DOI: 10.37190/ABB-02396-2024-04

# Mechanical Properties of the Patellar Tendon in Weightlifting Athletes - the Utility of Myotonometry

## Adaptations of patellar tendon to mechanical loading

Sebastian Szajkowski[1], Jarosław Pasek[2*], Michał Dwornik[3], Grzegorz Cieślar[4]

[1]Faculty of Medical and Social Sciences, Warsaw Medical Academy of Applied Sciences, Warsaw
[2]Collegium Medicum im dr Władysława Biegańskiego; Jan Długosz University in Częstochowa, Częstochowa
[3]Center of Medical Rehabilitation and Osteopathy Rehapunkt, Piastów
[4]Department of Internal Medicine, Angiology and Physical Medicine, Faculty of Medical Sciences in Zabrze, Medical University of Silesia in Katowice, Bytom
[*]Corresponding author: Jarosław Pasek, Collegium Medicum im dr Władysława Biegańskiego. Jan Długosz University in Częstochowa, Częstochowa, e-mail address: jarus_tomus@o2.pl

**Submitted: 5th February 2024**
**Accepted: 3rd June 2024**

## Abstract

**Purpose:** Tendons adapt to loads applied to them, by changing their own mechanical properties. The purpose of the study was to examine the influence of practicing sport in the form of weightlifting/strength training by individuals of various age groups upon the mechanical properties of the patellar tendon.

**Methods:** 200 people participated in the study. Group 1 (n=109) comprised individuals training strength sports as amateurs, group 2 (n=91) consisted of people who were not physically active. The patellar tendon was examined in various positions of the knee joint: 0°, 30°, 60°, 90°, 120° respectively. The following mechanical parameters were measured with the use of a device for myotonometric measurements, MyotonPRO: frequency [Hz], stiffness [N/m], decrement [log], relaxation time [ms] and creep [De]. The results were compared as regards physical activity, training history, BMI value, and gender.

**Results:** Stiffness and tone increased while elasticity decreased with patellar tendon stretching degree. In the group of individuals in training, greater stiffness and tone and lower elasticity were noted. Moreover, stiffness and tone appeared to be higher in elderly people and individuals with longer training experience.

**Conclusions:** Mechanical loads connected with strength training result in development of adaptive changes in the patellar tendon, in the form of higher stiffness and tone, as well as lower elasticity. The MyotonPRO device is useful for quantitative assessment of the mechanical properties of patellar tendon.

**Key words:** patellar tendon, stiffness, mechanical properties, myotonometry, athletes



## Introduction

Tendons are connective tissue structures rich in collagen, responsible for effective transferring of forces from muscles to the skeleton. Their mechanical properties directly influence movement patterns. Factors such as: aging, refraining from use, or over-exploitation negatively affect the structure and mechanical features of tendons *(in vivo)*. Changing these properties can reduce the functional efficiency of the entire locomotor system. Regular loading of tendons protects connective tissue from the negative effects of aging and non-use, by increasing their tensile stiffness [16,17]. In the case of tendons, their morphology and functions are closely interdependent and therefore studying the mechanical properties of tendons can help us understand the underlying mechanisms of adaptation to mechanical loads. Research shows that different types of sports may have different effects on tendons. Training with high loads results in a more sustantial increase in tendon stiffness, compared to training with moderate loads, in case of middle age subjects [7,25]. However, studies assessing the effect of training length on tendon stiffness do not confirm an equally important effect in this respect as in the case of the volume of load. No significant effect has been found concerning the influence of duration of training on tendon stiffness after 18 months (elder adults) [13] or after 4 years (young adults) of training [29]. Thus, it seems that further research and studies are required, in order to determine the impact of long-term loads in strength training on the mechanical properties of tendons in individuals of different ages.

The main factor affecting the stiffness of the tendons during stretching is collagen type I, which makes up most of the tendon matrix. The results of previous studies suggest that the vast majority of collagen fibers constituting the tendon core is not renewed after the end of maturation period [39,40] Therefore, repeated training loads elicit adaptation mechanisms which depend on other molecular components of the matrix which, as a result, change the mechanical properties of the tendon [18]. Collagen crosslinks constitute a vital element of the matrix, which may have direct influence upon the change of mechanical properties of tendons, [37]. Stimulating action of resistance exercises upon the formation of those crosslinks has been demonstrated [41]. Moreover, collagen synthesis and turnover, increase in water binding proteins (e.g., proteoglycans) of the extra-cellular matrix, and enlarged collagen fibril diameter have been proposed as the underlying mechanisms that change tendons' structure and composition, following the application of different mechanical-loading stimuli [5,46]. Data from most *in vivo* studies show that human tendons become more stiff as a result of prolonged exposure to loads [1,19,48]. This remains a physiological adaptive change, provided it occurs without increasing the cross-sectional area (CSA) of the tendon, coexisting with/accompanied by a decrease in its echogenicity in ultrasound examination [21,32]. From the metabolic point of view, the elevated peritendon collagen synthesis typically observed with acute and chronic overloading [26] seems to be coordinated with myofibrillar protein and muscle collagen synthesis following one bout of exercise [6].

Tone and stiffness measurements are used for clinical evaluation of muscles and tendons. The values of those parameters change in the course of various pathological conditions. To assess the tone and stiffness of the tissue before implementing appropriate treatment, as well as to evaluate the effectiveness of treatment, palpation technique is often used [3,4]. Palpation techniques are widely criticized, due to their subjective limitations. In addition to these, shear wave elastography (SWE) is used in the assessment of mechanical properties of muscles and tendons [28,43]. Unfortunately, the cost of equipment used in this method is high and, in addition, specialist knowledge is required. Crucial for quantifying the mechanical properties of muscles and tendons in a fast and reliable way is the application of devices that are simple to use, portable, and relatively cheap. Such requirements are met by MyotonPRO device (Myoton AS, Tallinn, Estonia). Studies conducted previously have shown that this device is reliable in the assessment of mechanical properties of quadriceps femoris and patellar tendon. MyotonPRO has been demonstrated to be a reliable device for testing the tone and stiffness of the femoral quadriceps muscle and patellar tendon, at various angles of knee flexion, achieving excellent inter-operator reliability (intra class correlation coefficient - ICC>0.78) and good to excellent intra-operator reliability (ICC>0.41) [11,22,27,47]. Measurement results obtained in myotonometric test performed *in vivo* precisely determine the mechanical properties of tendons and muscles. They find application in both diagnosis and evaluation of treatment effects. They should also be used as input data for determining training programs and preventive actions. It is therefore important to establish normative data for myotonometric measurements by means of MyotonPRO.

The literature on the subject lacks studies that assess the mechanical properties of patellar tendon at different angles of knee flexion. So far, most of the research concerns the quadriceps femoris muscle, in addition using parameters measured only with knee joint fully extended [2,24]. For a reliable functional assessment, it is necessary to examine the patellar tendon at different levels of stretching. It remains unclear whether a stiffer tendon or a tendon more susceptible to deformation is beneficial in terms of physical fitness and whether it reduces the risk of an injury or development of degenerative changes. According to some authors, increasing tendon stiffness can be beneficial for strengths sports, and vice versa [7,35].

The aim of the study was to investigate the effect of strength training in people of different ages on the mechanical properties of patellar tendon. The hypothesis which was formulated assumed that in people undergoing training the obtained measurement results will be better, in comparison with physically inactive individuals, while the MyotonPRO device ensures proper reliability and high accuracy of measurements of mechanical properties of the tendon examined.

