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Original scientific paper

Biomechanical Analysis of the Gracilis and Superficial Third of the Quadriceps Tendons Concerning MPFL Biomechanics

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Abstract: The primary goal of this research is the analysis of the biomechanical performances of most common transplants (distal tendon of m.gracilis and upper third of m.quadriceps femoris) used for the reconstruction of the medial patellofemoral ligament (MPFL). The secondary goal is the comparison of the data obtained from the research with the data available in the literature.The research was conducted on 16 samples of the human tendon, of which there are 8 gracilis tendons and 8 quadriceps tendons. Tensile strength is significantly higher in gracilis tendon (26 MPa - 92 MPa) than in quadriceps tendon (30 MPa - 44 MPa). The extensibility is significantly higher in the quadriceps tendon (10% - 15%) than in the gracilis tendon (13% - 17%). Regarding stiffness (N/mm) there are no significant differences between the groups of gracilis and quadriceps tendons. The module of elasticity is significantly higher in gracilis tendon (235 MPa - 855 MPa) in comparison to quadriceps tendon (239 MPa - 361 MPa).The biomechanical characteristics of the distal surface third of the quadriceps tendon are more favourable than the distal tendon of the gracilis which could prove applicable in operative techniques of reconstruction of the medial patellofemoral ligament when choosing a transplant.

Keywords: biomechanics; gracilis tendon; Medial Patellofemoral Ligament (MPFL); quadriceps femoris tendon

1 INTRODUCTION

The medial patellofemoral complex, which consists of the medial patellofemoral ligament [MPFL] and the medial patellotibial ligament, is the major passive stabilizer of the patellofemoral knee joint. It has been shown that the rupture of MPFL is a major pathological consequence of patellar dislocation and that MPFL is a major passive stabilizer in patellofemoral instability and lateral patellar displacement [1].

MPFL is located in the middle layer of tissue on the anteromedial side of the knee, above which is the fascia, while below are the medial patellomeniscal ligament, the articular capsule, and the deep layer of the medial collateral ligament [2]. The instability of the patella, associated with the reversible dislocation of the patella, belongs to the frequent pathological conditions in young active patients. Analyzing the literature 2% - 3% of all knee injuries include patellar instability [3-5]. 99% of injuries involve dislocations of the patella toward the lateral side of the knee [1]. Cartilage damage and the development of patellofemoral osteoarthritis have been shown to have long-term consequences of back patellar dislocation [5,6]. MPFL is present in every knee [7-9] despite the first research going in the direction that it is a variable structure [10, 11].

Reconstruction of MPFL is, therefore, a generally accepted method of treatment for these conditions. Many techniques have been developed to reconstruct MPFL, to preserve patellofemoral stability, and their goal is to achieve the anatomical reconstruction of MPFL. Given the above, many studies have been conducted related to the anatomy, biomechanics, and kinematics of MPFL, including radiological studies, and postoperative results [12-16].

The anatomical and biomechanical characteristics of MPFL are essential for further research in transplant selection. On the anatomical side, MPFL is characterized by thin fascial tissue approximately 55 mm long and 3 to 30 mm wide [13]. Large differences in latitude are the result of various researches, but also different latitudes in certain locations. Thus, the range from 10 mm to 30 mm refers to 10 mm width at the femoral grip, while in the same review the range from 3 mm to 10 mm refers to its lateral part and 5 mm to 12 mm medially [13]. It is the femoral grip on the medial epicondyle that is relatively compact where, in addition to MPFL, the superficial medial collateral ligament and the tendon of the great adductor are also gripped. The patellar grip of the MPFL is much wider than the femoral and refers to the proximal medial edge of the patella up to 20 mm in length [13]. From a biomechanical point of view, despite the fact that the ligament is thin, the maximum braking force of MPFL is 208 N, [13, 14] while the elongation of the same is 26 mm [14].

