Title

Alterations in mechanical properties of the patellar tendon is associated with pain in athletes with patellar tendinopathy

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Abstract

Purpose

To compare tendon strain and stiffness between athletes with patellar tendinopathy and healthy controls, and explore whether the intensity of pain and dysfunction were related to the mechanical properties of the tendon.

Methods

Thirty-four male athletes with patellar tendinopathy and 13 healthy controls matched by age and activity levels were recruited. The in vivo mechanical properties of the patellar tendon were examined by ultrasonography and dynamometry. In subjects with patellar tendinopathy, the intensities of self-perceived pain (maximal pain in the past 7 days and pain during a single-legged declined-squat test) using the visual analogue scale and the assessment of functional disability using the Victorian Institute of Sport Assessment—patellar questionnaire, were collected.

Results

In subjects with patellar tendinopathy, tendon strain was significantly reduced by 22% (8.9 ± 3.7 vs. 14.3 ± 4.7%, $P = 0.005$) when compared with healthy controls. There was no significant group difference in tendon stiffness ($P = 0.27$). Significant negative correlations between tendon strain and the maximal self-perceived pain over 7 days ($r = -0.37$, $P = 0.03$), and pain during a single-legged declined-squat test ($r = -0.37$, $P = 0.03$) were detected. A trend of significant positive correlation was found between tendon stiffness and pain during a single-legged declined-squat test ($r = 0.30$, $P = 0.09$).

Conclusion

Our findings show that tendon strain is reduced in athletes with patellar tendinopathy, and a lower tendon strain is associated with a greater magnitude of pain perceived.

Introduction

Tendon overload is believed to be one of the major etiological factors for tendinopathy, which results in pain and dysfunctions (Magnusson et al. 2010). Histopathological examinations reveal discontinuous and disorganized collagen fibers (Aström and Rausing 1995; Kalebo et al. 1991) and substantial increase of mucoid ground substance (Khan et al. 1996) in a pathologic tendon. These changes in tendon morphology might induce mechanical changes in the pathological tendons.

Possible changes in the mechanical properties of pathologic patellar tendon have been studied but with inconsistent findings (Couppé et al. 2013; Helland et al. 2013; Kongsgaard et al. 2009, 2010). Kongsgaard et al. (2009) were the first group to use ultrasonography and dynamometry to compare tendons' mechanical properties between the painful and non-painful sides in subjects with unilateral patellar tendinopathy. The authors observed reduced tendon stiffness in the painful leg. The difference, however, could not reach a statistically significant value. Heales et al. (2014) suggested that deficits in motor systems are present bilaterally in unilateral tendinopathy. The contralateral and non-painful could not be regarded as "healthy" control. When tendon mechanical properties were compared between subjects with tendinopathic tendon and healthy individuals, Kongsgaard et al. (2010) detected a no significant reduction in tendon stiffness and increased strain on 8 tendinopathic tendon compared with 9 controls. Similarly, Couppé et al. (2013) observed no significant group differences on tendon stiffness and strain on elite badminton players with pathological tendon and controls. On the contrary, Helland et al. (2013) recruited young volleyball players and reported significantly lower tendon stiffness and modulus on the pathological group compared with healthy controls. In Helland’s study, young athletes involving in jumping sports were recruited. However, the dysfunction scores in the pathological group were relatively high. It is unclear whether such changes on tendon mechanical properties would be modulated in athletes with patellar tendinopathy with lower functional scores, i.e., Victorian Institute of Sport Assessment (VISA-p) less than 80 (Visentini et al. 1998; Zwerver et al. 2011).

Ultrasound imaging with dynamometry was used to capture tendon images and force during ramped maximum voluntary isometric contraction. Elastic modulus was computed based on a number of assumptions. One of them is tendon unity. However, pathological change including hypoechoic area or a fibrotic knot has been reported in the proximal and dorsal region of a tendon (Aström and Rausing 1995; Kalebo et al. 1991) which signifies that the tendon might not have a uniform dimension. A recent review commented that the calculation process with in vivo tendon testing might introduce a certain amount of error (Seynnes et al. 2015). The authors suggested that primary measurements, such as tendon stiffness and strain could be used to reflect tendon mechanical properties.

