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PROCESSING OF EXPERIMENTAL RESULTS FOR MECHANICAL BEHAVIOUR OF HUMAN FASCIA USING STATISTICAL METHODS*

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Uniaxial tensile tests of human umbilical and transversal fascia were performed using a testing machine FU1000/E. The obtained force-elongation curves were presented as stress-stretch ratio relationships. All experimental curves show great variability due to effects of age and localization. The mean curve from the entire family of curves was estimated with the sample median and arithmetic mean. The variability of the results were assessed by standard deviation and standard error of mean. The results show that the median test is more suitable than arithmetic mean for processing of our experimental results.

Introduction. Soft biological tissues are subjected to large deformations. Their mechanical behaviour is nonlinear, anisotropic, time and direction dependant, highly extensible and their properties depend significantly on localization. Mechanical testing of biological material usually leads to a number of problems. A main peculiarity of soft biological tissues is the fact that material properties measured in a small region may not adequately reflect the mechanical behaviour of investigated area. That is why it is necessary to perform experiments with large number of specimens. Very often however, processing of the obtained experimental results is a real challenge, because of great variability between samples.

Analyzing data from the experiments we usually assume that the variable of interest is normally distributed. Then in repeated samples of equal size it will be possible to calculate the particular mean and variance of investigated perameter. The size of the sample data is another important factor that often limits the applicability of basic statistical tests. We can assume that the sampling distribution is normal if our sample is large enough (100 or more observations). But usually the number of investigated biological samples, especially in the case of human material are less then 15-20. In such a case we need a statistical procedure that allow to process data from small samples, with statistics which distribution we do not know.

Nonparametric methods were developed to be used when nothing is known about distribution of the variables. They do not make restrictive assumptions about the shape

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and size of population distribution. In this study we used arithmetical mean and nonparametric median tests to obtain the mean curve for the family of curves representing the mechanical properties of investigated fasciae.

The aim of the study is to analyze the data from uniaxial tensile tests of two type of human fascia and to compare the mean curves obtained with the method of median and arithmetical mean for the both family of curves. The best method according to their standard deviation and standard error will be chosen.

Materials and methods. A computer-controlled uniaxial testing machine FU1000/E was used to investigate the mechanical properties of human fascia. The main components of the system are stretching mechanism, force measurement system and elongation measurement system. The resultant force and displacement was digitized and recorded in the computer.

Samples from umbilical (UF) and transversalis fascia (FT) were cut out from human cadavers, 24h after death. Tissues were stored in physiological solution at 4°C. Fascia specimens were cut in two directions – parallel and perpendicular to the primary connective tissue orientation. The number of investigated samples were 31. Ten samples of fascia transversalis and 21 from umbilical fascia. 14 specimens were loaded parallel to the fibers direction (L1) and 17 were loaded perpendicular to the fibers direction (L2). The dimensions of fascia specimens were between 10×40 mm to 10×70 mm, their thickness changes in the interval 0.7 mm to 1.8 mm. The age of the samples were between 46-78 years.

The specimen was mounted in the testing device and a load of 0.98 N was applied for preconditioning. Every specimen was sequentially loaded and unloaded until the force-elongation curve became reproducible. Calculation of Lagrangian stress T_L is accomplished using the values of unstressed geometry of each specimen and following the definition:

$$T_L = \frac{F}{S_0}, \tag{1}$$

where S_0 is undeformed specimen cross-section, F is applied load. Thus the obtained force-elongation curves were presented as stress-stretch ratio relationships [1].

The mean of the samples was estimated with the sample median and arithmetical mean.

The sample median is those value from an arranged row which is exceeded by as many sample values as it exceeds [2]. If a sample contains an even number of measurements the median is defined as the mean of the two middle values of arranged data. By definition median of the arranged variation row $x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(n)}$ $(i = 1, \ldots, n)$ is:

$$med\ x = \begin{cases} x_{(n/2+1/2)} & \text{if } n \text{ is odd,} \\ 0.5x_{(n/2)} + 0.5x_{(n/2+1)} & \text{if } n \text{ is even.} \end{cases} \tag{2}$$

We are interesting in the nature of distribution of data above and below the investigated statistics. The standard deviation and mid-range were used as a measures of variability. The mid-range is the mean of the smallest and the largest values of the parameter. As a estimation of median variability the robust estimation of standard deviation of the median $S(x)$ was used [3].

$$S(x) = 1.48148\, a_n(x), \tag{3}$$

$a_n(x)$ is an absolute median deviation which is calculated as:

$$a_n(x) = med(|x_i - med\ x|), \qquad (1 \le i \le n) \tag{4}$$

Results and discussion. Typical stress-stretch ratio relationships for fascia transversalis in direction perpendicular to the primary connective tissue orientation are presented (Fig. 1). The results confirm the nonlinearity and age-dependant properties of fascia transversalis. The tensile test data shows considerable sample to sample variation.

