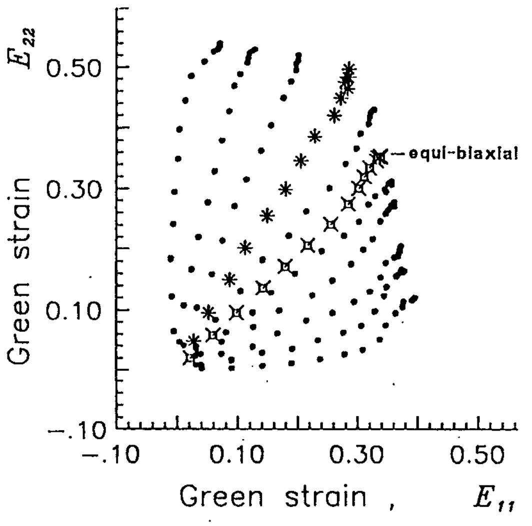

Figure (3). Strain trajectories in a complete data set. .

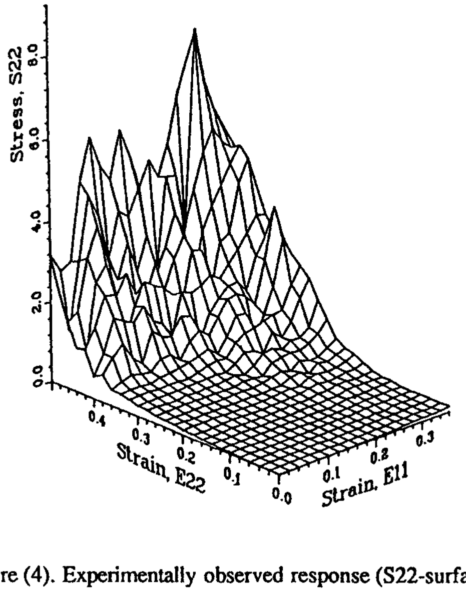

Figure (4). Experimentally observed response (S22-surface)

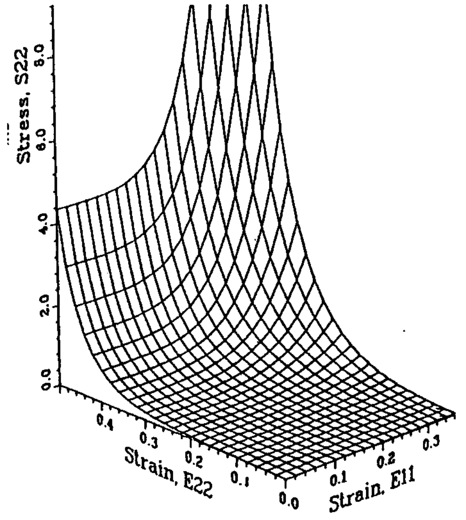

Figure (5). Theoretically predicted response (S22-surface).

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