## Material and Methods

## Participants

The study comprised 200 participants (138 males and 62 females), their age range was 18-55 years (mean age: 32.04±9.47 years). The study subjects were divided into 2 groups. Group 1 (n=109; 87 males, mean age: 32.29±8.72 years and 22 females, mean age: 35.13±10.11 years) consisted of people training strength sports as amateurs, those sports included: weightlifting (n=25; 22,9%), powerlifting (n=38; 34,8%), and crossfit (n=46; 42.2%), for minimum 3 years, at least 3 times a week. Group 2 (n=91; 51 males, mean age: 29.76±8.83 years and 40 females, mean age: 32.67±10.62 years) was made up of physically inactive individuals, not practicing any sports. Only healthy individuals were included in the study. In the case of confirmation of orthopedic or neurological diseases, including previous surgical procedures, which may influence the mechanical properties of the patellar tendon, the affected participant was excluded from the study. The exclusion criteria also included the occurrence of pain in the lower limbs on the day of the examination, as well as lack of informed and voluntary consent to participate in the study.

## Demographics

Descriptive statistics of demographic data: age, training history, and Body Mass Index (BMI) for both groups of participants has been included in Table 1.

Table 1. General characteristics of study participants.

| | Group 1 – in training (n=109) | | | Group 2 – not in training (n=91) | | | p-value |
|---|---|---|---|---|---|---|---|
| | Mean ± SD | Min. | Max. | Mean ± SD | Min. | Max. | |
| Age (years) | 32.87 ± 9.14 | 18 | 55 | 31.04 ± 9.82 | 18 | 54 | 0.089 |
| Length of training history (years) | 7.71 ± 4.78 | 3 | 25 | N/A | N/A | N/A | N/A |
| Body Mass Index (BMI) ($kg/m^2$) | 26.76 ± 2.95 | 20.20 | 34.52 | 25.33 ± 3.97 | 18.78 | 34.72 | 0.071 |

## Measurements

Upon arrival at the examination site, participants rested at room temperature for a quarter of an hour. Measurements were made on a non-training day, as well as not on the day following the day of training. The study subjects were advised to refrain from physical exertion on the day before the examination and on the day of the examination. During the procedure, the subject was lying on her/his back. On the dominant limb, a point has been marked with a marker in the middle of the patellar tendon, mid-distance between the distal part of the patella and the tibial tuberosity, when the knee was bent at 90°, in accordance with measurement methodology [11]. The person performing the procedure passively bent the knee of the study subject and held the lower limb in a position at 0°, 30°, 60°, 90°, 120° of knee flexion/bending, consecutively. The foot was resting on the floor, and the hip joint was bent accordingly. The above setting arrangement ensured the stability of the lower limb. Each study subject was requested not to tighten her/his muscles. During the examination, the coefficient of variation (CV) of each test result was noted, and if the CV was more than 3%, the test was repeated once again. The average value of the two measurements was recorded and analyzed.

The hand-held probe of MyotonPRO device (Myoton AS, Tallinn, Estonia) was applied perpendicularly to the surface of the skin, following the projection of the previously marked point. The device automatically exerted preliminary pressure on the tissue examined, with the force of 0.18 N, and when the conditions for carrying out the correct measurement were complied with, it automatically generated 5 times a short mechanical impulse having the force of 0.4 N and duration of 15 ms. The accelerometer recorded oscillations of the examined tissue. The following were calculated: Frequency (F); [Hz], which characterizes tone; Stiffness (S); [N/m], indicating the ability of the tissue to resist an external force that modifies its shape; Decrement (D); [log], which characterizes elasticity (the ability of a muscle to recover its shape after being deformed, the lower its value the higher the elasticity. and the lower the damping of the tissue's oscillation); Relaxation time of mechanical stress (R); [ms], that is the time needed for a reference amount of deformation to occur under a reference load applied suddenly; the ratio of relaxation time to deformation time, characterizing creep (C); [Deborah number]. In more fluid-like materials, less time was required for flow (shorter relaxation time), resulting in a lower Deborah number. The criteria for the interpretation of outcomes were as follows: the higher the values of (F) and (S), the greater the tone and stiffness of tissue; the lower the value of (D), the lower/smaller the dissipation of mechanical energy during oscillation and the higher the elasticity of tissue; the lower the (R) and (C) values, the higher the tone or stiffness [33].

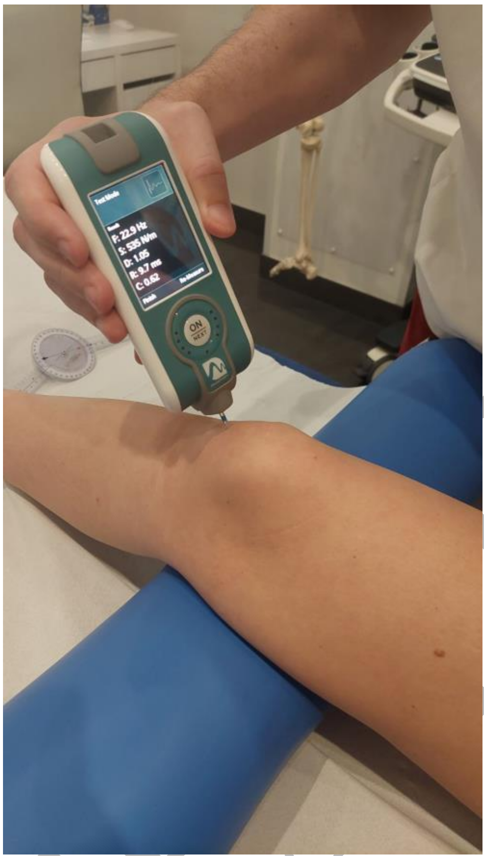

Figure 1. The MyotonPRO measurement technique.

All the measurements taken by means of MyotonPRO device and qualification for the study were performed by an experienced physiotherapist, trained in the field of myotonometry and performing scientific research.

The study was performed in the Didactic and Scientific Centre of Warsaw Medical Academy of Applied Sciences in Warsaw, Poland. The study was conducted in accordance with the Declaration of Helsinki (1964) and its protocol has been accepted by the Bioethics Committee at the Medical University of Mazovia in Warsaw, Poland (approval reference number: 2022/09/MUM-01).

**Statistical analysis**

Statistical analysis was performed with the use of Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). The consistency of variables with normal distribution was verified by means of the Shapiro-Wilk test. The comparison of independent samples of demographic data was performed using the Student's t-test. The statistical significance of differences between the 2 independent samples was tested using the Mann-Whitney U test and Kruskall-Wallis test in case of 3 independent samples. The results were considered statistically significant for $p<0.05$. The effect size (*r* for Mann-Whitney U test) was calculated, with $r$=0.1 indicating a small effect, $r$=0.3 indicating a medium effect, and $r$=0.5 indicating a large effect. The effect size ($\eta^2$ for Kruskall-Wallis test) was also calculated, with $\eta^2$=0.01 indicating a small effect, $\eta^2$=0.06 indicating a medium effect, and $\eta^2$=0.14 indicating a large effect.

## Results

### Differences in myotonometric parameters of patellar tendon at particular positions of knee joint.

The results of measurements of mechanical properties of patellar tendon in group 1 (n=109) and in group 2 (n=91) were compared in Table 2. The values of frequency (F), determining tissue tone, were higher in group 1 in comparison with group 2 in case of all 5 knee joint positions studied: 0º, 30º, 60º, 90º, and 120º of flexion. The highest difference in the average frequency between group 1 (42.09±6.59Hz) and group 2 (40.51±6.48Hz) was noted for knee flexion of 120°, whereas the smallest difference in the average frequency between group 1 (17.57±2.20Hz) and group 2 (17.08±1.90Hz) for knee flexion amounting to 0°, so for fully extended knee. This means that the tone of the patellar tendon has a growing trend along with the increasing degree of flexion, the differences between groups showed no statistical significance ($p>0.05$).

