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Ex-Vivo Mechanical Characterisation of the Breast Cooper's Ligaments

N. Briot^a, G. Chagnon^a, C. Masri^a, E. Girard^{a,b}, Y. Payan^a

^aUniversité Grenoble Alpes, TIMC-IMAG, F-38000 Grenoble, France, CNRS, TIMC-IMAG, F-38000 Grenoble

^bLaboratoire d'Anatomie des Alpes Française, Faculté de Médecine, Domaine de la Merci, F-38700 La Tronche Cedex

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1. Introduction

Biomechanical modelling of human breast tissues has been widely studied for various medical applications such as surgical procedure training, pre-operative planning, diagnosis and clinical biopsy or image-guided surgery. Most research teams have designed subject-specific Finite Element (FE) models that are for example used to simulate breast deformations due to repositioning, compressions between plaques during mammography or tissue deformations due to needle biopsies. Such FE models usually include various breast tissues such as the skin, the mammary gland, adipose tissue and pectoral muscles. Mira and colleagues recently showed the importance of also including some suspensory ligaments as well as the superficial and deep fascia in these FE models (Mira et al, 2018). Among the suspensory ligaments, the net of Cooper's ligaments (Gaskin et al, 2019) probably plays a role in the global deformation of the breast. However, to the better of our knowledge, these ligaments have never been included in any biomechanical model. This is probably due to the fact that the constitutive behaviour of such ligaments has never been investigated, because (1) of the difficulty to extract them from a specimen and (2) of their extreme fragility once extracted, which makes any experimental characterisation complicated. This paper addresses this issue with samples of Cooper's ligament that were extracted and tested ex vivo in uniaxial tension. The results of the tests were fitted with an original hyperelastic constitutive equation. The variations of the parameters of that equation are highlighted.

2. Methods

2.1 Cooper's Ligaments Specimens

Cooper's ligaments are described as a mesh or a three-dimensional net containing the fatty tissue and the mammary gland. They are attached to the dermis and pectoral muscle and merge on fascia layers. To sample Cooper's ligaments from a cadaver, the technique consists in making a lateral incision at the level of the ribs until reaching the pectoral muscles and the intercostal muscles and thus being able to access the breast from below going up toward the dermis. This allows a clear reading of the tissues found. Our sampling of Cooper's ligaments was distributed over the entire volume of the breast of one cadaver. Sizes of

samples varied between 13.9 mm and 15.1 mm long, 1.4 mm and 4.9 mm wide and 0.04 mm and 0.3 mm thick. Each sample was cut in the direction of the main fibres visible to the naked eye. The sample should be cut in such a way to respect the dimensions of the uniaxial tensile specimens as well as possible, by respecting a ratio of approximately four between the length and the width of the sample. The uniaxial tensile tests were performed on an MTS model C42.503 machine with 25 N sensors (see panel on figure 1). To reproduce physiological conditions, each sample was placed on the tensile machine with a bath filled with a physiological serum heated to a temperature of 37°C (Masri et al, 2018). A tensile fracture test was performed on each sample.

3. Results and discussion

Figure 1 shows the results of the uniaxial tensile tests performed on 28 Cooper's ligament samples. The amplitudes of rupture stress and rupture strain during these tests are plotted on that figure. A relatively strong dispersion can be observed. The rupture stresses range from 250 kPa to 13 MPa with an average of 2.0 MPa. Rupture strains range from 1% to 16% with an average of 8.6%.