Currently, few anatomical studies are dealing with the biomechanics of tendon grafts used for the reconstruction of MPFL, tendon of m. Gracilis [17-20] and tendon of m. Quadriceps femoris [17, 18, 21], and thus the choice of reconstruction method for MPFL, in addition to pre-existing grafts such as the semitendinosus tendon, Achilles tendon, or iliotibial tract, which are nevertheless less used for MPFL reconstruction [22]. In these studies, the number of analyzed samples is extremely small, the sizes of the tested samples are between 6 and 11, so the obtained results of biomechanical properties are different and incomparable [22], and statistically negligible. The research performed also differs in the way the tendons are accepted in the clamps on the test module. Due to the viscoelastic characteristics of the tendon and the low friction between the module clamps and the tendon, the problem is in the adequately rigid adhesion of the tendon during in vitro testing. Too much compression will cause the sample to crack at the clamps, while too little compression will cause the tendon to slip out of the clamps, resulting in a potential misinterpretation of the values obtained. There is still no universal model of tendon acceptance [23-26]. Thus, the results of previously published studies differ significantly due to the very small sample on which the tests were conducted and due to potential technical problems of tendon admission into the module.

2 MATERIALS AND METHODS

The samples used in this research are tendons from the archive collection of the Department of Anatomy and Neuroscience of the Medical Faculty in Osijek. Tendon samples of patients with knee joint collagenosis and knee joint injuries are excluded from our study. 16 selected human tendons that met the criteria were stored at −80 °C until analysis [27].

Just before analysis, the tendons were placed in Ringer's solution [28] at room temperature to carry out the dissolution process for an average duration of 30 minutes. The length of the tendon, the width at the ends and the thickness in the central part of the tendon were measured with a digital calliper five times and the average value was taken for each measured size, Tab. 1. As seen in Fig. 1, visual inspection of the tendon was performed using a digital microscope camera (0,3 m CMOS, 2MP, 1000× optical zoom) eventually to detect the appearance of indications that could potentially cause premature rupture of the tendon during tensile testing and thus present erroneous results.

Table 1 Length, width, thickness and cross-section of the gracilis and quadriceps tendons

	Arithmetic mean	
	Gracilis	Quadriceps
Lenght / mm	90,55	85,45
Width / mm	5,19	9,61
Tickness / mm	2,64	2,45
Cross section / mm^2	10,51	19,28

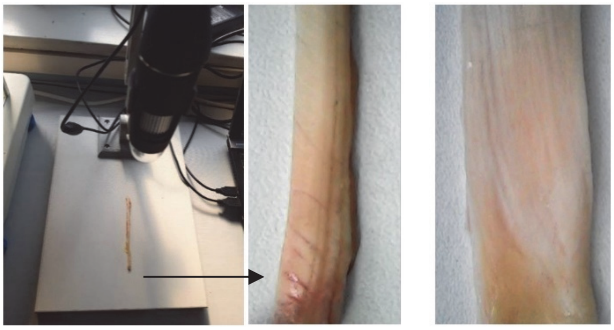
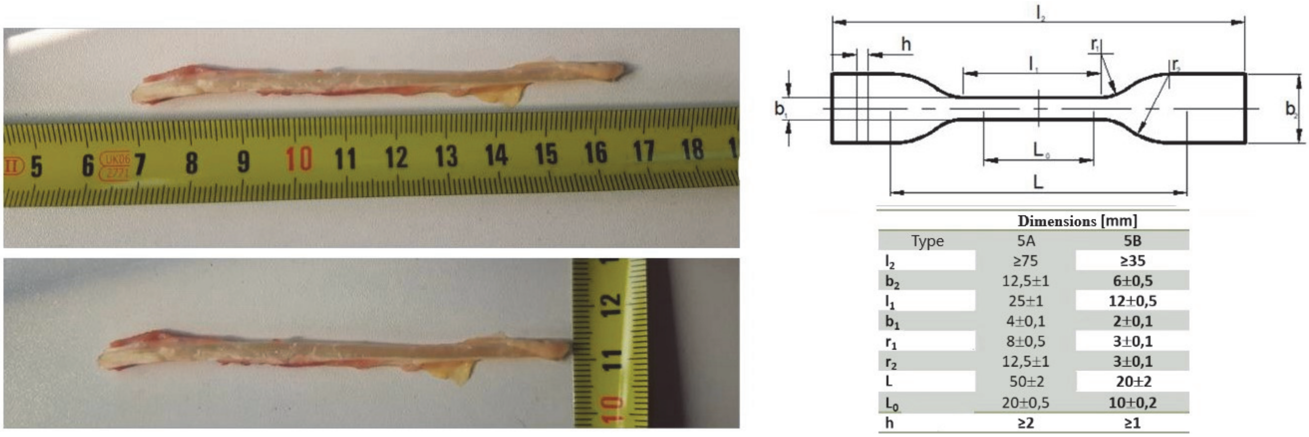


