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The effects of strain amplitude and localization on viscoelastic mechanical behaviour of human abdominal fascia

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Purpose: The purpose of the paper is to examine and compare the viscoelastic mechanical properties of human transversalis and umbilical fasciae according to chosen strain levels. *Methods:* A sequence of relaxation tests of finite deformation ranging from 4 to 6% strain with increment 0.3% was performed at strain rate 1.26 mm/s. Initial and equilibrium stresses T_0, T_{eq}, initial modulus E and equilibrium modulus E_{eq}, reduction of the stress during relaxation process ΔT, as well as the ratio $(1 - E_{eq}/E)$ were calculated. *Results:* The range in which parameters change their values are (0.184–1.74 MPa) for initial stress, (0.098–0.95 MPa) for equilibrium stress, (43.5–4.6 MPa) for initial modulus E. For E_{eq} this interval is (23.75–2.45 MPa). There are no statistically significant differences between the values of these parameters according to localization. The differences in viscoelastic properties of both fasciae are demonstrated by reduction of the stress during relaxation process and ratio $(1 - E_{eq}/E)$. The values of ΔT and $(1 - E_{eq}/E)$ ratio for umbilical fascia are significantly greater than that of fascia transversalis. An increase of 2% in strain leads to change of the normalized relaxation ratio of fasciae between 28%–66%. There is a weak contribution of viscous elements in fascia transversalis samples during relaxation, while in umbilical fascia the contribution of viscous component increases with strain level to 0.66 at 5.3% strain. *Conclusions:* This study adds new data for the material properties of human abdominal fascia. The results demonstrate that in chosen range of strain there is an influence of localization on visco-elastic tissue properties.

Key words: *human fascia, viscoelastic properties, experimental testing*

1. Introduction

Hernia operations are very common in the adult population and are a significant social problem. More than 20 million hernias are repaired every year around the world [9]. The process of surgical intervention includes injury of layers that compose abdominal wall which contribute to the high rate of recurrent incisional hernias. The investigation and modelling of the mechanisms of injury will provide understanding of normal tissue function and the effects of pathological changes in the layers. The simulation of herniation may find applications in surgeon training systems where a better knowledge of the local deformations and post-operative conditions are required [3]. Numerical simulations of hernia treatment could also allow development of an artificial fascia of the human abdominal wall used as a material for testing suture quality [18].

The number of studies concerning the mechanical properties of human abdominal wall as homogenous object, increase recently [5], [12], [16]. They include maximum forces acting on the abdominal wall and its elasticity because of their significance for rehabilitation, manual therapy and the design of incision. The proper model should be based on experiments and should account for stress–strain relations obtained after determination of individual structures and properties of sheet-like layers of abdominal wall. The behaviour of abdominal wall layers: linea alba, rectus sheet, fascia, were investigated in the studies [7], [10], [17], [19].

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In order to understand better the biomechanics of the abdominal wall and evaluate the contributions of its components to the mechanical response it is necessary to characterize its viscoelastic properties. This knowledge has important implications for the development of synthetic implants, which must match the viscoelastic properties of native tissues to ensure long-term mechanical compatibility.

Although there is some amount of articles on the elastic mechanical properties of human abdominal fascia [10], [17], [19], the viscoelastic properties of human abdominal fascia have not been well investigated. The authors have not found in the available literature any reports on the stress relaxation results for human umbilical and transversal fascia except their own previously reported investigations [10]–[12]. These results revealed orthotropic viscoelastic mechanical properties of umbilical fascia and fascia transversalis [11] and suggested their regional differences. Since it is very important to characterize the behaviour of biological tissues at physiological loads and strains, we intend to study the viscoelastic behaviour of human abdominal fascia using fascia transversalis (FT) and umbilical fascia (UF) in the strain range 4–6%. Fascia transversalis builds the posterior wall of inguinal canal and umbilical fascia is situated around the umbilical area. The main reason for this choice was the fact that inguinal hernia is the most frequently performed operation concerning men, while the umbilical hernia is wide spread among women (66% of females were operated on for incisional and umbilical hernia) [1]. The results will help to describe the local stresses and strain inside a fascia more accurately.

The aim of the study is to examine and compare viscoelastic mechanical properties of human transversalis and umbilical fasciae according to chosen strain levels.