The values of stiffness (S) were higher in group 1 in comparison with group 2 for all the examined positions of the knee, as well. The most profound difference in mean stiffness values between group 1 (1014.69±178.71 N/m) and group 2 (996.64±151.60 N/m) was recorded for the knee flexion of 120°, with the least significant difference in mean stiffness between the group 1 (327.30±93.19 N/m) and group 2 (319.82±84.16 N/m) recorded for knee flexion of 0°, that is for fully extended knee. This means that the stiffness of the patellar tendon tends to increase with the increasing degree of flexion, with differences between groups showing no statistical significance ($p>0.05$).

Thus, both the values of frequency (F), which determine tone, and the values of stiffness (S) of patellar tendon increased with the stretching of the patellar tendon and decreased as it contracted.

The values of decrement (D), inversely describing flexibility, were higher in group 1 in comparison with group 2, for all the examined positions of the knee, as well. As in the case of tone and stiffness, the values of decrement (D) increased with increasing angle of knee flexion (from 0° to 120°). The most profound difference in the mean value of decrement between group 1 (1.10±0.18 log) and group 2 (1.08±0.19 log) was recorded for the knee flexion of 120°, with the least difference in mean decrement values between group 1 (0.79±0.15log) and group 2 (0.76±0.15log) for the flexion angle of 0°. This means that the elasticity of the patellar tendon decreases with the increase in the angle of knee flexion, with differences in the mean value of decrement (D) between groups, demonstrating statistical significance in case the knee flexion angle amounting to 30° ($p=0.044$) and 90° ($p=0.033$).

The highest values of relaxation time (R) were observed for the position of 0° knee flexion. The values of relaxation time (R) in both groups showed decreasing tendency following the increasing degree of knee flexion – from 16.45±3.34 ms in group 1 and 16.50±3.46 ms in group 2 for the knee flexion angle of 0°, to the mean value of 6.01±1.06 ms in group 1 and 6.14±0.94 ms in group 2 for the knee flexion angle of 90°, with differences between groups showing no statistical significance ($p>0.05$).

The values of creep (C) in both groups showed a decreasing tendency, as the degree of knee flexion increased – from the mean value of Deborah No. of 1.00±0.18 in group 1 to Deborah No. of 0.99±0.17 in group 2 for 0° of knee flexion, and from the mean value of Deborah No. of 0.42±0.09 in group 1 to Deborah No. of 0.43±0.08 in group 2 for the knee flexion of 90°, with differences between groups showing no statistical significance ($p>0.05$).

Table 2. The results of measurements of all parameters recorded by MyotonPRO device in specific positions of knee joint in group 1 and group 2.

| | Group 1 – in training (n=109) | Group 2 – not in training (n=91) | | | |
|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 0° [Hz] | 17.57 ±2 .20 | 17.08 ± 1.90 | 0.24 | (-0.04, 0.52) | 0.150 |
| F 30° [Hz] | 22.61 ± 2.64 | 22.09 ± 2.52 | 0.20 | (-0.08, 0.48) | 0.266 |
| F 60° [Hz] | 25.09 ± 3.06 | 24.62 ± 2.58 | 0.16 | (-0.11, 0.44) | 0.540 |
| F 90° [Hz] | 31.67 ± 4.80 | 30.45 ± 3.87 | 0.28 | (0.00, 0.56) | 0.086 |
| F 120° [Hz] | 42.09 ± 6.59 | 40.51 ± 6.48 | 0.24 | (-0.04, 0.52) | 0.081 |
| S 0° [N/m] | 327.3 ± 93.2 | 319.8 ± 84.2 | 0.08 | (-0.19, 0.36) | 0.589 |
| S 30° [N/m] | 585.8 ± 98.2 | 577.1 ± 89.0 | 0.09 | (-0.19, 0.37) | 0.975 |
| S 60° [N/m] | 703.0 ± 97.0 | 700.4 ± 103.7 | 0.03 | (-0.25, 0.30) | 0.638 |
| S 90° [N/m] | 868.6 ± 108.0 | 865.2 ± 96.2 | 0.03 | (-0.25, 0.31) | 0.626 |
| S 120° [N/m] | 1014.7 ± 178.7 | 996.6 ± 151.6 | 0.11 | (-0.17, 0.39) | 0.974 |
| D 0° [log] | 0.79 ± 0.15 | 0.76 ± 0.15 | 0.20 | (-0.08, 0.48) | 0.191 |

| | | | | | |
|---|---|---|---|---|---|
| D 30° [log] | 0.94 ± 0.29 | 0.87 ± 0.32 | 0.23 | (-0.05, 0.51) | 0.033 |
| D 60° [log] | 0.96 ± 0.15 | 0.92 ± 0.14 | 0.27 | (-0.01, 0.55) | 0.110 |
| D 90° [log] | 1.03 ± 0.15 | 0.99 ± 0.15 | 0.27 | (-0.01, 0.55) | 0.044 |
| D 120° [log] | 1.10 ± 0.18 | 1.08 ± 0.19 | 0.11 | (-0.17, 0.39) | 0.329 |
| R 0° [ms] | 16.45 ± 3.34 | 16.50 ± 3.46 | 0.01 | (-0.26, 0.29) | 0.912 |
| R 30° [ms] | 9.07 ± 1.43 | 9.46 ± 1.76 | 0.25 | (-0.03, 0.52) | 0.290 |
| R 60° [ms] | 7.63 ± 1.21 | 7.69 ± 1.23 | 0.05 | (-0.23, 0.33) | 0.928 |
| R 90° [ms] | 6.01 ± 1.06 | 6.14 ± 0.94 | 0.13 | (-0.15, 0.41) | 0.333 |
| R 120° [ms] | 6.32 ± 1.45 | 6.42 ± 1.48 | 0.07 | (-0.21, 0.35) | 0.816 |
| C 0° [Deborah No.] | 1.00 ± 0.18 | 0.99 ± 0.17 | 0.06 | (-0.22, 0.34) | 0.478 |
| C 30° [Deborah No.] | 0.58 ± 0.08 | 0.61 ± 0.10 | 0.33 | (-0.05, 0.61) | 0.131 |
| C 60° [Deborah No.] | 0.50 ± 0.07 | 0.51 ± 0.08 | 0.13 | (-0.15, 0.41) | 0.399 |
| C 90° [Deborah No.] | 0.42 ± 0.09 | 0.43 ± 0.08 | 0.12 | (-0.16, 0.39) | 0.243 |
| C 120° [Deborah No.] | 0.55 ± 0.24 | 0.57 ± 0.24 | 0.08 | (-0.20, 0.36) | 0.986 |

Results of myotonometric measurements taken in both groups – individuals in training and not in training – have been compared in sub-groups, taking the following into account: age, BMI, and length of training experience, as well as gender.

The assessment of the influence of the age of subjects in training and not in training upon the results of myotonometric measurements revealed that in the group of subjects in training, in the age range of: 31-55 years (n=59) the values of tone, stiffness and decrement for patellar tendons were higher, whereas the values of relaxation an creep were lower, in comparison with the group of subjects in training, in the age range of: 18-30 years (n=50), throughout the range of knee flexion angles examined (from 0° to 120°), while the observed differences showed statistical significance for most parameters and knee positions presented in Table 3.

