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The *in vivo* Mechanical Properties of Muscular Bulk Tissue

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Abstract— **The aim of this study was to characterize the bulk modulus properties of the upper arm under relaxed and controlled contraction which is defined as 25% of the maximum voluntary contraction. A new testing machine was designed to generate a continually increasing load on the upper arm and measure the load over time. The machine consists of a device which is effectively a cuff that applies controllable pressure on a 47 mm wide band of the upper arm. A set of four different constant strain rates was used to test the stiffness of the arm bulk tissue. The stress-strain test consisted of 0.5, 1, 2, and 4 mm.s^{-1} constant strain rates. The stress-strain curves obtained show strongly non-linear response of the bulk tissue. The nonlinearity is evident that the stress–strain curve for bulk tissue is time dependent.**

Keywords—**biomechanics, bulk modulus, *In Vivo* mechanical properties, muscular bulk tissue, test machine.**

I. Introduction

HUMAN beings are always in touch with their surrounding environment in all their life spans. The outer surface of the human body is mainly composed of soft tissues and most of the interaction with the surrounding environment is done by these tissues. That is why understanding and classifying the mechanical response of soft biological tissues is a fundamental problem in biomechanics. Soft tissue usually exhibits nonhomogeneity, anisotropy, non-linearity, and viscoelasticity. Some difficulties are encountered in characterizing the mechanical response of viscoelastic materials [1]. Soft tissues are relatively compliant at low strain rates and become dramatically stiffer at high strain rates. There is a continuing need to develop methods that reveal the complete set of anisotropic material properties. There are several procedures and instruments in mechanical engineering for material testing. For work on solid biomaterials, the "*Universal Testing Machine"* is the most useful general purpose machine. On the other hand, studying soft biological tissue on these machines can be inadequate. Usually adaptation of mechanical engineering tests has been used for soft tissue research. Most of these tests are very specialized but have not been standardized [1] [2].

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Although, there is numerous research based on *in vitro* studies, there are few *in vivo* studies. *In vivo* experiments are performed on a living human body. This type of experiment gives the most accurate information about the mechanical behavior of the tissue [3]. In order to observe the mechanical properties of soft tissue, it is necessary to design a special machine. Therefore *in vivo* mechanical properties of muscular bulk tissue have not yet been investigated sufficiently.

A muscle is ordinarily thought of as an active system; its prime function is to generate force. Muscles are composite materials, composed of stiff strong fibers, plates or particles in a relatively complaint matrix. Like many soft composites, muscles change their mechanical properties as part of their normal functioning. Muscle is stiffened by contraction and softened by relaxation. The object of this study was to design an instrument to apply uniform controllable pressure on the upper arm and obtain the bulk modulus of the upper arm under relaxed and controlled contraction that was 25% of the maximum voluntary contraction (MVC).

II. Methods

A. Test Machine Design and Instrumentation

A new testing machine was designed to generate a continually increasing compression on the upper arm. A schematic representation of the compression test design is shown in fig. 1. The movement of cylinders (Fig.1. (13)) was transmitted to the upper arm with a squeezing chamber (9). Reference [4] shows a detailed explanation of the squeezing chamber. This device is a cuff that applies controllable compression on a 47 mm wide band of the upper arm. A seat belt was preferred as the compression band for many reasons. Firstly, its mechanical properties that have not shown any time dependent behavior. Secondly, it is flexible enough to cover the upper arm without causing discomfort and finally it has an optimum width and a texture that eliminating the rough edges of conventional belts that are likely to cause pain due to friction and cut into the skin. The controlled deformation of the arm was achieved by using pneumatic cylinders, a constant speed of the cylinders was achieved by using a linear stepper motor (10). In order to prevent the linear stepper motor stalling, a voltage-to-pressure converter (2) and a feedback control unit were added to regulate the air pressure with respect to the load. A schematic diagram of the pneumatic system can be seen in the fig. 2. Stress-strain response of the upper arm was collected by using a load cell (5). The analog signal from the load cell was digitized by using a 12-bit analog-to digital converter (ADC). The output of the load cell was amplified by a strain gauge amplifier, up to a suitable level for the ADC.