2. Materials and methods

The investigation included 17 specimens taken from 7 donors. It was approved by the Ethics committee at Bulgarian Academy of Sciences. The average age of the subjects was in the range of 59–83 years (67.4 years for group of samples from UF and 73 years for group of samples from FT). All available samples were harvested from non-herniated subjects. Nine strips were extracted from posterior wall of inguinal canal and another nine strips from umbilical region. The samples were cut parallel to the main fibres direction (L) and were divided in two groups according to their localization. The size of each sample was between 10×50–10×70 mm and was measured prior to investigation (Fig. 1). Mechanical testing of abdominal wall strips was performed immediately after excision and less than 36 hours after death, in order to avoid post mortem changes. The experiments were conducted at an ambient temperature of 21 ± 2 °C. Relaxation curves were generated using a universal testing machine model FU1000e (fabricated in Germany), equipped with a 500 N load cell, minimal value of the load of 0.2 N and minimal value of the displacement of 0.1 mm. The initial reference configuration of the samples was established as the length when a nominal load of 0.2 N was reached in tensile direction. In the testing procedure the strain exerted on the tissue samples aligned with fibres family. The test protocol was designed to reveal changes in mechanical properties of tissue due to the strain in the range 4%–6% with the increment 0.3%. Thus the mechanical behaviour of abdominal fascia was characterized at strains associated with physiological loadings. The specimens were loaded at a rate of elongation 1.26 mm/s.

Fig. 1. Typical image of abdominal fascia before testing (solid lines indicate samples cut parallel to fascia fibres)

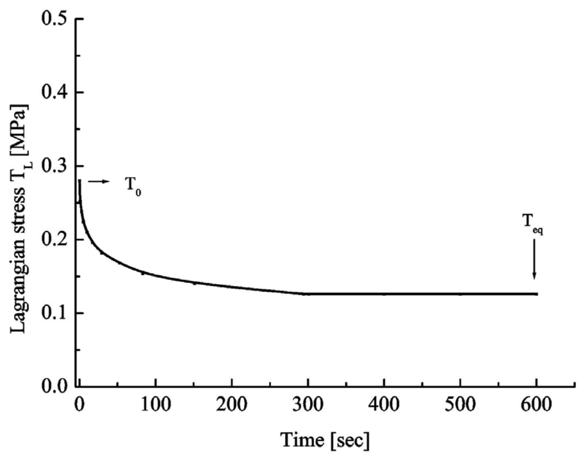

Fig. 2. Schematic representation of a typical relaxation curve

First relaxation test of the tissue was followed by second one. The samples were returned to the initial length and after a 15–30 min rest period the samples were loaded again. Such a procedure was followed for 8 UF samples and 9 FT samples. All UF samples and four FT samples were tested twice while five FT samples were tested only once. Thus, the numbers of experiments included in the study are 13 for FT and 16 for UF.

The duration of the test was 600 s. Digital recorded values of force and elongation were used to draw the load-elongation curves and to present the relaxation. Data from the relaxation tests were used to determine the following biomechanical parameters: initial Lagrangian stress T_0 (determined as load F divided by the undeformed initial cross-sectional area of the specimen S_0), equilibrium stress T_{eq} (calculated at t = 600 s) (Fig. 2), initial elastic modulus $E = T_0/\varepsilon_0$ (ε_0 is the initial strain), equilibrium modulus E_{eq} calculated as T_{eq}/ε_0, reduction of the stress during relaxation process ΔT defined as $\Delta T = \frac{(T_0 - T_{eq})}{T_0} * 100\,[\%]$, and the ratio ($1 - E_{eq}/E$) which reveals the viscous response of test samples at applied strain [6].

The values of parameters were calculated. Median and absolute median deviation (AMD) at chosen strain levels for all parameters are presented. The statistical analyses for evaluation of statistically significant differences between parameters were performed applying paired t-test with significance level 0.05.

3. Results

The relaxation behaviour of human abdominal fascia from inguinal (FT) and umbilical region (UF) in longitudinal direction was investigated at physiological strain levels. The results from the test protocol are summarized in Table 1 and Table 2.