Table 3. The results of measurements of parameters recorded by MyotonPRO device in group 1, with regard to age range: 18-30 years vs. 31-55 years – only statistically significant differences are included.

| | Age 18-30 years (n=50) | Age 31-55 years (n=59) | | | |
|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 0° [Hz] | 16.96 ± 2.03 | 18.09 ±2.21 | 0.53 | (-0.14, 0.91) | 0.002 |
| S 0° [N/m] | 308.9 ± 100.5 | 342.9 ± 84.3 | 0.37 | (-0.01, 0.75) | 0.003 |
| D 0° [log] | 0.79 ± 0.16 | 0.80 ± 0.14 | 0.07 | (-0.31, 0.44) | 0.012 |
| R 0° [ms] | 17.25 ± 3.44 | 15.76 ± 3.12 | 0.46 | (0.07, 0.83) | 0.021 |
| F 30° [Hz] | 21.43 ± 1.99 | 23.62 ± 2.72 | 0.91 | (-0.51, 1.30) | <0.001 |
| S 30° [N/m] | 557.0 ± 91.21 | 610.3 ± 98.11 | 0.56 | (-0.17, 0.94) | 0.002 |
| R 30° [ms] | 9.52 ± 1.45 | 8.69 ± 1.30 | 0.61 | (0.22, 0.99) | 0.003 |
| C 30° [Deborah No.] | 0.61 ± 0.09 | 0.56 ± 0.07 | 0.63 | (0.24, 1.01) | 0.002 |
| F 60° [Hz] | 23.69 ± 2.16 | 26.28 ± 3.22 | 0.93 | (-0.53, 1.32) | <0.001 |

| | | | | | |
|---|---|---|---|---|---|
| S 60° [N/m] | 664.3 ± 90.2 | 730.9 ± 105.3 | 0.67 | (-0.28, 1.06) | 0.001 |
| R 60° [ms] | 8.03 ± 1.13 | 7.29 ± 1.18 | 0.64 | (0.25, 1.02) | 0.002 |
| C 60° [Deborah No.] | 0.52 ± 0.07 | 0.48 ± 0.07 | 0.57 | (0.18, 0.95) | 0.002 |
| F 90° [Hz] | 30.14 ± 3.11 | 32.96 ± 5.58 | 0.61 | (-0.22, 0.99) | 0.016 |
| F 120° [Hz] | 40.60 ± 5.63 | 43.36 ± 7.11 | 0.43 | (-0.04, 0.80) | 0.042 |
| S 120° [N/m] | 967.5 ± 141.6 | 1054.7 ± 197.4 | 0.50 | (-0.11, 0.88) | 0.012 |

On the other hand, in case of subjects not in training and in the age range of 31-55 years (n=37), the values of tone, stiffness, and decrement for patellar tendons were higher, whereas the values of relaxation an creep were lower than in the group of subjects not in training, in the age range of 18-30 years (n=54), practically speaking (with the exception of one measurement of decrement in case of knee flexion of 30°), unlike the case of subjects in training, where the observed differences showed statistical significance only in the knee flexion position of 0°, that is with the knee extended (Table 4).

Table 4. The results of measurements of parameters recorded by MyotonPRO device in group 2, with regard to age range: 18-30 years vs. 31-55 years – only statistically significant differences are included.

| Parameter | Age: 18-30 years (n=54) | Age: 31-55 years (n=37) | | | |
|---|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 0° [Hz] | 16.31 ± 1.75 | 18.20 ± 1.54 | 0.13 | (-0.28, 1.55) | <0.001 |
| S 0° [N/m] | 282.5 ± 70.7 | 374.3 ± 72.1 | 0.29 | (-0.82, 1.73) | <0.001 |
| D 0° [log] | 0.77 ± 0.16 | 0.75 ± 0.14 | 0.13 | (-0.29, 0.55) | <0.001 |
| R 0° [ms] | 18.09 ± 3.15 | 14.19 ± 2.45 | 0.35 | (-0.88, 1.80) | <0.001 |
| C 0° [Deborah No.] | 1.06 ± 0.16 | 0.88 ± 0.13 | 0.21 | (-0.75, 1.65) | <0.001 |
| D 30° [log] | 0.88 ± 0.34 | 0.86 ± 0.31 | 0.06 | (-0.36, 0.48) | 0.015 |

The assessment of the influence exerted by the value of BMI upon the results of myotonometric measurements indicated that in group 1 – subjects in training, with increase in BMI, the value of tone, stiffness and decrement for patellar tendon increased, the value of relaxation decreased, with changeable direction of changes in case of creep values, while the observed differences showed statistical significance solely in case of the knee flexion angle of 0°, that is for knee fully extended (Table 5).

Table 5. The results of measurements of parameters recorded by MyotonPRO device in group 1, with regard to BMI range: 18.50-24.99 kg/m² vs.25.00-29.99 kg/m² vs. 30.00-34.99 kg/m² – only statistically significant are included.

| | BMI 18.50-24.99 kg/m² (n=30) | BMI 25.00-29.99 kg/m² (n=67) | BMI 30.00-34.99 kg/m² (n=12) | | | |
|---|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 0°[Hz] | 17.16 ± 2.13 | 17.41 ±.1.98 | 19.50 ± 2.68 | 0.068 | (0.000, 0.293) | 0.010 |
| S 0°[N/m] | 308.9 ± 89.8 | 321.8 ± 76.9 | 404.2 ± 144.9 | 0.058 | (0.000, 0.287) | 0.016 |
| D 0°[log] | 0.78 ± 0.17 | 0.80 ± 0.14 | 0.81 ± 0.13 | 0.049 | (0.000, 0.268) | 0.027 |
| R 0°[ms] | 16.86 ± 3.56 | 16.74 ± 3.02 | 13.78 ± 3.55 | 0.046 | (0.000, 0.265) | 0.032 |
| C 0°[Deborah No.] | 1.01 ± 0.18 | 1.02 ± 0.17 | 0.85 ± 0.20 | 0.044 | (0.000, 0.252) | 0.035 |

On the other hand, in group 2 – subjects not in training, the values of BMI had no significant influence upon the values of myotonometric measurements taken.

The evaluation of the impact of training experience on the results of myotonometric measurements showed that in subjects in training the values of tone, stiffness, and decrement for patellar tendons increased when the training experience was longer. The highest values of specific parameters were most frequently noted in case of the second range of training history: 6-10 years. The observed differences showed statistical significance for knee flexion positions from 0° to 90° (Table 6).

Table 6. The results of measurements of parameters recorded by MyotonPRO device in group 1, with regard to length of training history: 3-5 years vs. 5.5-10 years vs. group 1 and vs. 11-25 years – only statistically significant differences are included.

| | Length of training | Length of training | Length of training history | | | |
|---|---|---|---|---|---|---|

| | history 3-5 years (n=47) | history 6-10 years (n=41) | 11-25 years (n=21) | | | |
|---|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 0°[Hz] | 16.96 ± 1.52 | 18.13 ± 2.62 | 17.87 ± 2.32 | 0.032 | (0.000, 0.241) | 0.048 |
| S 0°[N/m] | 302.5 ± 74.5 | 344.9 ± 110.2 | 348.5 ± 85.3 | 0.061 | (0.000, 0.289) | 0.014 |
| D 0° [log] | 0.78 ± 0.16 | 0.81 ± 0.16 | 0.79 ± 0.10 | 0.09 | (0.000, 0.041) | 0.001 |
| F 30°[Hz] | 21.83 ± 2,02 | 23.17 ± 2.68 | 23.26 ± 3.39 | 0.041 | (0.000, 0.212) | 0.041 |
| F 60°[Hz] | 24.13 ± 2.44 | 25.84 ± 3.01 | 25.8 ± 3.86 | 0.035 | (0.000, 0.244) | 0.038 |
| S 60°[N/m] | 672.9 ± 101.9 | 726.1 ± 93.7 | 711.8 ± 115.4 | 0.037 | (0.000, 0.253) | 0.049 |
| F 90°[Hz] | 29.46 ± 3.17 | 33.85 ± 5.36 | 32.37 ± 4.72 | 0.12 | (0.031, 0.419) | <0.001 |
| S 90°[N/m] | 826.6 ± 104.5 | 910.1 ± 93.9 | 881.4 ± 111.4 | 0.095 | (0.000, 0.308) | 0.001 |