Control of the stepper motor and pneumatic relays during the test was accomplished by a computer program. The program was written in the C programming language in the DOS environment. Timing of data collection was arranged by re-programming the PC interrupt 8 for counting one tenth of millisecond [5]. The measurement and the control of the pneumatic relays and the linear stepper motor were synchronized and data were stored in the computer. The load-time curve was plotted in real time as feedback to the researcher. Before running the test procedure, the seat belt was set on the participant's arm and tightened initially by setting the initial load.

A set of four different constant compression rates was used to test the stiffness of the arm bulk tissue. The compression-deflection test consisted of 0.5, 1, 2, and 4 $mm.s^{-1}$ constant loading rates. The main reason for choosing such increases of the loading rate was to show a clear difference between the increments.

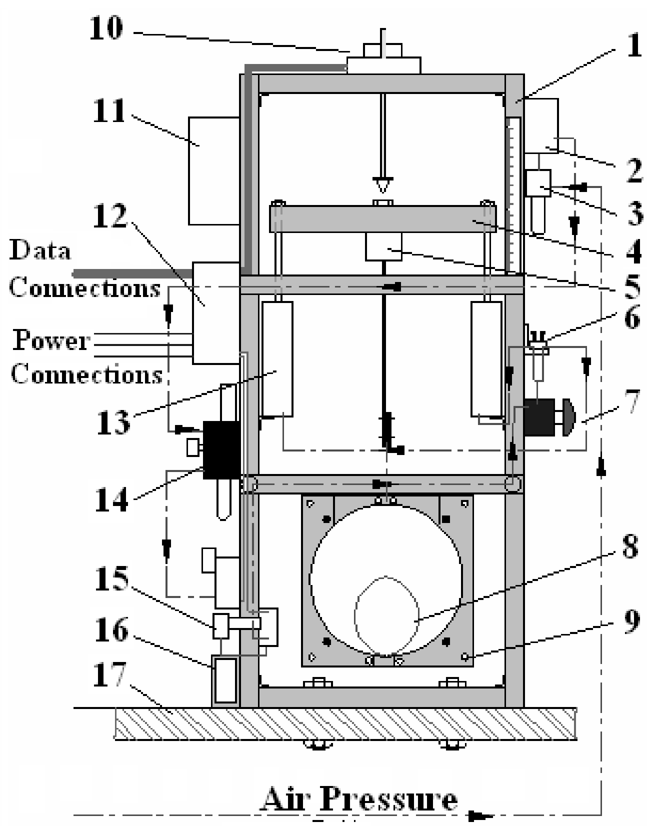

Fig.1. Overall view of the compression test, where: (1) Main frame, (2) Voltage-to-pressure converter, (3) Air filter (25 μm), (4) Load cell carrier, (5) Load cell, (6) Valves, (7) Emergency stop valve, (8) Closed loop belt, (9) Squeezing chamber, (10) Linear stepping motor, (11) Strain gauge amplifier, (12) Control box, (13) Pneumatic cylinder, (14) Pressure regulator and lubricator, (15) Pneumatic poppet valve, (16) Stabilizer, (17) Table.

B. Calculation of Bulk Modulus

The bulk properties of a material determine how much it will deform under a given amount of uniform compression. The ratio of the change in pressure to the partial volume compression is called the bulk modulus of the material. The bulk modulus (*K*) properties were calculated as in;

$$K(t) = \frac{c(t)v_0}{s(t)[v(t) - v_0]} \tag{1}$$

where *c(t)* is the load reading from the load cell, v_0 is the original volume of the strapped section of the upper arm that is shown in (2). The surface area *s(t)* of the strapped section of the upper arm was altered over time, which was also a function of the displacement *x(t)* at time *t*, shown in (3). The volume of the strapped section of the upper arm, that is *v(t)*, was changed over time, which is a function of displacement *x(t)* at time *t*, shown in (4). *L* is the original length of the strapped section of the upper arm and R the original radius of the strapped section of the upper arm, as in (2)–(4).

$$v_0 = \pi R^2 L \tag{2}$$

$$s(t) = [2\pi R - x(t)]L \tag{3}$$

$$v(t) = \pi \left(R - \frac{x(t)}{2\pi} \right)^2 L \tag{4}$$

It should be noted that the change in volume of the bulk tissue of the upper arm has been taken account of in (1), which causes a change in the surface area of the strapped section of the upper arm. This automatically corrects the applied pressure with time.

