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Multiaxial mechanical properties and constitutive modeling of human adipose tissue: A basis for preoperative simulations in plastic and reconstructive surgery

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ABSTRACT

A preoperative simulation of soft tissue deformations during plastic and reconstructive surgery is desirable to support the surgeon's planning and to improve surgical outcomes. The current development of constitutive adipose tissue models, for the implementation in multilayer computational frameworks for the simulation of human soft tissue deformations, has proved difficult because knowledge of the required mechanical parameters of fat tissue is limited. Therefore, for the first time, human abdominal adipose tissues were mechanically investigated by biaxial tensile and triaxial shear tests. The results of this study suggest that human abdominal adipose tissues under quasi-static and dynamic multiaxial loadings can be characterized as a nonlinear, anisotropic and viscoelastic soft biological material. The nonlinear and anisotropic features are consequences of the material's collagenous microstructure. The aligned collagenous septa observed in histological investigations causes the anisotropy of the tissue. A hyperelastic model used in this study was appropriate to represent the quasi-static multiaxial mechanical behavior of fat tissue. The constitutive parameters are intended to serve as a basis for soft tissue simulations using the finite element method, which is an apparent method for obtaining promising results in the field of plastic and reconstructive surgery.

1. Introduction

A considerable number of plastic surgery patients are related to the field of reconstructive surgery associated with complex soft tissue contour defects, mainly subcutaneous adipose tissue, in different anatomical regions related to trauma, burn injuries, cancer resections and congenital deformities [1]. These patients often suffer from severe body disfigurements caused by mutilating injuries and surgeries inducing tremendous physical and psychological stresses, resulting in personal and social burdens [2–4]. Autologous tissue transfer from the patient's own healthy body regions to the affected anatomical area, is the most appropriate surgical intervention [5–7]. By reconstructing the contour defect with equivalent soft tissue, optimal restoration of its form and function can be obtained. The so-called local or microvascular transplanted free flaps consist mainly of different soft tissue layers such as skin, fat or muscle. These flaps are subjected to significant intra- and postoperative soft tissue deformations, which require the development of methods to quantify three-dimensional (3-D) soft tissue changes accurately, are non-invasive and without major side effects or inconvenience for the patient [8]. A preoperative simulation of the resulting soft tissue deformation would be desirable to support the surgeon's preoperative planning and to potentially improve surgical outcomes [9]. Promising results in the field of plastic and reconstructive surgery are apparent in breast and facial soft tissue simulation using the finite element (FE) method [10,11]. The ability of these FE models to predict the soft tissue behavior depends on (i) accurate geometric anatomical models, (ii) realistic boundary and loading conditions, (iii) the development of reliable constitutive models and (iv) the accuracy of the (assumed) mechanical properties of the implemented tissue components [12]. The development of constitutive adipose tissue models, which can be

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implemented in multilayer computational frameworks for human soft tissue deformation simulation, is currently difficult. This is due to the limited and inconsistent knowledge of the mechanical parameters of fat tissue because of the inherent geometric soft tissue complexity, heterogeneous and varying boundary conditions [13].

Adipose tissue is a soft connective tissue which is placed under the dermal layer of skin and it is mainly composed of lipid filled cells, called adipocytes [14]. From the mechanical point of view, adipocytes are enclosed with an extracellular matrix which is made of two collagen main structures, the reinforced basement membrane and the interlobular fibers. In particular, the reinforced basement membrane (with a thickness of about 100 nm) consists of sheet-like type IV collagen adjacent to the phospholipid membrane of the adipocyte [15]. The interlobular septa consists of long fibrous bundles of predominantly type I collagen and are several millimeters in length and can range in diameter from 10 nm (for a single fiber) to 30 μm (for a bundle of fibers). The septa bundles share a similar structure to that of fibrous collagen bundles in the dermis, where arteries and veins align with the septa [15].

The mechanical properties of adipose tissue are usually determined using unconfined compression tests [16–20], sometimes indentation tests [21,22] or uniaxial tension tests [19,23]. Under compression and indentation, adipose tissue exhibits a nonlinear stress versus strain response at large strains [16–19]. At a low strain level, the response is linear whereas at strain levels above 30%, the tissue 'locks up' and the stress level increases rapidly [19,20,24]. Rheological shear experiments on porcine subcutaneous adipose tissue showed that the linear regime is only valid for very small strains up to 0.1% [25]. Under uniaxial tension, porcine adipose tissue showed also nonlinear behavior, very similar to the behavior in unconfined compression [19]. Although the adipose tissue reveals nonlinear mechanical properties in compression [21,22] and tension [19], in many studies only linear material model parameters, i.e., the Young's modulus, are stated (see, e.g., [22,26]). Only a few studies are known which state (nonlinear) hyperelastic parameters to characterize the nonlinear mechanical response of the adipose tissue [19,21,23].