Are tendon mechanical properties associated with pain or dysfunction in subjects with patellar tendinopathy? Kongsgaard et al. (2010) reported significant reduction of tendon stiffness after a heavy slow resistance training programme. Clinical improvement on pain and function was also reported after the exercise programme. Such findings suggest a possible relationship between tendons’ mechanical properties and the magnitude of tendon-related pain in subjects with tendinopathy.

This study aimed to compare tendon mechanical properties between athletes with pathologic tendon and healthy control. Possible relationships between tendon mechanical properties and the intensity of tendon-related pain and dysfunction would be explored. We hypothesized that (1) tendon stiffness and strain would be altered in athletes with patellar tendinopathy compared with healthy controls and (2) tendon stiffness and tendon strain would be associated with the intensity of tendon-related pain and dysfunction. Findings from this study would shed the light on the influence of tendon mechanical properties, impairments, and dysfunctions in patellar tendinopathy.

Methods

Ethics statement

This study was approved by the Human Subject Ethics Sub-committee of the administrating institution. The experimental procedures were conducted in accordance with the Declaration of Helsinki. The procedures of the study were fully explained to the participants and they provided their informed written consent before testing.

Subject recruitment

Thirty-four male subjects with patellar tendinopathy were recruited from local volleyball, basketball, and handball teams. Subjects were included if they had a history of pain during activity/training at the inferior pole of the patellar with visual analogue scale (VAS) equal to or greater than 2 for at least 3 months and with a VISA-p questionnaire score less than 80 (Visentini et al. 1998; Zwerver et al. 2011). Clinical tests such as palpation of the inferior pole of patella elicited comparable pain. Thickening of the proximal part of the patellar tendon with an area of hypoechoic signals was detected under ultrasonographic examination (Kulig et al. 2013). A physical therapist with 15 years of experience in treating musculoskeletal-related injuries conducted the clinical tests. Subjects were excluded if they suffered from patellofemoral pain syndrome, fat pad irritations, meniscal injury, osteoarthritis, rheumatoid arthritis, or infection; had a history of fracture of the lower limbs and inflammatory myopathies; and had received cortisone injections and other interventions within 3 months.

Thirteen healthy subjects without any knee problems matched by age and activity level were recruited.

In vivo tendon mechanical property examination using ultrasonography and dynamometry

The procedure was adopted from the studies of Kubo et al. (2006) and Reeves et al. (2003). An isokinetic dynamometer (HUMAC® NORM, Cybex, International Inc., USA) was used to capture the torque output during maximum isometric knee extension at 90° of knee flexion (full extension = 0°). Subjects sat with the knee joint axis aligned against the dynamometer axis of rotation (Fig. 1). Torque signals were converted at a sampling rate of 1000 Hz (LabView™ 8.6, National Instruments, USA). An ultrasound (US) probe (8 MHz, linear array with 58 mm scanning length; Nemio, Toshiba, Tokyo, Japan) was used to capture images of the proximal half of the patellar tendon. The US probe was placed on the patellar tendon along its sagittal plane and aligned with the direction of the tendon fibers. An echo-absorptive external marker was used to demarcate the mid-point of the patellar tendon. US images were captured at a rate of 10 Hz. Activities of the hamstring muscles were captured using surface EMG with 10 mm inter-electrode distance (DE-2.1 single differential detection, Delsys, USA). It was placed on clean, shaved, and previously abraded skin at a site corresponding to the mid-point of the length between the ischial tuberosity and lateral tibial epicondyle, with reference to the guideline of the SENIAM European recommendations for surface electromyography (Hermens 1999). A reference electrode was placed at the bony point of the lateral malleolus of the ipsilateral ankle. All the signals captured were synchronized and stored for off-line analysis.