C. Test Procedure

Two different test procedures were followed. In the first one, the relaxed condition, the participant did not contract his elbow flexors muscles during the data collection. In the second test, the participant sustained his muscle contraction at 25% of his MVC during the test. The load cell was connected to the participant's right wrist so that the force exerted by the muscles could be recorded. During the contraction, the subject's elbow was fixed by the elbow-resting corner.

The compression test was applied to a healthy male (age 32) by using 0.5, 1, 2, and 4 $mm.s^{-1}$ loading rates without causing discomfort. Owing to the long recovery time of the bulk tissue, a 60 minute rest period was given between the tests. Some of the tests were done on different days to avoid tissue damage and biological adaptation to the test. The squeezing area on the participant's upper arm was marked and all the tests were carried out on this surface. In order to ensure that all displacements were made with respect to the same initial reference position, the seat belt on the participant's arm was tightened by slight increments until reaching the initial load.

III. Results And Discussion

To describe the compressive deformation, a volume strain is used, defined as $\Delta V/V_0$ where V_0 is the initial volume of the upper arm and ΔV is the deformation of the upper arm from its initial volume.

A set of compression test experiment results can be seen in fig. 2 and fig.3. It is clear that constant loading rates do not correspond to a linear increase in the deflection.

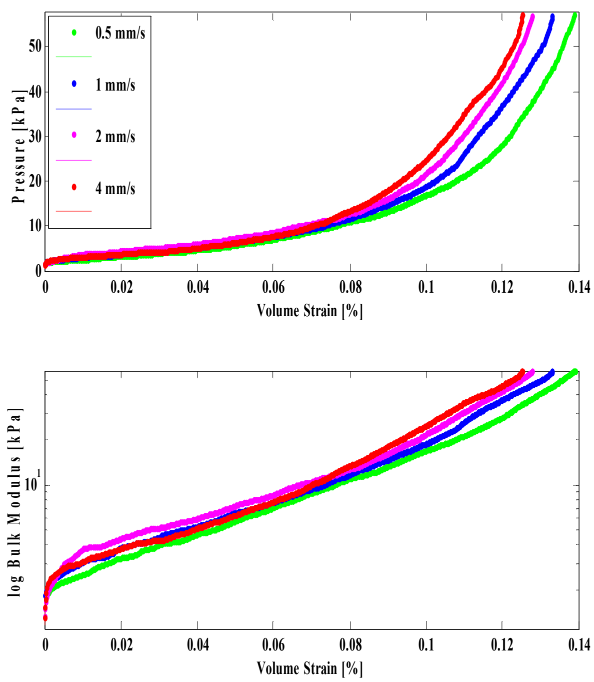

Fig.2. A set of compression test data from the relaxed muscle test procedure.

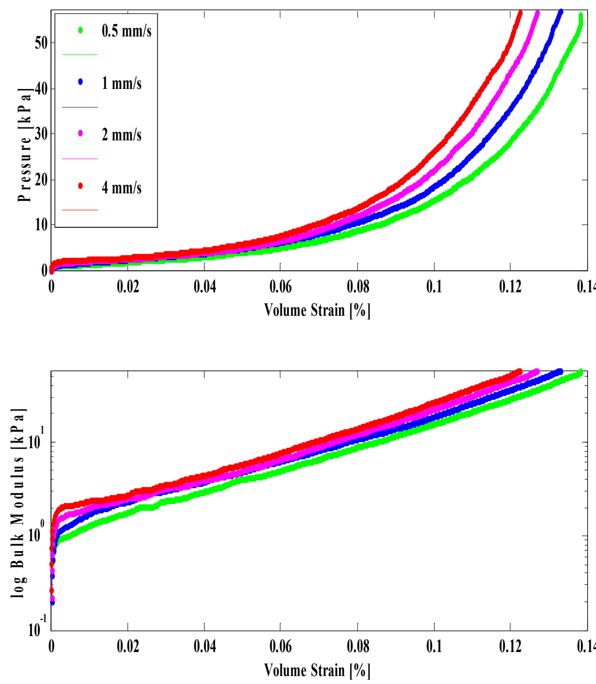

Fig.3. A set of compression test data from the contracted muscle test procedure.