Figure 1 Tendon visual inspection



Type	Dimensions [mm] 5A	5B
l_2	≥75	≥35
b_2	12,5±1	6±0,5
l_1	25±1	12±0,5
b_1	4±0,1	2±0,1
r_1	8±0,5	3±0,1
r_2	12,5±1	3±0,1
L	50±2	20±2
L_0	20±0,5	10±0,2
h	≥2	≥1

a) b)

Figure 2 a) The length of a tendon; b) ISO 527-1:1993 regulative used for tendon preparation

Regarding tendon viscoelastic properties and differences in the tendon preparation protocols throughout the literature, in this study, the calibration procedure is based on the ISO 527-1:1993 regulative since polymer materials also possess viscoelastic properties. If the length of the tendon is ≥ 75 mm 5A specimen type preparation will be used and for tendons of ≥ 35mm the specimen type 5B in case that the tendon length is less than 75 mm, Fig. 2a and Fig. 2b. According to the specimen preparation type, we put markers on the specific places to spot the measurement range and clamp position as well. Tendons have remained in their natural shape without any geometry changes. Next step was the tendon positioning within the calibration module according to the marked spots over the tendon surface. After fixation of the upper end of tendon with the clamps, we have put the calibration module in the upright position to relax the lower free end of the tendon followed by fixing it in the clamps as well. This procedure resulted in a tendon-clamp assembly presented in Fig 3.

Such prepared tendon-clamps assembly has been moved into the specially developed module, Fig. 4 and left 1 hour submerged in the Ringer´s solution for the testing temperature adjustment before the testing procedure.