Figures 3 and 4 show the results of the relaxation tests on a plot of initial/equilibrium stress versus strain. Two conclusions can be drawn from the results presented. Firstly, the trends of the curves which show a relationship between initial or equilibrium stress and ε_0 for UF are sigmoidal while the initial and equilibrium stresses of FT increase to 5% and then rapidly decrease at applied strain levels (Fig. 3 and Fig. 4). Secondly, there is a wide variation in visco-elastic response of fascia from one donor to another which leads to high values of standard deviation of pa-

Table 1. The values of model parameters (median ± AMD) obtained for FT samples, (n – number of experiments)

Groups	ε [%]	T_0 [MPa]	T_{eq} [MPa]	ΔT [%]	E [MPa]	E_{eq} [MPa]	$1 - E_{eq}/E$
FT, n = 2	4.0	0.184 ± 0.009	0.098 ± 0.20	41.30 ± 24	4.60 ± 2.2	2.45 ± 0.21	0.41 ± 0.24
FT, n = 2	4.3	0.46 ± 0.05	0.37 ± 0.20	32.67 ± 19	10.89 ± 1.5	8.67 ± 2.10	0.32 ± 0.19
FT, n = 1	4.6	0.245	0.147	40.20 ± 16	4.90	2.94	0.40
FT, n = 2	5.0	1.28 ± 0.73	0.97 ± 0.73	28.60 ± 16	25.65 ± 14.6	19.59 ± 14.60	0.28 ± 16
FT, n = 3	5.3	0.95 ± 0.04	0.71 ± 0.16	49.75 ± 14	17.98 ± 0.77	13.3 ± 0.56	0.43 ± 0.12
FT, n = 2	5.6	0.27 ± 0.19	0.143 ± 0.04	39.20 ± 25	4.91 ± 3.44	2.55 ± 0.83	0.39 ± 0.25
FT, n = 1	6.0	0.32	0.22	31.02	5.33	3.66	0.32

Table 2. The values of model parameters (median ± AMD) obtained for UF samples, (n – number of experiments)

Groups	ε [%]	T_0 [MPa]	T_{eq} [MPa]	ΔT [%]	E [MPa]	E_{eq} [MPa]	$1 - E_{eq}/E$
UF, n = 1	4.0	1.74	0.95	45.4	43.50	23.75	0.45
UF, n = 4	4.3	1.06 ± 0.65	0.79 ± 0.53	28.6 ± 7	24.72 ± 14.3	18.55 ± 12.5	0.32 ± 0.09
UF, n = 4	4.6	0.47 ± 0.14	0.26 ± 0.08	44.2 ± 5	10.38 ± 2.9	5.43 ± 1.9	0.43 ± 0.06
UF, n = 1	5.0	0.55	0.19	64.4	11.04	3.92	0.64
UF, n = 2	5.3	1.15 ± 0.46	0.42 ± 0.2	66.1 ± 11	21.81 ± 6.2	7.83 ± 3.86	0.66 ±0.11
UF, n = 1	5.6	0.42	0.21	50.0	7.57	3.78	0.5
UF, n = 3	6.0	1.07 ± 0.69	0.44 ± 0.19	54.02 ± 5	17.9 ± 11.03	7.35 ± 3.26	0.54±0.08

rameters. No statistically significant difference between these parameters ($p = 0.067$ for T_0 and $p = 0.39$ for T_{eq}) was obtained.