The assessment of the influence of gender of subjects in training and not in training upon the results of myotonometric measurements performed revealed the in group 1 – males in training, the values of tone, stiffness for patellar tendons were higher than in the group of females in training, whereas the observed differences showed statistical significance only in the knee flexion angles of 90° and 120°, when the patellar tendon was most extended (Table 7)

Table 7. The results of measurements of parameters recorded by MyotonPRO device in group 1, with regard to gender: female vs. male – only statistically significant differences are included.

| | Female (n=22) | Male (n=87) | | | |
|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 90° [Hz] | 29.51 ± 4.51 | 32.22 ± 4.75 | 0.58 | (-0.10, 1.05) | 0.004 |
| S 90° [N/m] | 819.3 ± 105.2 | 881.0 ± 105.7 | 0.58 | (-0.11, 1.05) | 0.020 |
| F 120° [Hz] | 38.67 ± 8.63 | 42.96 ± 5.71 | 0.67 | (-0.19, 1.14) | 0.011 |

On the other hand, in case of group 2 - males not in training, the values of tone and stiffness of tendons were higher, whereas the values of relaxation and creep were lower, in comparison with females not in training, and the observed differences showed statistical significance only for the knee flexion angle of 90° (Table 8).

Table 8. The results of measurements of parameters recorded by MyotonPRO device in group 2, with regard to gender: female vs. male – only statistically significant differences are included.

| | Group 2 – not in training and female (n=40) | Group 2 – not in training and male (n=51) | | | |
|---|---|---|---|---|---|
| Parameter | Mean ± SD | Mean ± SD | Effect Size | 95% CI | p-value |
| F 90° [Hz] | 29.84 ± 4.53 | 30.93 ± 3.22 | 0.28 | (-0.14, 0.70) | 0.038 |
| S 90° [N/m] | 836.2 ± 101.4 | 888.0 ± 86.3 | 0.56 | (-0.13, 0.97) | 0.010 |
| R 90° [ms] | 6.41 ± 0.94 | 5.93 ± 0.89 | 0.53 | (0.10, 0.94) | 0.014 |
| C 90° [Deborah No.] | 0.44 ± 0.08 | 0.41 ± 0.07 | 0.40 | (-0.02, 0.82) | 0.019 |

## Discussion

Key findings concerning the mechanical properties of patellar tendons obtained by myotonometric measurements taken in course of the study reported here were as follows: the values of both tone and stiffness of the patellar tendon were higher while flexibility was lower in the group of subjects in training. Tone and stiffness increased, while elasticity decreased with increase in the degree of stretching of the patellar tendon. According to our observations and literature data, such characteristics of the results of measurements reflect the adaptive changes of connective tissue to prolonged, repeated mechanical loads [14,31,42], in this case in the form of strength training. Some time is required for those changes to develop, which finds confirmation in the results obtained by us, that showed that the characteristics of studied parameters described above was found significantly more often in people training in elderly age and with longer training experience. Strength training also resulted in the development of better mechanical properties of the patellar tendon, confirmed by changes in myotonometric parameters, which were observed for the entire range of knee flexion studied, from 0° to 120°. For the sake of comparison, in subjects that were not physically active, the desirable mechanical features such as: substantial stiffness and tone values were observed only when the knee was fully extended. On the other hand, extending the patellar tendon as the knee flexion increased led to disturbing its proper biomechanics, i.e., stiffness did not increase linearly, and elasticity did not decrease. This is an indication of inferior structural and functional condition of the tendon, possibly as a result of lack of stimulation of fibroblasts by mechanical load in the form of training [14,36].

MyotonPRO is an innovative device consisting of a three-axis accelerometer and a stability enhancing system, which allows for making multidirectional measurements in relation to the gravity vector. The values of ICC may be related to the subcutaneous fat content within the knee joint [11]. When the knee joint is extended, the accumulated subcutaneous fat can affect the measurements of loose patellar tendon. When the angle of flexion reaches 90°, and the patellar tendon tightens, subcutaneous fat has little effect on the measurements obtained. According to the value of ICC, the best angle at which to measure the mechanical properties of patellar tendon is 90°. The average values of tone obtained by the authors of study [11] amounted to: 14.4 Hz for 0°, 16.9 Hz for 30°, 21.0 Hz for 60°, and 24.1 Hz for 90°, while the mean values of stiffness amounted to: 223.1 N/m for 0°, 387.2 N/m for 30°, 612.1 N/m for 60°, and 703.1N/m for 90°. Compared to our results, the average values of tone and stiffness for each knee flexion degree were lower, despite the fact that measurements were taken in the same position as in our study. These differences result from different characteristics of the research group. This study included only people who did not practice sports, and who were from the age range of 20-30 years. The results of the above study confirm our observations regarding the increasing value of tone and stiffness of the patellar tendon with increasing values of knee flexion angles. In our study, elasticity was additionally assessed by measuring the values of decrement, and it was demonstrated that elasticity diminishes as stiffness and tone increase. Such behaviour of mechanical parameters during patellar tendon stretching was related to the entire range of knee flexion: 0°-120°.

In another study, the mechanical properties of patellar tendons were assessed in track cyclists, with the use of ultrasonography and myotonometry [23]. Significantly higher values of patellar tendon stiffness were observed in sprinters, as compared to individuals practicing endurance sports. The differences concerned measurements performed before and immediately after physical exertion/exercise. Moreover, the difference between post- and pre-stiffness was more substantial after sprint, in comparison with long-distance cycling, which confirms that the effort of a strength-oriented nature resulted in a greater increase of stiffness, as well as tendon thickness assessed by means of ultrasonographic examination. Larger differences in the thickness of the tendon after and before the sprint, that is strength-oriented effort can be related to changes in intratendinous fluid, because short intense effort results in alterations in tendon fluid, which are the most commonly theorized mechanisms for short-term changes in tendon size or shape *in vivo*, matching those directly measured *in vitro*. Moreover, increased tendon glycosaminoglycan content in tendinopathy, causing increased binding of water, may provide some explanation for the changes in fluid metabolism [30], and greater vascularization of tendons [45].

In case of strength-related efforts after many years of training history and, what is connected with it in case of elderly subjects, in assessing the mechanical properties of the tendon, changes in connective tissue should be taken into account, e.g. migration of fibroblasts, activity of myo-fibroblasts, and synthesis of collagen, which translates into an adaptive increase of tendon stiffness [20,36]. In our study, in elderly people as compared to younger people in training, higher stiffness was observed for the entire range of knee flexion: 0°-120°. In the studies conducted so far [22,34] it has also been proven that stiffness increases linearly with increasing tendon tone, which has been confirmed by the results of our study, too. Increase in tone with simultaneous decrease in elasticity immediately after strength training occurs mainly as a result of glycogen depletion and increased production of lactic acid and hydrogen ions [22]. In turn, Freedman et al. as well as Chainani et al. demonstrated the effect of tendon micro-injuries on its stiffness. The degenerative model assumes a decrease in stiffness in the long-term after-exertion phase, causing an increase in plastic deformation and fibers redistribution loads from damaged tissue, which can be observed in case of tendinopathy [10,15].