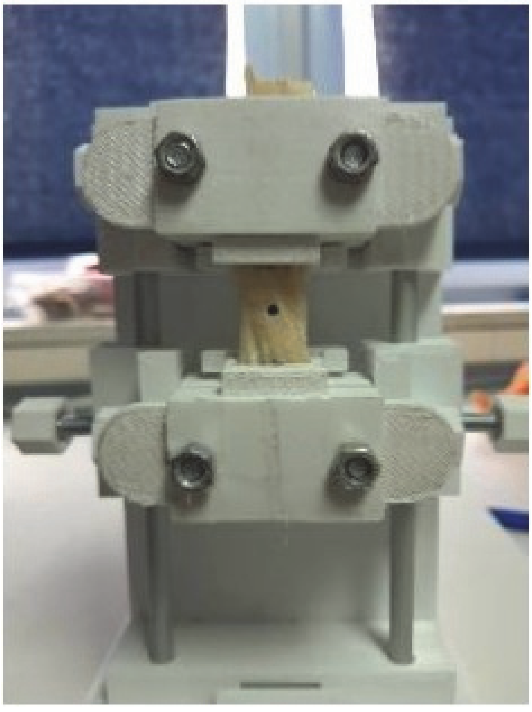


Figure 3 The tendon-clamps assembly

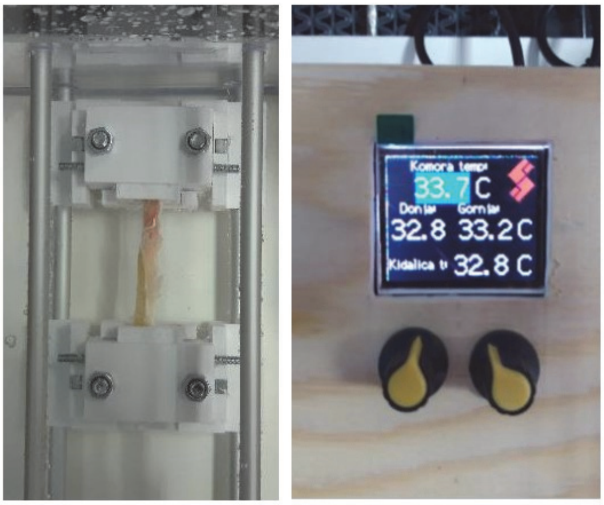


Figure 4 Tendon temperature adjustment submerged in the Ringer's solution

Tendons underwent a 10-cycle preload procedure from 0 to 10 N at a rate of 10 mm/min to minimize the effect of hysteresis on the biomechanical properties of the tendon, a phenomenon related to the orientation of molecules in connective tissue. The tendons were then subjected to a tensile test at a speed of 10 mm/min. Based on the obtained data, a force-elongation diagram or stress-strain diagram was generated and the following parameters were determined: maximum force (N), total elongation (mm), modulus of elasticity (MPa) measured in the range of 3 - 6% of deformation, tensile strength (MPa), total deformation (mm/mm) and stiffness (N/mm) Tab. 2.

The developed innovative testing module used for this study is presented below in Fig. 5.

Figure 5 Innovative testing module implemented in device workspace

The results obtained by measuring the biomechanical properties of the tendon were processed by the program Statistica for Windows 12.0. For descriptive statistics, the following parameters were calculated: arithmetic mean, standard deviation, minimum result, maximum result, reliability range. Student's *t*-test for independent samples was used to determine significant differences between the two groups of tendons and to compare with other studies.

3 DISCUSSION AND RESULTS

The following biomechanical properties were determined in this study conducted on 16 tendon samples, of which 8 were gracilis tendons and 8 quadriceps tendons. In the group of quadriceps tendon samples, the values of maximum force ranged from 610 N to 1009 N, which results in a statistically significant difference with the values of the maximum force of the gracilis tendon, whose values ranged from 422 N to 1024 N (difference −224,3 N, Student's *t*-test, p = 0,006). Elongation was also statistically significantly greater in the quadriceps tendon (elongation from 2,5 mm to 3,5 mm) (difference −0,43 mm. The following biomechanical properties were determined in this study conducted on 16 tendon samples, of which 8 were gracilis tendons and 8 quadriceps tendons. In the group of quadriceps tendon samples, the values of maximum force ranged from 610 N to 1009 N, which results in a statistically significant difference with the values of the maximum force of the gracilis tendon, whose values ranged from 422 N to 1024 N (difference −224,3 N, Student's *t*-test, p = 0,006). Elongation was also statistically significantly greater in the quadriceps tendon (elongation from 2,5 mm to 3,5 mm) (difference −0,43 mm, Student's *t*-test, p = 0,01) compared to the m. Gracilis tendon (range extensions from 2 mm to 3 mm).

Tensile strength is statistically significantly higher in the gracilis tendon (range 26 MPa to 92 MPa) compared to the quadriceps tendon (range 30 MPa to 44 MPa) (difference 19,9 MPa, Student's *t*-test, p = 0,03). The extensibility is significantly higher in the quadriceps tendon (range 10% to 15%) compared to the gracilis tendon (range 13% to 17%) (difference −2.2%, Student's *t*-test, p = 0,01). In stiffness (N/mm) there are no statistically significant differences between the groups of m. Gracilis and m. Quadriceps tendons. The modulus of elasticity is significantly higher in the tendon of the gracilis (range 235 MPa to 855 MPa) compared to the quadriceps tendon (range 239 MPa to 361 MPa) (difference 252,8 MPa, Student's *t*-test, p = 0,008) (Tab. 3., Fig. 6.). By comparing the biomechanical properties of the tendons of the m. Gracilis and m. Quadriceps with MPFL in individual variables, the m. Quadriceps are placed superior as the transplant selection. The MPFL stiffness values according to Crescenda et al. [29] are 42,5 ± 10,2 N/mm, and according to the research of Herbort et al. [12] shows very similar values of the quadriceps tendon 33,6 ± 6,8 N/mm, and compared to this study the values are lower for which as the main reason is the way of testing. In the same research conducted on a cadaver, it was found that stiffness and maximum force are two variables possible to compare the original MPFL with the reconstruction technique using the quadriceps tendon, but it is important to note that the sample width of 10 mm and 3 mm thick, its size ideally covers MPFL.