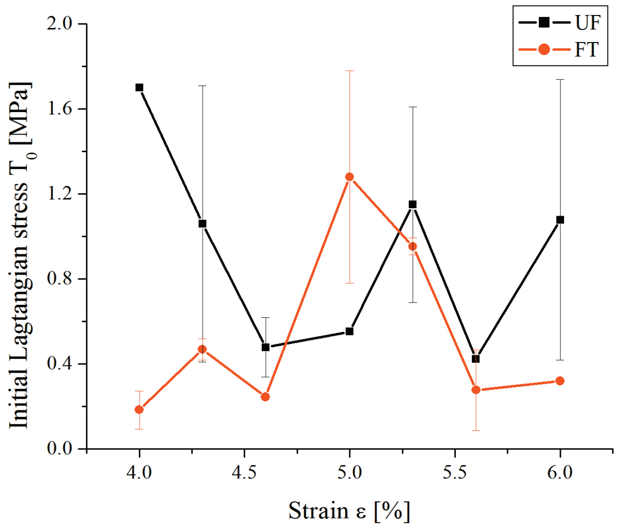

Fig. 3. Initial Lagrangian stress vs. strain levels

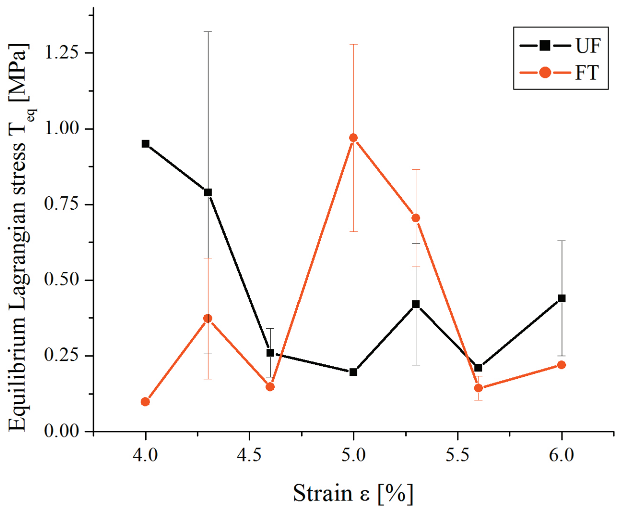

Fig. 4. Equilibrium Lagrangian stress vs. strain levels

The mechanical behaviour of calculated elastic modulus for both fasciae followed the behaviour of initial stress of the samples. The elastic modulus of fascia transversalis increases about 5 times, reaching its largest value of 25.65 MPa and then decreases to 5.33 MPa at 6% strain. The largest value of umbilical fascia's elastic modulus was observed at 4% strain and was 43.5 MPa (Fig. 5). The behaviour of equilibrium modulus for umbilical fascia is sigmoidal (Fig. 6). Because of the big diversity of sample values there is no statistically significant difference between both moduli ($p = 0.18$ for E and $p = 0.65$ for E_{eq}).

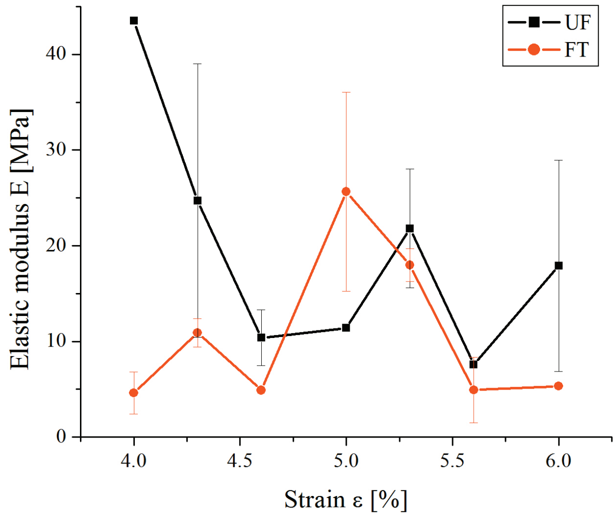

Fig. 5. The relationship between elastic moduli and strain levels

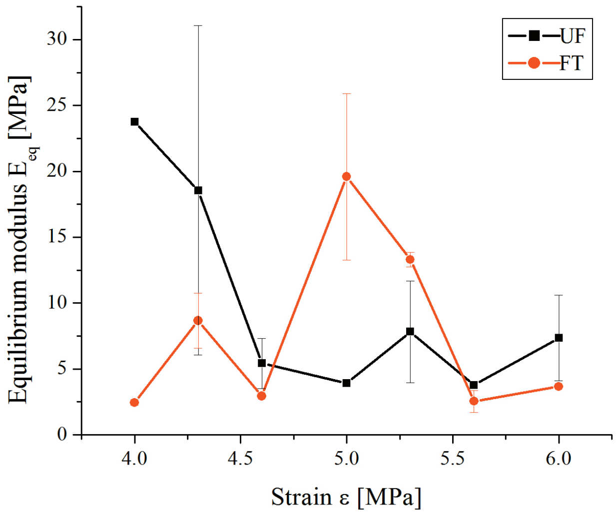

Fig. 6. The relationship between equilibrium moduli and strain levels

The parameter ΔT was used to estimate the effect of strain levels on the total stress reduction during relaxation process (Fig. 7). The amount of relaxation for FT samples is in the range 28–49%, while the value of ΔT for UF increases almost 40% from 28% to 66%. The percentage reduction of stress indicates a greater level of relaxation in the loaded UF samples. The difference in stress reduction between FT and UF samples was further investigated by statistical analysis. With $p = 0.008$ the differences in stress reduction in FT and UF are statistically significant.