All the above mentioned studies treated the adipose tissue as isotropic and do not account for any possible anisotropic features of adipose tissues. Moreover, for the characterization of the mechanical behavior of the adipose tissue, previous studies performed only uniaxial tests on mainly animal adipose tissue specimens. Since every tissue in the body is subjected to multiaxial loadings, our goal is to identify the *multiaxial* mechanical properties of human adipose tissue with the aid of biaxial tensile and triaxial shear tests. These types of tests represent the physiological state better than uniaxial tests, and additionally provide direction-dependent mechanical information of the tested tissues.

The aim of this study is to determine the multiaxial mechanical response of human adipose tissue and its mathematically representation in terms of constitutive parameters of a hyperelastic strain-energy function. Additionally, the tissue's microstructure responsible for the mechanical properties is utilized by histological investigations. These novel and compact set of data are indented to serve as a basis for soft tissue simulations using the finite element method, which is an apparent method for obtaining promising results in the field of plastic and reconstructive surgery.

2. Materials and methods

2.1. Material

Remaining human abdominal adipose tissue samples ($n = 9$) obtained from breast reconstruction and abdominal plastic surgeries were mechanically investigated. The Declaration of Helsinki protocols were followed and all patients gave their written informed consent with all surgical and non-surgical procedures in accordance with the Ethical Committee of the Medical Faculty at the Klinikum rechts der Isar of the Technische Universität München, Germany. The schematic in Fig. 1(a) shows the location in the body from where the samples were obtained. In seven out of nine cases, the tissue sample was obtained from the right side of the donor's body (Table 1). Donor information, i.e., age, weight, size, and body mass index (BMI) are stated in Table 1. After removal, all samples were stored in phosphate-buffered physiological saline (PBS) at 4 °C and tested within 36 h. A representative tissue sample obtained from surgery is shown in Fig. 1(b).

2.2. Preparations and mechanical test

2.2.1. Biaxial tensile test

For the biaxial tensile tests, squared (cuboid) specimens with the dimensions $50 \times 50 \times \sim 5$ mm were prepared. Preliminary studies revealed varying mechanical properties of the tissue with distance from the skin. In particular, we observed stiffer behavior of the adipose tissue directly under the skin and in deep regions at a distance of ~30–40 mm from the skin (see discussion in section 4). Therefore, specimens were prepared only from the middle part of the tissue sample, at a distance between 10 to 20 mm from the skin. From cooled (~4 °C) adipose tissue, it was possible to prepare uniformly thick slices with the aid of an electric universal cutter (Silva AS 522). At 4 °C, the adipose tissue showed higher form stability than at room temperature, and therefore allowed proper specimen preparation. From these slices, squared specimens with a side-length of 50 mm were cut with their sides aligned in the transversal and longitudinal directions of the human body (Fig. 1). Unfortunately, due to the limited thickness of the samples obtained, we were not able to prepare biaxial tensile specimens oriented also in the sagittal direction. For the Cauchy stress calculations, the thickness of the specimen was measured before and after testing by means of a videoextensometer. For the deformation measurements during biaxial testing, four black markers were attached in the center of each specimen with a distance of ~10 mm and tracked by the aid of a videoextensometer. For proper clamping of this very soft and fragile tissue, we used specially designed clamps made of acrylic glass. Each clamp consists of an upper and a lower plate with a distance of 4 mm in order to avoid squeezing of the fat tissue. The plates were reusable due to the screwable design (Fig. 2(a)). Cyanoacrylate adhesive was used to bond the tissue to the plates of the clamps. Therefore, a thin layer of cyanoacrylate adhesive was spread on the upper and lower plate to hold the tissue from both sides. Then, the specimen could easily be mounted in the biaxial testing rig (Fig. 2(b)).

A custom-built low-force planar biaxial soft tissue system was used to perform the biaxial tests. In particular, four electromechanical actuators are mounted every 90° to a user configurable isolation table, to prevent the vibrations caused by other laboratory equipment from compromising the integrity of the measurements. A temperature-controlled tissue bath is available to simulate the physiological environment for the specimen. The non-contact 2D video strain measurement technique (videoextensometer) including analysis software are able to determine accurately the high deformations of the specimen during biaxial testing. Each of the four linear actuators operates with a stroke resolution of 1 μm and a maximum travel range of 50 mm. The four load-cells are waterproof and specified by the manufacturer with a maximum load capacity of 100 N and a resolution of 0.6 mN. Actuator control and data acquisition is achieved using the software 'Test&Motion' Version 2.0 by DOLI Elektronik Gmbh, Munich, Germany. For the non-contacting strain-measurements we used the software 'Laser