The tendon sample size of this study is shown in Tab. 1 on the basis of which the optimal quadriceps tendon sample is visible. It is important to note that certain comparisons with other research are sometimes not possible to establish precisely because of different procedures for testing biomechanical properties, whether it is an optical measurement system or completely mechanical, the type of tear, the angle of laying the tendon, the size of the tendon or knee complex. However, despite the differences in the testing process, the higher biomechanical potential of the quadriceps tendon can be seen concerning MPFL due to closer values of elongation (2,1 ± 0,8 mm), higher maximum values of force (205 ± 77,8) which confirms the research of Herbort et al. [12].

If we look at the quadriceps tendon from a broader perspective, its application has many positive outcomes in anterior cruciate ligament reconstruction and is also biomechanically superior to the Achilles tendon, also used in the reconstruction [21].

Given the available data on biomechanical properties published so far in the literature, comparing this reserch with data published in 2017 [22] (K. Smeets et al. Mechanical Analysis of extra-Articular Knee Ligaments/ The Knee), we observed significantly higher tensile strength in the tendon gracilis (Student's *t*-test, $p < 0,001$), and significantly lower values of the modulus of elasticity (Student's *t*-test, $p < 0,001$). Code t. quadriceps, in this study there were significantly lower values of extensibility ($p < 0,001$) and modulus of elasticity ($p = 0,02$), and significantly higher tensile strength ($p = 0,002$), compared to the observed study (Tab. 3). Of great importance is the fact obtained by the research of Smeets et al. [21] on how the hamstrings tendon groups have higher values of modulus of elasticity and tensile strength in contrast to the quadriceps tendon, but also others tested by this study. The fact that each tendon has different biomechanical properties determines the further course of reconstruction and rehabilitation. When comparing the results of these two studies, the big difference in the modulus of elasticity potentially lies in the position at which the parameters are tested since the mechanical properties of the tendons differ whether it is their starting point or grip. Most values increase as the distal part of the grip is approached. Smeets et al. [21] used the distal parts of the hamstrings in their study, while the quadriceps tendons were measured in the area of the central third. In contrast to their research, both tendons from the distal ends of the grip were used in this study. In part, it is possible to expect precisely because of these differences that there have been large differences in the achieved values of tensile strength and modulus of elasticity for the tendon gracilis. On the other hand, in a study by Smeets et al. [21] the values analyzed were persons with an average age of 82 years, in contrast to this study in which the average age of the subjects was 64 years. At the moment, we cannot know exactly how many years they have an impact because these are unknown values, but it is to be assumed that a certain significant effect also arises from the age of the respondents. Unlike other studies, the research by Noyes et al. [18] referred to the examination of a sample taken from the corpses of young people, and that of Butler et al. [17] examined a sample of young donors with an average age of 26 years, while all other studies based their research on the elderly population. Despite this, two studies [18 and 19] showed high tensile strength values, but while Noyes et al. [18] in their study obtained a statistically significant difference between the quadriceps and gracilis tendons, Mabe et al. [21] in their study did not obtain a statistically significant difference in tensile strength for the quadriceps tendon compared to the Achilles tendon, while the stiffness of 161 ± 48 N/mm is statistically significantly lower, but compared to this study still higher values of tendon stiffness quadriceps. In a study by Abramowitch et al. [20] with very similar results obtained for the tendon, gracilis came to one very interesting conclusion, and it refers to differences in biomechanical properties when testing the same tendon. That is, the results of this test indicated differences between testing the proximal and distal portions of the same tendon gracilis while comparing tensile strength. As in previous research, it is extremely difficult to relate the obtained value given that it is not a standardized way of testing biomechanical properties, but different, and this testing served as a pilot project for standardization of a new measuring instrument.