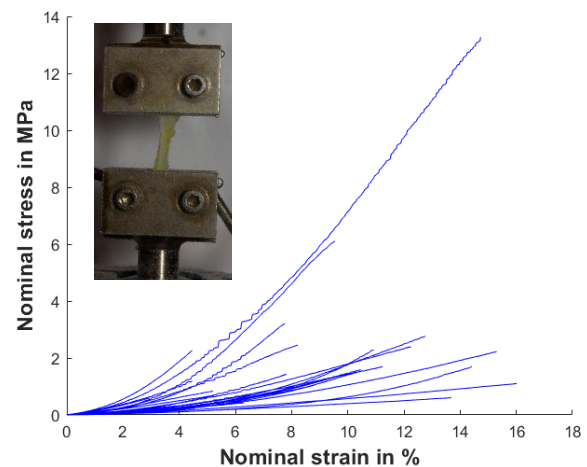


Figure 1. The uniaxial tensile tests on 28 Cooper ligaments. The panel shows a ligament during a tensile test

The experimental curves present a horizontal step before a strain hardening. We propose to use a Neo-Hookean model (Treolar et al, 1943) to describe the

horizontal step and to use a power function to describe the hardening, thus assuming the strain-energy density function W with:

$$W = C_1(I_1 - 3) + C_2(I_1 - 3)^{C_3} \quad (1)$$

where I_1 is the first invariant of the left Cauchy-Green tensor. The model has three parameters, C_1 describing the initial slope and C_2 and C_3 describing the hardening. For each curve, an optimization process estimates the values of these three parameters to fit the experimental data.

Figure 2 provides the range of variation of the three parameters estimated from experimental data on the 28 samples. The C_1 parameter varies between 230 kPa and 2.5 MPa, with a median of 710 kPa, 50% of the population being between 480 kPa and 1.2 MPa. The C_2 parameter varies between 1.3 MPa and 110 MPa, with a median of 16 MPa, 50% of the population being between 7.6 MPa and 33 MPa. The C_3 parameter varies between 1.4 and 2.2, with a median of 1.7, 50% of the population being between 1.5 and 1.7.

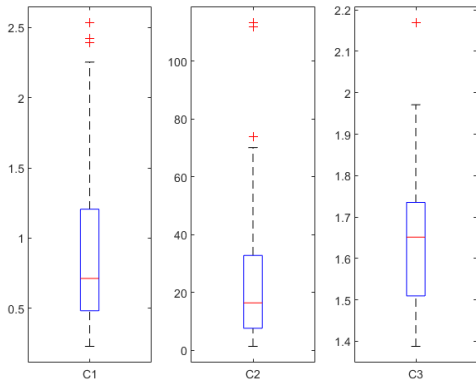


Figure 2. Summary of all parameters obtained for the 28 Cooper ligaments (C_1 and C_2 are in MPa)

Table 1 gathers the average, maximal, minimal and standard deviation values for the rupture strain, rupture stress and Young modulus estimated from all the tests. The Young modulus was computed as $E=6 \times C_1$ (assuming ligaments as quasi-incompressible).

The first point raised by table 1 is the high values for the equivalent Young modulus of Cooper's ligaments (two to three orders of magnitude stiffer than most breast soft tissue). The other point is the dispersion of the data (high standard deviations) as observed on the experimental curves. This can be explained in several ways: the freshness of the tissue (the cadaver was conserved in formalin), errors in section measurements (samples were sectioned by hand) or the various location of the tissue (the localisation can affect results).

Table 1. Summary of the mechanical values estimated from the 28 experimental tests

	Average	Max	Min	Standard deviation
Young Modulus in MPa	5.8	15	1.4	4.2
Rupture Strain in %	8.6	16	1.0	4.2
Rupture Stress in MPa	1.9	13	0.25	2.5

However, this is to our knowledge the first time that many samples of Cooper's ligaments were extracted and experimentally characterised by a tensile test.

4. Conclusions

Uniaxial tensile tests were performed on 28 Cooper's ligaments of a single cadaver. A wide dispersion of the results was observed for the rupture stress, the rupture strain and the Young modulus. Surprisingly, the stiffness of these Cooper's ligament is two to three orders of magnitude higher than the stiffness of most breast soft tissue.

An original constitutive law was proposed to model the hyperelastic behaviour of the ligaments with an accurate approximation of the stress-strain curve during the uniaxial traction.

As a perspective, other mechanical tests such as plane traction or channel compression could be used to check the behaviour of the model in these different cases of stress. Especially the anisotropy of Cooper's ligaments will have to be investigated.

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