All subjects attained two assessment sessions. The first session aimed for probe adjustment and subject's familiarization with the procedures. Each subject performed a standardized warm-up with 5 min of low intensity exercise on a stationary bike and two sets of five repetitions of 10-s static stretching of quadriceps and hamstrings before testing. The subject also performed 4–7 smooth ramped knee isometric extensions with visual feedback using a torque gauge with 90 s of rest in between. In the second session, a similar procedure was conducted—four contractions with ramped knee extensions with the maximal effort to obtain clear ultrasound images. Each contraction lasted for 10 s.

Calculation of tendon strain and stiffness

A software (Sante® DICOM viewer, Santesoft, Greece) was used to import the video clips (frame rate of 10 Hz) obtained from the ultrasound unit into a personal computer. Tendon resting length (L), defined as the distance between the posterior border of the patella apex to the superior aspect of the tibial tuberosity, was measured using the "caliper" function. Two measurements were made and averaged. As the ultrasound probe was not long enough to measure the entire tendon length during muscle contraction, the tendon length between the apex of the patella with respect to the echo-absorptive external marker was measured during the ramped quadriceps contraction. Change in tendon length was defined as deformation (d).

Estimation of muscle co-contraction of the hamstrings during ramped quadriceps contraction was done by analyzing the EMG signals captured on the biceps femoris (BF) during the action. The raw EMG signal was pre-amplified (×10000, Bagnoli™ Handheld system, Delsys, USA) and filtered using high- and low-pass filters set at 10 and 500 Hz, respectively. To determine the level of antagonist co-activation of the knee flexors, the root mean square (RMS) EMG activity of the BF muscle was measured during the ramp isometric knee extension contraction over 50 ms time periods at intervals of 10% of maximal torque. To determine the maximal activation of the BF muscle when acting as an agonist, two maximal knee isometric flexion contractions with 5 s each were performed at the position studied. The RMS BF muscle EMG activity was measured at the time point of maximal torque over a 500 ms time period, and was then normalized for a 1 s time period. The average of the two values of EMG–torque ratio was used for analysis. The antagonist torque, T ant, of the knee flexors during knee extension was calculated assuming a linear EMG–torque relationship from the EMG–torque relationship of BF muscle when acting as an agonist (Lippold 1952).

Tendon force was calculated as follows: F = (T ob + T ant)/PMA, where F is the isometric tendon force, T ob is the observed isometric knee extensor torque, T ant is the antagonist (biceps femoris) co-contraction torque, and PMA is the patellar tendon moment arm. The patellar tendon moment arm length was estimated by a fixed value (44.7 mm) for knee joint angle of 90° taken from study of Baltzopoulos (1995). After determining the maximal deformation for the four ramped contractions, the two contractions with the highest and lowest maximal deformation were excluded. Tendon force (F) and deformation (d) data from the remaining attempts were further analyzed to a greatest common force and averaged. Tendon deformations (d) at intervals of 10% of the common maximal force in these two attempts were measured. Force–deformation curve (F–d curve) was fitted with second-order polynomial fit, with $R^2 \geq 0.95$. Tendon stiffness was calculated at the highest 10% interval of the F–d curve. Tendon strain was calculated as the change in length related to the original length (d/L) at maximal contraction force and expressed as a percentage.

Reliability of measuring tendon mechanical properties were assessed among a subset of twelve participants. They repeated the same procedure after 2 h where participants were taken out of the dynamometer chair with rest. Intra-rater reliability was estimated using interclass correlation coefficients for maximum force (0.91, 95% CI 0.71–0.97), maximum deformation (0.91, 95% CI 0.62–0.96), tendon resting length (0.98, 95% CI 0.93–0.99), tendon strain (0.85, 95% CI 0.57–0.96), and stiffness (0.81, 95% CI 0.46–0.94).

Tendon-related pain and dysfunction

Self-perceived pain, activity-related pain, and VISA-p were used to measure the intensity of tendon-related pain and dysfunction.

Each subject rated the intensity of pain using the VAS on a 10 cm continuous line marked "no pain" at one end and "worst pain" at the other end, by recalling the maximal pain level during activities in the last 7 days.