Table 2 Basic descriptive parameters of biomechanical properties of tendons gracilis and quadriceps with the value of the confidence interval and the magnitude of the error of the Student's *t*-test

	Arithmetic mean (standard deviation SD)		Divergence	95% CI		p* (*student *t*-test)
	Gracilis	Quadriceps		from	to	
Maximum force / N	563,9 (119,6)	788,3 (155,3)	−224,3	−373	−75,7	0,006
Extension / mm	2,45 (0,25)	2,90 (0,4)	−0,43	−0,77	−0,11	0,01
Tensile strength / MPa	55,9 (20,5)	36,0 (4,6)	19,9	2,68	37,2	0,03
Elongation / %	12,2 (1,2)	14,4 (1,8)	−2,2	−3,83	−0,54	0,01
Stiffness / N/mm	66,6 (23,0)	78,4 (17,5)	−11,9	−33,8	10,1	0,27
Elastic modulus / MPa	555,9 (226,6)	303,2 (35,1)	252,8	62,8	442,8	0,008

Table 3 Comparison of biomechanical properties of our research with similar ones from 2017

	Arithmetic mean (SD)		Divergency	95% CI		p*
	Our research	Previous research†		from	to	
Gracilis	$n = 8$	$n = 11$				
Tensile strenght / MPa	55,9 (20,5)	155 (30,7)	99,1	72,7	125,5	< 0,001
Extensibility / %	12,2 (1,2)	14,5 (3,1)	2,3	−0,2	4,8	0,06
Moule of elasticity / MPa	555,9 (226,6)	1458 (476)	902,1	517	1287	< 0,001
Quardiceps	$n = 8$	$n = 9$				
Tensile strenght / MPa	36,0 (4,6)	81 (27,6)	45	23,9	66,1	< 0,001
Extensibility / %	14,4 (1,8)	21,1 (6,8)	6,7	1,4	12	0,02
Modulus of elasticity / MPa	303,2 (35,1)	568 (194)	264,8	115,9	413,6	0,002