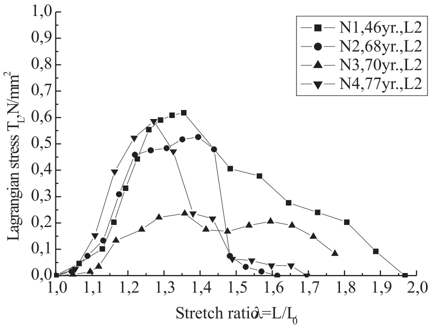


Fig. 1. Lagrangian stress versus stretch ratio from uniaxial tests in transversal direction for fascia transversalis

The large variability in the shape of stress-strain curves for fascia samples requires using of the statistical methods mention above. For this reason the values of Lagrangian stress T_L for all samples were grouped according to the type of fascia and the direction of loading. Then the values $T_L^{j,i}$ were arranged in the ascending order for every i ($i = 1, \ldots, \lambda_{\max}$, $j = 1, \ldots, n$, where n is the number of samples) and methods of median and arithmetical mean were used.

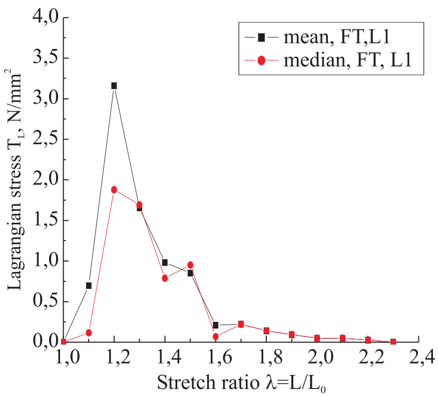


Fig. 2. Results for fascia transversalis, direction L1

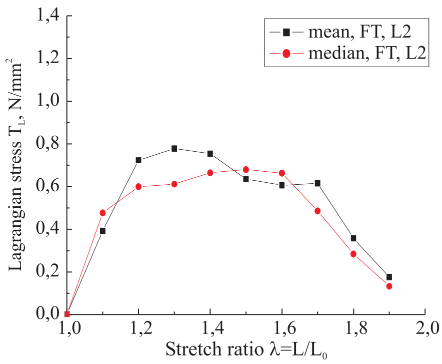


Fig. 3. Results for fascia transversalis, direction L2

Thus the average experimental curve for both type of fascia were obtained. The results are presented in Figs 2 to 5.

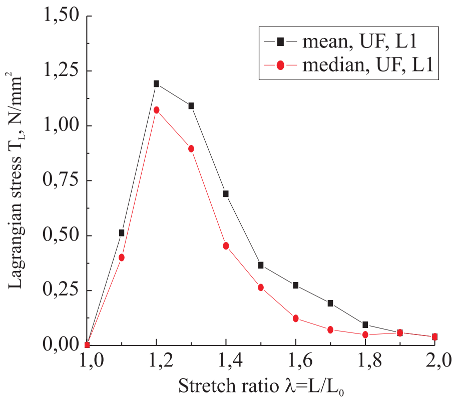


Fig. 4. Results for umbilical fascia, direction L1

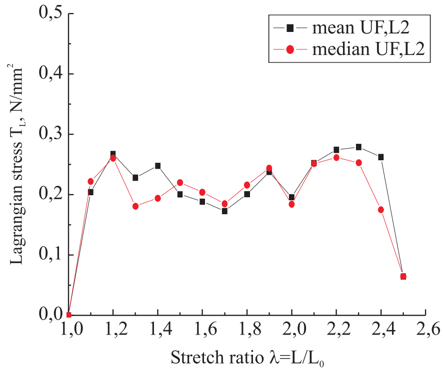
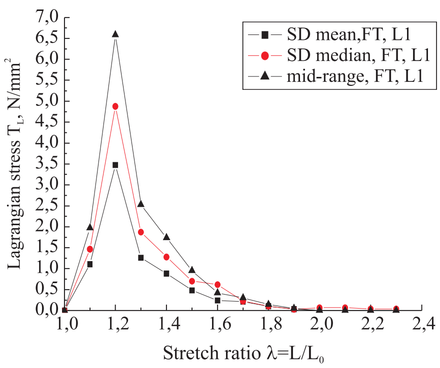


Fig. 5. Results for umbilical fascia, direction L2

The figures show that the values of average curves obtained with median test are lower or coincident with arithmetical mean values. The difference between two curves calculated at $\lambda = 1.3$ ranged in the interval 4.5% for umbilical fascia, direction L2 to 70% for inguinal fascia, direction L1.

The assessment of applicability of applied tests was done on the basis of distribution of data above and below the investigated statistical measures. The question is which estimator will lead to the curve closest to the real average curve. In our case the values of Lagrangian stress have a considerable variability, so we can not expect these estimates to be close. Figures 6 to 9 graphically depict the variation of mean stress from the stress obtained using median test. It is seen that the standard deviation of median curves is below the standard deviation of arithmetic mean curves.