Higher stiffness of the patellar tendon was found, as was in our study, also in case of professional dancers, compared with healthy individuals not in training [47]. This phenomenon is consistent with the adaptation of the tendon to loads. The tendon was examined at the knee flexion angle of 90°. The mean value of stiffness for this knee position was 1045±202 N/m vs. 868.58±108.01 N/m in case of our study. The difference may be due to a different position in which the measurements were taken. The dancers were examined in a sitting position, with lower leg/shin hanging loosely outside the couch, and foot not fully supported on the floor. The patellar tendon thus could have been gravitationally loaded in the direction of further stretching, resulting in higher stiffness values. In our study, similar values of stiffness, namely 1014.69±178.71 N/m, were observed only for the knee flexion of 120°.

In yet another study, the patellar tendon was examined, as in the above-cited study, in knee flexion angle of 90° with lower leg/shin hanging loosely outside the couch, and foot not fully supported on the floor. The value of stiffness thus obtained was 1138.0±215.5 N/m, that is, much higher than in our study for the same angle of knee flexion, but with the lower limb not loaded and stabilized. Interestingly, higher stiffness values amounting to 897.7±190.1 N/m, in comparison to our results, were also obtained by researchers in the control group in healthy individuals who did not practice sports [12].

In the study reported by Bravo-Sánchez et al. [9], mechanical properties of patellar tendons were evaluated in badminton players, for the knee flexion up to 15° and limb not loaded. The obtained values of stiffness: 515.13±180.50 N/m, tone: 20.45±4.19 Hz, and decrement: 0.88±0.11 log, turned out to be higher than the respective values measured in our study for the knee flexion of 0° and lower than those measured for the knee flexion of 30°. This confirms the importance of the specific position in which myotonometric measurements are performed for ensuring the comparability of results of individual studies.

When tendons are adapted to mechanical loads, they show modifications in their structures and functions. Adaptive changes may develop after weeks or years of training, as shown in available studies. After 12 weeks of training with loads applied, the tendon becomes stiffer, and thus the adaptive change on the reflex pathway occurs, which affects its function, i.e. the mechanical properties are changed. On the other hand, the structure (i.e., cross sectional area) remains unchanged because the time of exposure to the stimulus was too short [7,46]. It has also been demonstrated that increased cross-sectional area (CSA), which is a morphological change, is responsible for the increase in tendon stiffness in response to long-term strength training, lasting for years. This explains why people who practice strength sports for at least 3 years, which was an inclusion criterion for our study, had greater stiffness of the patellar tendon in all the examined knee flexion positions [7,8,46].

The results of the study performed by Sohirad et al. with the application of myotonometry confirm our observations pertaining to greater tendon stiffness in men as compared to women [38]. That is also confirmed by the results of studies with the application of Shear Wave Elastography (SWE) [44]. Another study also revealed that muscle and tendon stiffness increased during adolescence [27].

Our research demonstrated that increase of BMI did not cause increase in tone and stiffness in the training population, nor did it result in reduction of elasticity during extending the patellar tendon for knee flexion angles from 30° to 120°. On the other hand, in case of subjects who were not in training, no significant effect of BMI value on the values of measured myotonometric parameters was observed throughout the examined flexion angle range of 0°-120°. No studies were found which would assess the influence of BMI on mechanical parameters of patellar tendon, yet the study with the use of SWE showed that the stiffness of the patellar tendon was lower in obese people, when compared to people with normal body weight [44]. In addition, the study also revealed a negative and weak correlation between BMI and stiffness, as well as negative and moderate correlation between fat content and stiffness of patellar tendon. This is confirmed by the results of another study with the use of SWE, in which no significant differences were found in athletes as regards the stiffness of the patellar tendon as depending on BMI value [35].

To sum up, myotonometry can be successfully used to assess the impact of physical activity on the condition of muscles and tendons in people of different ages. Monitoring potential tissue overload by using myotonometry is important for assessing the risk of injury and managing training and rehabilitation. It constitutes a valuable supplement to imaging techniques applied for examination of the locomotor system, due to the possibility of quantitative assessment of the mechanical properties of tendons. Deviations from norms may indicate a preclinical phase of tendinopathy, which may not be detected at an early stage of diagnostic imaging. However, this method still requires standardization of measurement methodology. The results obtained by us are a contribution to the determination of reference values for the future.

**Conclusions**

The study reported here investigated the mechanical properties of patellar tendons in people practicing strength sports and physically inactive people of different ages. The hypothesis assuming that better results will be obtained in people actively practicing sports has been partly confirmed. High tone and stiffness and low elasticity of tendon are desirable mechanical properties for weightlifters. The adaptive response of connective tissue to mechanical loading includes an increased synthesis and turnover of matrix proteins, including the collagen. The tendons respond to chronic resistance by increasing diameter of collagen fibrils and fibril packing density. In case of subjects in training, tone and stiffness of the patellar tendon were higher, and its elasticity was lower, as compared to subjects not in training, for the entire range of knee flexion angles (0-120°). People in training, who were of older age and had longer training experience had higher values of tone and stiffness of patellar tendon, as well as lower flexibility, for the entire examined range of knee joint movement (0-120°). People who were not training recorded such characteristics of mechanical parameters only for extended knee joint (0° flexion angle). In case of people in training, increased BMI did not result in higher tone and stiffness of the patellar tendon, with lower elasticity in a position other than the fully extended knee joint (0° of flexion). The values of tone and stiffness were higher in males than in females, regardless the training status, yet the above was true only for the knee flexion angle of 90°. As the patellar tendon extended, its tone and rigidity increased, while elasticity decreased.

The results of the conducted research confirmed the hypothesis that myotonometry can be used in the quantitative assessment of mechanical properties of patellar tendon in people of various ages, because it ensures high accuracy and repeatability of measurements. When used in the course of physical examination, it may supplement and, where justified, replace the subjective method of palpation. Our study is a contribution to the establishment of reference values in the field of myotonometry of patellar tendon for healthy people of various ages, practicing sports as amateurs, as well as for people not practicing any form of physical exercises.

**Study Limitations and Strengths**

The study reported here has certain limitations. Mechanical properties of the tendon were examined only in case of passive movement. The body composition of the people participating in the study has not been studied – therefore, it is not known to what extent dry muscle mass was responsible for the higher BMI index. No ultrasound examination was performed, which could exclude a person with asymptomatic tendinopathy from the study.

The strengths of the work include the homogeneity of the group of people practicing sports. All study subjects trained strength sports in official/affiliated clubs, which ensures high repeatability of the type of physical exercises practiced. All measurements were performed by one person, trained and experienced in the field of methodology of studies involving the use of myotonometry.



**Ethics statement**

The study was performed in the Didactic and Scientific Centre of Warsaw Medical Academy of Applied Sciences in Warsaw, Poland. The study was conducted in accordance with the Declaration of Helsinki (1964) and its protocol has been accepted by the Bioethics Committee at the Medical University of Mazovia in Warsaw, Poland (approval reference number: 2022/09/MUM-01).