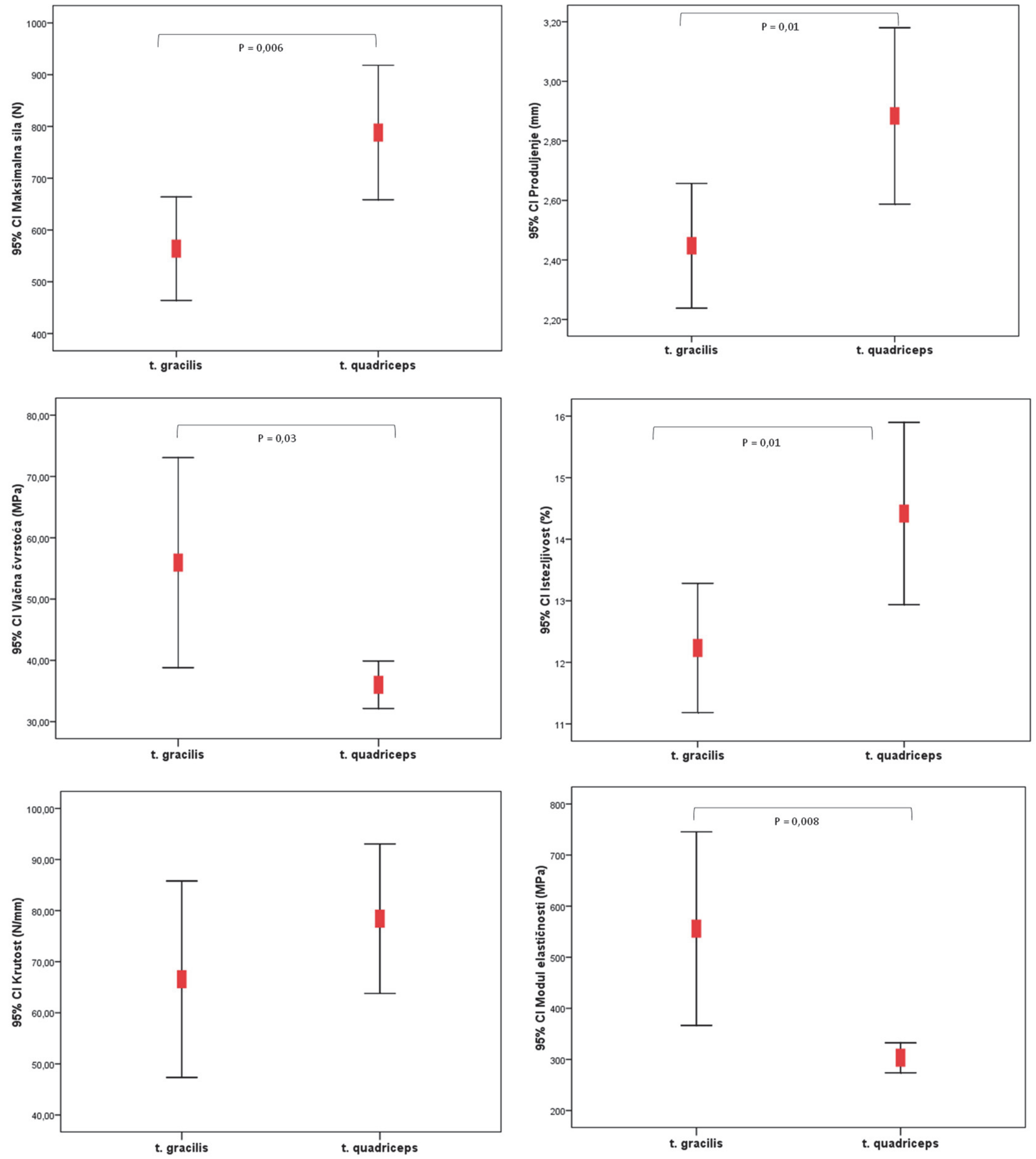


Figure 6 Graphical representation of biomechanical properties and differences of gracilis and quadriceps tendons

Table 4 Comparison of biomechanical properties of our research in relation to previous research

	n	Biomechanical properties (Mean (SD))		
		Modulus of elasticity / MPa	Tensile strength / MPa	Extensibility / %
Gracilis				
Noyes et al.	11	-	115,5 (4)	-
Handl et al.	7	-	95,1 (13,1)	-
Abramowitch et al.	10	625,5 (148)	63 (13,3)	13,6 (2,1)
Butler et al.	11	612,8 (40,6)	111,5 (4)	26,7 (1,4)
Smeets et. al.	11	1458 (476)	155 (30,7)	14,5 (3,1)
Our study	8	555,9 (226,6)	55,9 (20,5)	12,1 (1,2)
Quadriceps				
Noyes et al.	6	-	16,1 (1,8)	-
Mabe	9	153 (46)	19,1 (5,42)	16 (2)
Staubli et al.	8	462,8 (68,5)	38 (5)	11,2 (2,2)
Shani et.al.	12	255,3 (61,4)	23,9 (7,4)	10,7 (1,4)
Smeets et. al.	9	568 (194)	81 (27,6)	21,1 (6,8)
Our study	8	303,2 (35,1)	36,0 (4,6)	14,4 (1,8)

4 CONCULSION

Considering this study on a sample of 8 quadriceps tendons and 8 m. Gracilis tendons, the biomechanical properties of quadriceps tendons showed better biomechanical properties and closer values to the original mediopatellar ligament, which could have an impact when selecting transplants for its reconstruction.

Further research on a larger sample and with standardization of tendon preparation and setup into the machine grippers is certainly needed.

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