The ratio $1 - E_{eq}/E$ indicates whether relaxation process was dominated by elastic or viscous properties. It helps to evaluate the viscous contribution of investigated fasciae to relaxation [6]. The ratio is plotted versus strain levels for both fasciae in Fig. 8. The values for FT are in the range 0.28–0.43 and for UF between 0.32 and 0.66. The trend of ratio for fascia transversalis is below 0.5, which reveals the weak contribution of viscous elements, and suggests their insensitiveness to strain levels. In umbilical fascia, however, the contribution of viscous component is higher and increases with strain level to 0.66 at 5.3% strain (Fig. 8). The values of the ratio $(1 - E_{eq}/E)$ for UF are significantly greater than that of FT, ($p = 0.03$).

Analysing the effect of sample localization on material properties of fasciae it was concluded that localization affects viscoelastic properties of fascia because of statistically significant differences between parameters ΔT (reduction of stress during relaxation) and the ratio $(1 - E_{eq}/E)$.

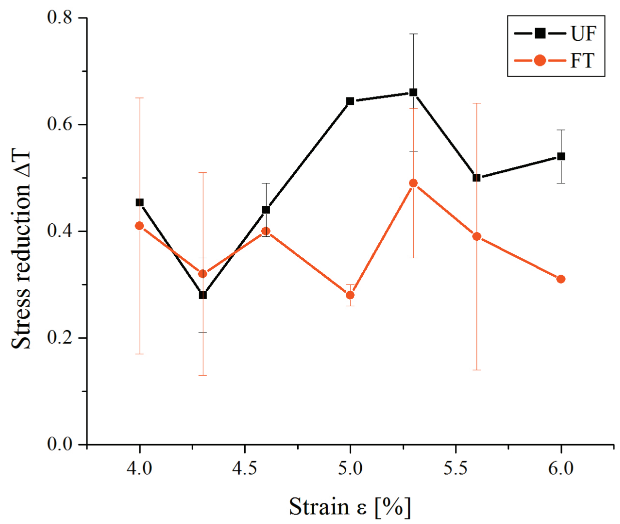

Fig. 7. Percentage reduction of stress for FT and UF according to strain level

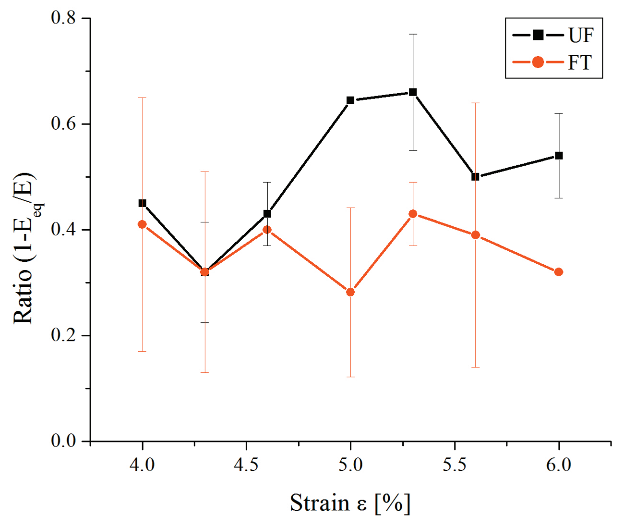

Fig. 8. The relationship between the ratio $(1 - E_{eq}/E)$ and strain level for FT and UF

4. Discussion

In this study we focus our attention on human abdominal fascia the mechanical properties of which are useful for developing a reality-based model for hernia simulation and surgical training.

The present study continues the investigation presented in [11], where it seems that tissue behaviour changes in regard to localization. Thus the hypothesis about regional variations in viscoelastic behaviour of FT and UF at chosen strain levels was proposed. The strain levels at which both fasciae were tested were extended and the strain related changes of their viscoelastic properties were assessed. A strain of 6% was chosen as the upper limit of physiological strain because damage to fascia often occurs at strain greater than 6% [10].

It is known that an increasing strain leads to alterations which influence the behaviour of soft tissues [8]. Material testing of the samples from umbilical and unguinal regions leads to sigmoidal change of the values of all parameters for UF. The trend of the parameters T, T_0, E and E_{eq} for FT exhibits reversed V shape. Such dependence of strain is reported in Langelier for bovine articular cartilage in compression tests [14]. The range in which parameters change their values are (0.184–1.74 MPa) for initial stress, (0.098–0.95 MPa) for equilibrium stress, (43.5–4.6 MPa) for initial elastic modulus and (23.75–2.45 MPa) for equilibrium modulus.