**Author Contribution's**

SSz – study design, data collection, data interpretation, manuscript preparation, literature search
JP – study design, data collection, manuscript preparation, literature search
MD – data collection, manuscript preparation
GC – data interpretation, manuscript preparation

**Acknowledgements**

Not applicable

**References**

1. ADAM N.C., SMITH C.R., HERZOG W., AMIS A.A., ARAMPATZIS A., TAYLOR W.R. *In Vivo Strain Patterns in the Achilles Tendon During Dynamic Activities: A Comprehensive Survey of the Literature.* Sports Med Open, 2023, 9(1), 60. doi: 10.1186/s40798-023-00604-5.
2. AGYAPONG-BADU S., WARNER M., SAMUEL D., STOKES M. *Measurement of ageing effects on muscle tone and mechanical properties of rectus femoris and biceps brachii in healthy males and females using a novel hand-held myometric device*. Arch Gerontol Geriatr, 2016, 62, 59-67. doi: 10.1016/j.archger.2015.09.011
3. ALVAREZ-DIAZ P., ALENTORN-GELI E., RAMON S., MARIN M., STEINBACHER G., BOFFA J.J. et al. *Effects of anterior cruciate ligament injury on neuromuscular tensiomyographic characteristics of the lower extremity in competitive male soccer players. Knee surgery, sports traumatology, arthroscopy*. Official journal of the ESSKA, 2016, 24(7), 2264-70. doi: 10.1007/s00167-014-3319-4
4. BIALAS P., GRONWALD B., ROLOFF K., KREUTZER S., GOTTSCHLING S., WELSCH K., et al. *Pain in tones - Is it possible to hear the pain quality? A pilot trial.* Patient education and counseling. 2019, 102(1), 134-8. doi. 10.1016/j.pec.2018.08.017
5. BENAGE L.G., SWEENEY J.D., GIERS M.B., BALASUBRAMANIAN R. *Dynamic Load Model Systems of Tendon Inflammation and Mechanobiology*. Front Bioeng Biotechnol, 2022, 15, doi: 10.3389/fbioe.2022.896336

6. BERSINER K., PARK S.Y., SCHAAF K., YANG W.H., THEIS C., JACKO D. et al. *Resistance exercise: a mighty tool that adapts, destroys, rebuilds and modulates the molecular and structural environment of skeletal muscle*. Phys Act Nutr, 2023, 27(2), 78-95. doi: 10.20463/pan.2023.0021.
7. BOHM S., MERSMANN F., ARAMPATZIS A. *Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults*. Sports Med Open, 2015, 1(1), 7. doi: 10.1186/s40798-015-0009-9
8. BONTEMPS B., GRUET M., LOUIS J., OWENS D.J., MIRÍC S., VERCRUYSSEN F. et al. *Patellar Tendon Adaptations to Downhill Running Training and Their Relationships With Changes in Mechanical Stress and Loading History*. J Strength Cond Res, 2024, 38(1), 21-29. doi: 10.1519/JSC.0000000000004617.
9. BRAVO-SÁNCHEZ A., ABIÁN P., JIMÉNEZ F., ABIÁN-VICÉN J. *Myotendinous asymmetries derived from the prolonged practice of badminton in professional players*. PLoS One, 2019, 14(9), e0222190. doi.org/10.1371/journal.pone.0222190
10. CHAINANI P.H., BUZO MENA M., YERITSYAN D., CARO D., MOMENZADEH K., GALLOWAY J.L. et al. *Successive tendon injury in an in vivo rat overload model induces early damage and acute healing responses*. Front Bioeng Biotechnol, 2024, 7, doi: 10.3389/fbioe.2024.1327094.
11. CHEN G., WU J., CHEN G., LU Y., REN W., XU W. et al. *Reliability of a portable device for quantifying tone and stiffness of quadriceps femoris and patellar tendon at different knee flexion angles.* PLoS One, 2019, 14, e0220521. doi: 10.1371/journal.pone.0220521
12. CRISTI-SÁNCHEZ I., DANES-DAETZ C., NEIRA A., FERRADA W., YÁÑEZ DÍAZ R., SILVESTRE AGUIRRE R. *Patellar and Achilles tendon stiffness in elite soccer players assessed using myotonometric measurements*. Sports Health, 2019, 11(2), 157-62. doi: 10.1177/1941738118820517
13. EPRO G., MIERAU A., DOERNER J., LUETKENS JA., SCHEEF L., KUKUK G.M., et al. *The Achilles tendon is mechanosensitive in older adults: adaptations following 14 weeks versus 1.5 years of cyclic strain exercise.* J Exp Biol, 2017, 220(6), 1008-18. doi: 10.1242/jeb.146407
14. ERIKSEN C.S., SVENSSON R.B., GYLLING A.T., COUPPÉ C., MAGNUSSON S.P., KJAER M. *Load magnitude affects patellar tendon mechanical properties but*

*not collagen or collagen cross-linking after long-term strength training in older adults.* BMC Geriatr, 2019, 19(1), 30. doi: 10.1186/s12877-019-1043-0

15. FREEDMAN B.R., SARVER J.J., BUCKLEY M.R., VOLETI P.B., SOSLOWSKY L.J. *Biomechanical and structural response of healing Achilles tendon to fatigue loading following acute injury*. J Biomech, 2014, 47, 2028-34. doi: 10.1016/j.jbiomech.2013.10.054
16. GERVASI M., BENELLI P., VENERANDI R., FERNÁNDEZ-PEÑA E. *Relationship between muscle-tendon stiffness and drop jump performance in young male basketball players during developmental stages*. Int J Environ Res Public Health, 2022, 19(24), 17017. doi.org/10.3390/ijerph192417017
17. GROSSET J.F., BREEN L., STEWART C.E., BURGESS K.E., ONAMBÉLÉ G.L. *Influence of exercise intensity on training-induced tendon mechanical properties changes in older individuals.* Age (Omaha), 2014, 36(3), 9657. doi: 10.1007/s11357-014-9657-9
18. HEINEMEIER K.M., SCHJERLING P., HEINEMEIER J., MAGNUSSON S.P., KJAER M. *Lack of tissue renewal in human adult Achilles tendon is revealed by nuclear bomb 14C*. Faseb J, 2013, 27(5), 2074-9. doi: 10.1096/fj.12-225599
19. HOLZER D., MILLARD M., HAHN D., SIEBERT T., SCHWIRTZ A., SEIBERL W. *Tendon compliance and preload must be considered when determining the in vivo force-velocity relationship from the torque-angular velocity relation.* Sci Rep, 2023, 13(1), 6588. doi: 10.1038/s41598-023-33643-9.
20. JIANG L., LIU T., LYU K., CHEN Y., LU J., WANG X. et al. *Inflammation-related signaling pathways in tendinopathy.* Open Life Sci, 2023, 18(1), 20220729. doi: 10.1515/biol-2022-0729.
21. KAY A.D., BLAZEVICH A.J., TYSOE J.C., BAXTER B.A. *Cross-Education Effects of Isokinetic Eccentric Plantarflexor Training on Flexibility, Strength, and Muscle-Tendon Mechanics.* Med Sci Sports Exerc, 2024, doi: 10.1249/MSS.0000000000003418.
22. KLICH S., FICEK K., KRYMSKI I., KLIMEK A., KAWCZYŃSKI A., MADELEINE P., FERNÁNDEZ-DE-LAS-PEÑAS C. *Quadriceps and patellar tendon thickness and stiffness in elite track cyclists: An ultrasonographic and myotonometric evaluation.* Front Physiol, 2020, 11, 607208. doi: 10.3389/fphys.2020.607208