A single-legged declined-squat test was conducted. The pain level at the point when pain was elicited during squatting on a 25° decline board was recorded (Purdam et al. 2003). With the subject standing in an erect position, he was asked to bend his knee slowly until there was knee pain in the proximal patellar tendon. The level of pain elicited during squatting was marked on a line with VAS. The average of three measurements was recorded for analysis.

The VISA-p questionnaire, a valid measure of patellar tendon symptoms with a 100-point maximum representing full pain-free function, was used in assessing the level of dysfunction (Visentini et al. 1998).

Statistical analysis

Based on the study of Kongsgaard et al. (2010), the effect size of 1.5 was adopted using the standard deviation and mean of tendon strain in subjects with and without patellar tendinopathy. Taking Alpha at 5%, and power at 90%, the estimated sample size for the between-group comparison was 11 subjects per group.

Normality tests were conducted using the Kolmogorov–Smirnov test. Independent t tests were used to compare the demographic data between healthy controls and subjects with patellar tendinopathy. Independent t tests were used to compare tendon resting length, elongation, maximum tendon force, stiffness, and tendon strain between the affected leg (or more severe side for subjects with bilateral symptom) of subjects with patellar tendinopathy and the healthy control (randomizing the leg order) (Kongsgaard et al. 2010). Pearson correlation tests were used to explore possible relationships between tendon stiffness and tendon strain with tendon-related pain and dysfunctions (VISA-p score). Pearson correlation tests were also used to explore whether ability of force exertion would affect pain, function, and its calculated tendon strain and stiffness. SPSS version 17.0 (SPSS Inc, Chicago, IL) was used to perform the statistical analyses. Statistical significance was set at a P value of ≤ 0.05.

Results

Anthropometric measures

Table 1 shows the subject characteristics of 34 subjects with patellar tendinopathy and 13 healthy subjects participating in this study. There was no significant difference between healthy controls and subjects with patellar tendinopathy pertaining to the demographic data.

Difference between tendon mechanical properties in athletes with patellar tendinopathy and healthy control

Tendon strain was significantly lower by around 22% (10.4 ± 4.0 vs. 13.4 ± 4.2%, P = 0.03) in subjects with patellar tendinopathy. There was no significant group difference on tendon stiffness (P = 0.27). No significant difference in tendon resting length (P = 0.28) and maximum tendon force (P = 0.53) was observed between the two groups (Table 2).

Correlation between tendon strain, stiffness, pain, and functions

Tendon strain was negatively correlated to the maximal intensity of self-perceived pain (r = −0.37, P = 0.03) and pain during single-legged declined-squat test (r = −0.37, P = 0.03) (Table 3). There was a trend of weak correlation between tendon stiffness and pain during single-legged declined-squat test (r = 0.30, P = 0.09). There was no significant correlation between tendon strain, stiffness, and VISA-p scores.

Tendon maximal force was not correlated with self-perceived pain (r = −0.15, P = 0.40), pain during single-legged declined-squat test (r = −0.25, P = 0.15), or VISA-p score (r = 0.21, P = 0.23). There was a trend of weak correlation between maximal force and tendon strain (r = 0.32, P = 0.07).

Discussion

Changes in tendon strain in athletes with patellar tendinopathy were observed in this study. The tendon strain was significantly reduced by about 22% in the pathologic tendon when compared with healthy control. More importantly, a lower tendon strain is associated with self-reported and activity-related pain in athletes with patellar tendinopathy.