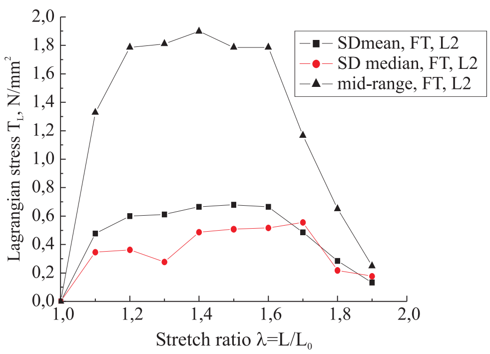
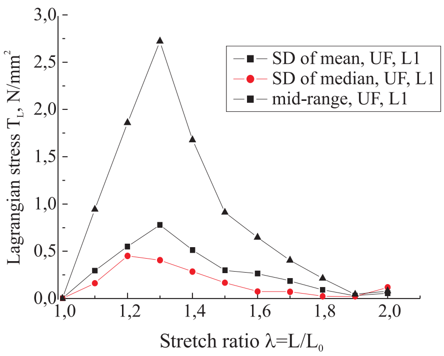


Fig. 6 (left) and Fig. 7 (right)– standard deviation and mid-range of fascia transversalis in longitudinal and transversal directions

Table 1 represents values of sample size, experimental maximum stress, mean and median maximum stress, mean and median maximum stretch ratio and standard error



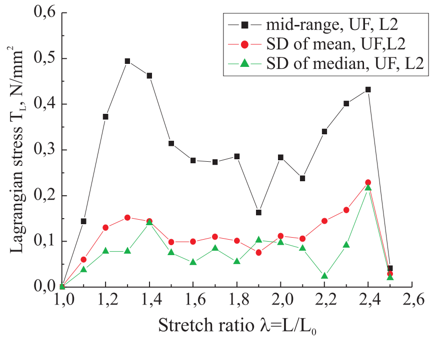


Fig. 8 (left) and Fig. 9 (right) – standard deviation and mid-range of umbilical fascia in longitudinal and transversal direction

of the mean (SEM) The tabulated data show considerable variation of mean and median maximum stress as evidenced by the range of obtained values. The values of SEM vary from +4% to +25.6% of the mean stress magnitude being the highest in the transversal direction of fascia transversalis. Because of small number of investigated samples for L1 direction of fascia transversalis the value of SEM was not calculated .

Table 1

Type of fascia	Sample size	$T_L^{\max}$	Mean $T_L^{\max}$	Median $T_L^{\max}$	Mean $\lambda_{\max}$	Median $\lambda_{\max}$	SEM %
FT, L1	N=3	7.094	3.161	1.878	2.06	2.3	2.3- /
FT, L2	N=7	2.085	0.778	0.536	1.77	1.8	7.7-25.6
UF, L1	N=11	2.931	1.192	1.072	1.72	1.75	2.1-23.4
UF,L2	N=10	0.534	0.278	0.261	1.82	1.9	1.9-8.4

The dimension of all parameters $T_L^{\max}$ is [N/mm^2].

Conclusion. In this article statistical methods for processing of stress-strain experimental curves from uniaxial loaded specimens is presented. As the relatively small number of samples were tested, the robust statistical method for analyzing the data about mechanical behaviour of human fascia was applied. Standard deviation of arithmetical mean and estimation of standard deviation of a median were used as a measure of the dispersion of data about the average curve. The main mechanical characteristics of the experimental curves- maximum stress and stretch ratio were obtained and compared. The results show that the arithmetical mean is not representative measure because some of the components of its standard deviation are very large compared to the others. Summarizing the obtained results we conclude that the median estimation of the average curve is more appropriate for estimating of the mechanical characteristics of the human fascia transversalis and their variations in dependence of direction of loading, age and localization.

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ОБРАБОТКА НА ЕКСПЕРИМЕНТАЛНИ РЕЗУЛТАТИ ЗА МЕХАНИЧНОТО ПОВЕДЕНИЕ НА ЧОВЕШКА ФАСЦИЯ СЪС СТАТИСТИЧЕСКИ МЕТОДИ

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Извършени са едномерни механични изпитания на опън на човешка ингвинална и пъпна фасция с изпитателна машина FU1000/E. Получените криви сила-удължение са представени като зависимости напрежение- деформационен параметър . Експерименталните криви се различават твърде много по форма, поради промени на механичните свойства, възникващи в следствие на възрастта и локализацията. Средните криви на фамилията от експериментални криви за всеки тип фасция са определени чрез метода на медианата и чрез на изчисляване на средното аритметично на изследваните напрежения за определени стойности на деформационния параметър. Разсейването на резултатите беше оценено чрез използване на стандартно отклонение и стандартна грешка. Резултатите показаха, че методът на медианите е по-подходящ за обработката на експерименталните зависимости от изчисляването на средните аритметични стойности на получените данни.