Because the reported values of parameters varied widely with amplitude of strain, it seems that the magnitude of stress relaxation parameters depends on the level of applied strain. Such hypothesis is not possible to be proved by statistical analysis because of limited number of experiments at chosen strain levels. The linear response of the tissue in this strain range, however, is probable because such linear viscoelastic behaviour is presented for human medial collateral ligament in Bonifasi-Lista [2]. In the study relaxation data obtained at three strain levels were compared. There was no significant difference between relaxation curves for 6% and 8% strains (longitudinal direction) and 12%/16% in transverse direction [2].

The strain level plays an important role in determining which structural component of tissue is included in the relaxation process. It is known that the relationship between deformation and stress relaxation parameters varies among the various tissues in the body [6]. In the study of Dunn viscose components linearly increase after 10% for tendon and after 30% for skin.

The evaluation of viscous contribution during the relaxation of fascia was done using methodology presented in the study of Dunn et al. [6]. Viscoelastic response was assessed by the ratio $(1 - E_{eq}/E)$. According to the results, the response is different in both fasciae. The viscous components are not included in the relaxation process of FT samples when strain is between 4–6% and present after 4.6% for UF samples. In the UF samples the viscous fraction increases with strain, while the FT samples are insensitive to strain level. It was found that the elastic component in fascia transversalis is greater than viscous component.

Viscoelastic behaviour of fasciae investigated suggests that the changes observed during testing are a function of their structure. This is an indication of different collagen content and structural reordering as a result of level of deformation. One possible explanation of the results is that collagen fibres are still crimped at this level of deformation and the ground substance matrix bears a load at lower strains [6].

The normalized parameter ΔT was used to estimate the total stress reduction during relaxation process (Fig. 7). A greater level of relaxation in the loaded UF samples compared with FT samples confirms earlier inclusion of UF viscous components in relaxation. The values for the stress reduction parameter ΔT for umbilical fascia obtained in this study are consistent with the reported values of 40–60% for nasal fascia [20].

Some limitations should be noted for the study. The effect of strain level is presented only in longitudinal direction because of insufficient samples in transversal direction for FT. It is known that load bearing is more considerable in longitudinal direction, when the load is applied along the fibre direction and some authors reported results only in this direction which gave us a reason to present the obtained results [19].

The limited number of samples imposes stretching the samples twice. This means that the values of parameters T_0, T_{eq}, E and E_{eq} are higher than normally obtained because of the strain hardening phenomenon which leads to an increase of stress after second stretch of the samples [12], [15]. The repeated relaxation tests conducted on the same specimen at the same or higher strain level result in the higher initial stress (strain hardening) [12], [15]. A possible alternative interpretation of the higher values of parameters would be the fact that the age of most of the donors is greater than 80 years when the elasticity of tissues decrease and the values of modulus of elasticity increase [8].

The obtained results described viscoelastic properties of donors in the range 59–83, which means that the conclusions cannot be applied to the biomechanical properties of young people. Further experiments with this type of fascia are necessary to describe the influence of direction of loading and strain levels on viscoelastic properties of young donors

The reported results highlighted the effects of localization on viscoelastic mechanical behaviour of the umbilical and transversalis fascia. It occurred that the values of T_0, T_{eq}, E and E_{eq} are not statistically significant for both types of fascia, although the mean age for both groups is close to 67.4 years for UF group and 73 years for FT group. We also found that in the range of applied strains the viscoelastic properties of UF are more clearly demonstrated than those of FT and these differences are statistically significant. An increase of 2% in strain change the normalized relaxation ratio of umbilical fascia by almost 40% and by 15% for fascia transversalis. This fact suggests that if we intend to model the viscoelastic properties of fascia it is not possible to combine samples from both groups.

Summing up, the interpretation of experimental results underlines the differences in mechanical properties between FT and UF groups. The viscoelastic mechanical response of abdominal fascia depends on localization. The differences of trends can be attributed to the structure and unloading collagen fibres. Some broader loading regimes that include large strains will reveal the yield point for linear viscoelastic behaviour. Further studies will be necessary to better clarify the possible alterations of the fascia in pathological conditions.

Competing interests

None declared; Ethical approval: The study was approved by the ethics committee at Bulgarian Academy of Sciences – Document N:17/17.01.2008

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