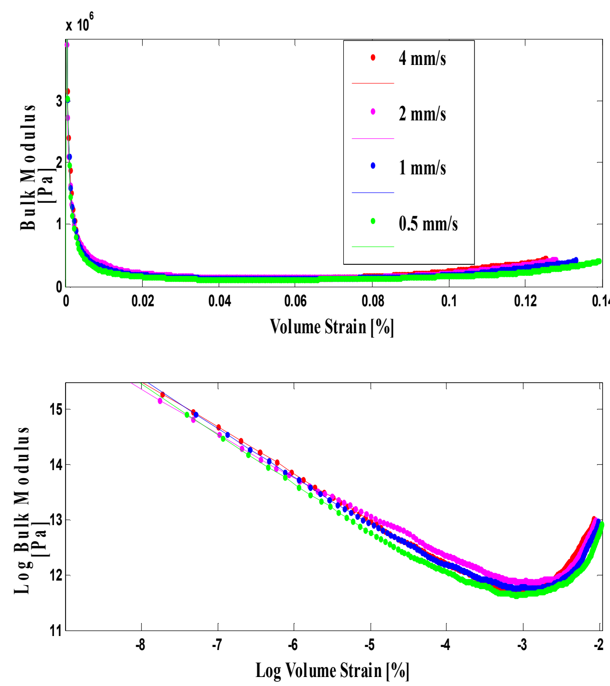

Fig.4. Bulk properties of muscular bulk tissue in relax condition.

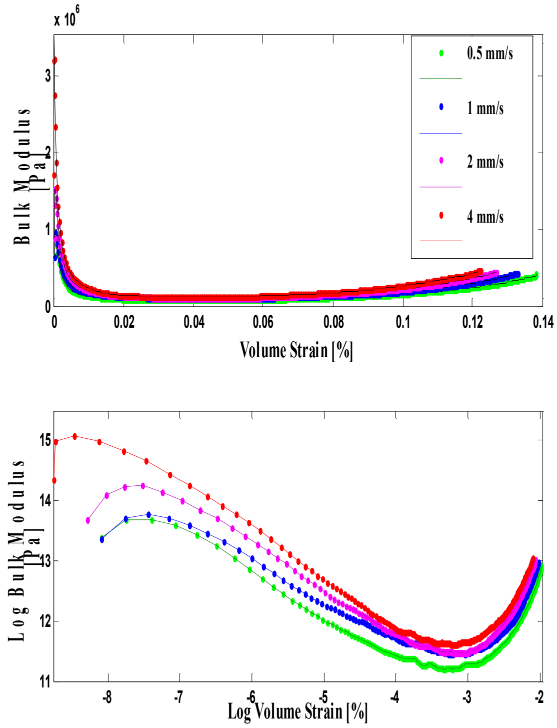

Fig.5. Bulk properties of muscular bulk tissue in contracted condition

The bulk properties of the muscular tissue calculated using the compression data in (1) can be seen in figs. 4 and 5.

These properties are essentially the bulk modulus of the muscular tissue under relaxed and controlled contraction conditions. It is obvious from fig.4 and fig.5 that the magnitude of the bulk modulus of the muscular bulk tissue depends on the magnitude of the applied load rate.

In the compression test, the relaxed test procedure showed similar behavior amongst the loading rates compared to the contracted test. This behavior can be explained as occurring since the contraction of the muscle has developed fluid in the muscle structure which causes higher variation than the relaxed muscle. The comparisons can be seen in figs.2 and 3.

According to the results, the compression-deflection curves obtained for bulk tissue manifested strongly non-linear response characteristics. The non-linearity occurs for both time- and load rate-dependency. Furthermore, it was shown that the magnitude of the bulk modulus of muscular bulk tissue depends on the level of muscular contraction.

IV. Conclusion

A new test machine and procedure have been developed to measure the mechanical properties of bulk tissue. An attempt has been made to solve some of the complex problems associated with *in vivo* measurement of the biomechanical properties of bulk tissue. These properties are important in case studies, control studies and in numerical implementations of constitutive equations in biological tissue. This study was developed to demonstrate these properties and to provide experience in analysis of this type of data.

The data presented in this paper pertained to one participant. But in the complete study, 2 were subjected to compression tests as well as to MRI scans of the upper arm while 3 other participants were subjected to compression tests only, without MRI scans of the upper arm. The main aim of this study is to find out mechanical properties of the skin, fat and muscle separately. In the current study, the combined bulk properties have been determined. The next phase of the research is to estimate the mechanical properties of the skin, fat and muscle by using mechanical model approach and then utilizing an inverse finite element simulation procedure for validation. The method presented in this work can also be applied to determine the mechanical properties of the skin, fat and muscle tissue of other suitable parts of the body.

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