23. KLICH S., KRYMSKI I., KAWCZYNSKI A. *Viscoelastic properties of lower extremity muscles after elite track cycling sprint events: a case report*. Central Eur J Sport Sci Med, 2020, 29, 5-10. doi: 10.18276/cej.2020.1-01
24. KOPECKÁ B., RAVNIK D., JELEN K., BITTNER V. *Objective Methods of Muscle Tone Diagnosis and Their Application-A Critical Review.* Sensors (Basel), 2023, 23(16),7189. doi: 10.3390/s23167189.
25. LEE J., BRIDGE J.E., CLARK D.R., STEWART C.E., ERSKINE R.M. *Collagen supplementation augments changes in patellar tendon properties in female soccer players.* Front Physiol, 2023, 14, 1089971. doi: 10.3389/fphys.2023.1089971.
26. LEE W.C., ZHANG Z.J., MASCI L. *Alterations in mechanical properties of the patellar tendon is associated with pain in athletes with patellar tendinopathy*. Eur J Appl Physiol, 2017, 117(5), 1039-45. doi: 10.1007/s00421-017-3593-1
27. LIANG X., WANG B., ZENG X., TANG Y., XIAO F., HAIWEI L. et al. *Effect of different resting time on patella-patellar tendon healing after acute injury.* Chin J Tissue Eng Res, 2017, 21, 1805-12. doi: 10.3389/fphys.2017.1191058
28. LIMA ME., COSTA JÚNIOR J.F.S., PEREIRA W.C.A., OLIVEIRA L.F. *Assessment of the mechanical properties of the muscle-tendon unit by supersonic shear wave imaging elastography: a review.* Ultrasonography, 2018, 37(1), 3-15. doi: 10.14366/usg.17017
29. MASSEY G.J., BALSHAW T.G., MADEN-WILKINSON T.M., FOLLAND J.P. *Tendinous tissue properties after short- and long-term functional overload: Differences between controls, 12 weeks and 4 years of resistance training.* Acta Physiol, 2018, 2017, e13019. doi: 10.3389/fphys.2018.01170
30. MCCREESH K.M., PURTILL H., DONNELLY A.E., LEWIS J.S. *Increased supraspinatus tendon thickness following fatigue loading in rotator cuff tendinopathy: potential implications for exercise therapy.* BMJ Open Sport Exerc Med, 2017, 3, e000279. doi: 10.1136/bmjsem-2017-000279
31. MCCRUM C., LEOW P., EPRO G., KÖNIG M., MEIJER K., KARAMANIDIS K. *Alterations in leg extensor muscle-tendon unit biomechanical properties with ageing and mechanical loading.* Front Physiol, 2018, 9, 150. doi: 10.3389/fphys.2018.00150
32. MCMAHON G. *No Strain, No Gain? The Role of Strain and Load Magnitude in Human Tendon Responses and Adaptation to Loading*. J Strength Cond Res, 2022, 36(10), 2950-56. doi: 10.1519/JSC.0000000000004288.

33. MENCEL J., MARUSIAK J., JASKÓLSKA A., JASKÓLSKI A., KISIEL-SAJEWICZ K. *Impact of the location of myometric measurement. Muscles Ligaments Tendons* J. Physiol, 2021, 11(3), 525-35. doi: 10.3389/fpsyg.2021.638780
34. OBST S.J., HEALES L.J., SCHRADER B.L., DAVIS S.A., DODD K.A., HOLZBERGER C.J. et al. *Are the Mechanical or Material Properties of the Achilles and Patellar Tendons Altered in Tendinopathy? A Systematic Review with Meta-analysis.* Sports Med, 2018, 48(9), 2179-98. doi: 10.1007/s40279-018-0956-7.
35. RÖMER C., ZESSIN E., CZUPAJLLO J., FISCHER T., WOLFARTH B., LERCHBAUMER M.H. *Effect of physical parameters and training load on patellar tendon stiffness in professional athletes*. Diagnostics (Basel), 2023, 13(15), 2541. doi: 10.3390/diagnostics13152541
36. SCHOENROCK B., ZANDER V., DERN S., LIMPER U., MULDER E., VERAKSITŠ A., VIIR R. et al. *Bed rest, exercise countermeasure and reconditioning effects on the human resting muscle tone system*. Front Physiol, 2018, 9, 810. doi: 10.3389/fphys.2018.00810
37. SKOPINSKA-WISNIEWSKA J., WEGRZYNOWSKA-DRZYMALSKA K., BAJEK A., MAJ M., SIONKOWSKA A. *Is dialdehyde starch a valuable cross-linking agent for collagen/elastin based materials?* J Mater Sci Mater Med, 2016, 27(4), 67. doi: 10.1007/s10856-016-5677-6
38. SOHIRAD S., WILSON D., WAUGH C., FINNAMORE E., SCOTT A. *Feasibility of using a hand-held device to characterize tendon tissue biomechanics.* PLoS One, 2017, 12(9), e0184463. doi: 10.1371/journal.pone.0184463
39. SPEED A., GROETSCH A., SCHWIEDRZIK J.J., WOLFRAM U. *Extrafibrillar matrix yield stress and failure envelopes for mineralised collagen fibril arrays*. J Mech Behav Biomed Mater, 2020, 105, 103563. doi: 10.1016/j.jmbbm.2019.103563.
40. SPIESZ E.M., ZYSSET P.K. *Structure-mechanics relationships in mineralized tendons.* J Mech Behav Biomed Mater, 2015, 52, 72-84. doi: 10.1016/j.jmbbm.2015.03.013.
41. SQUIER K., MOUSAVIZADEH R., DAMJI F., BECK C., HUNT M., SCOTT A. *In vitro collagen biomarkers in mechanically stimulated human tendon cells: a systematic review.* Connect Tissue Res, 2024, 65(2), 89-101. doi: 10.1080/03008207.2024.2313582.
42. SZAJKOWSKI S., PASEK J., DWORNIK M., ZAJĄCZKOWSKI M., CIEŚLAR G. *Are the mechanical properties of Achilles tendon altered in CrossFit athletes?*

*Reliability and accuracy of myotonometry*. Acta Bioeng Biomech, 2023, 25(2), 103-13. doi: 10.37190/ABB-02283-2023-01

43. TALJANOVIC M.S., GIMBER L.H., BECKER G.W., LATT L.D., KLAUSER A.S., MELVILLE D.M., GAO L., WITTE R.S. *Shear-wave elastography: basic physics and musculoskeletal applications*. Radiographics, 2017, 37(3), 855-70. doi: 10.1148/rg.2017160116
44. TAŞ S., YILMAZ S., ONUR M.R., SOYLU A.R., ALTUNTAŞ O., KORKUSUZ F. *Patellar tendon mechanical properties change with gender, body mass index and quadriceps femoris muscle strength*. Acta Orthop Traumatol Turc, 2017, 51(1), 54-9. doi.org/10.1016/j.aott.2016.12.003
45. TSUI S.S., LEONG H.T., LEUNG V.Y., YING M., FU S.N. *Tendon vascularity in overhead athletes with subacromial pain syndrome and its correlation with the resting subacromial space*. J Shoulder Elbow Surg, 2017, 26, 774-80. doi: 10.1016/j.jse.2016.09.041
46. WIESINGER H.P., KOSTERS A., MULLER E., SEYNNES O.R. *Effects of increased loading on in vivo tendon properties: a systematic review*. Med Sci Sports Exerc, 2015, 47(9), 1885-95. doi: 10.1249/MSS.0000000000000603
47. YOUNG F.C., CRISTI-SÁNCHEZ I., DANES-DAETZ C., MONCKEBERG J.E., AGUIRRE R.S. *Patellar tendon stiffness in elite breakdancers assessed by myotonometric measurement*. J Dance Med Sci, 2018, 22, 179-83. doi: 10.12678/1089-313X.22.4.179
48. ZHANG Q., ADAM N.C., HOSSEINI NASAB S.H., TAYLOR W.R., SMITH C.R. *Techniques for In Vivo Measurement of Ligament and Tendon Strain: A Review*. Ann Biomed Eng, 2021, 49(1), 7-28. doi: 10.1007/s10439-020-02635-5.



**Conflict of Interests**

The author's declare no conflict of interests regarding this study.

**Funding**

The author's received no financial support for the research, authorship and publication of this article.