Changes in tendon structures have been previously confirmed and reported (Aström and Rausing 1995; Kalebo et al. 1991; Khan et al. 1996). Such changes would likely alter the mechanical properties of a diseased tendon. However, controversial findings were reported when tendinopathic tendons were compared with healthy tendons in previous studies. The present study used primary data that assessed the ability of a tendon to lengthen during maximal isometric contraction. Our findings indicate a decrease in tendon strain under maximal isometric contraction in pathologic than healthy patellar tendons. These findings may suggest that a diseased tendon has less extensibility. In this connection, Helland et al. (2013) reported no significant group difference in tendon strain in male volleyball players with patellar tendinopathy compared with healthy controls. The recruited subjects had dysfunction scores ranging from 64 to 87. In the present study, we recruited subjects with VISA-p score below 80 whom were more likely to have patellar tendinopathy (Frohm et al. 2007; Visentini et al. 1998). Nevertheless, similar to previous studies, no significant group differences on tendon stiffness were detected between the pathological and healthy tendon. We would expect that the reduced strain in tendinopathic tendon be mirrored by higher tendon stiffness. Tendon strain reflects the extensibility of a tendon at maximal voluntary contraction. Direct measurements on resting and changes in tendon length were conducted by an ultrasound imaging system. Tendon stiffness was the ratio between force and length at its highest 10% interval of F–d curve. Despite higher tendon stiffness was observed in the tendinopathic tendon compared with healthy control, the differences could not reach a statistical significant level. The magnitude of maximal contraction force, a factor that might influence tendon stiffness, shows non-significant reduction in the pathological group. Such findings might suggest that tendon stiffness is less affected than tendon strain in subjects with patellar tendinopathy.

Surgical findings have reported fibrocartilaginous or calcifying tissues around the painful region of a tendon (Maffulli et al. 2006). In addition, changes that occur in tendons with tendinopathy such as transition of collagen fibers between type I and type III (Goncalves-Neto et al. 2002; Ireland et al. 2001), increase in collagen cross-links (Kongsgaard et al. 2009), and formation of scar tissue (Hooley and Cohen 1979) would likely decrease tissue compliance. More recently, Bah et al. (2016) proposed that the increased glycosaminoglycan content might limit fluid flow, and thus reduce tissue compliance of pathologic tendons.

Kongsgaard et al. (2010) first reported a reduction in tendon stiffness and pain after an exercise programme in subjects with patellar tendinopathy. Such findings, together with those in the present study, substantiate the relationship between tendons' mechanical properties and pain in individuals with patellar tendinopathy. During jumping, tendons are lengthened during the preparation and landing phases. The abrupt increase in tendon strain may elicit pain and put them at risk for further tissue damage if they are less extensible (Lichtwark and Wilson 2005). Furthermore, tendons act like a spring and function as a mechanical buffer by reducing the rate of force transmission to the attached muscle to prevent injury (Krevolin et al. 2004; Magnusson et al. 2003). A more elastic or extensible patellar tendon might help to buffer the loading to the quadriceps muscle during jumping and landing activities.

We could not establish the relationship between tendon mechanical properties and dysfunction in this group of subjects as all the subjects were still actively participating in their usual sports. Bah et al. (2016) reported that tendons with less compliance were associated with poorer functional scores in subjects with Achilles tendinopathy receiving surgical debridement. Whether a similar observation could be found in subjects with patellar tendinopathy receiving debridement surgery and in those receiving conservative intervention requires further study.

In all the assessment done in the laboratory, no subject complained of pain during the maximal isometric knee extension. The possibility of pain inhibition of force production leading to a lower tendon strain is therefore, less likely, but cannot be excluded. In our pilot study, we found difficulty and unable to capture the whole tendon length from apex of patellar to the tibial tuberosity, therefore, tendon elongation was tracked between the patellar apex and an external marker at tendon mid-length. Although this method had been utilized in previous studies (Malliaras et al. 2013; Reeves et al. 2003; Seynnes et al. 2009), possible underestimation might happen when accounting possible elongation on distal portion.

Generalization of our findings can only be made on male athletes who had continued their training and competition. Despite finding a relationship between tendon strain and pain in this present cross-sectional study, the cause–effect relationship between the two could not be established. Follow-up studies are warranted to examine whether changes in pain relate to changes in tendon strain.

Conclusions

The present study assessed the ability of patellar tendons to elongate during maximal isometric contraction. Tendon strain is decreased in pathologic patellar tendon when compared with healthy controls in young athletes. The intensity of activity-related pain is related to tendon strain in athletes with patellar tendinopathy. Intervention targeting improvement in tendon strain might improve tendon-related pain in athletes with patellar tendinopathy.

Abbreviations

BF: Biceps femoris

BMI: Body mass index

d : Deformation

F : Force

L: Length

MDD: Minimal detectable differences

PMA: Patellar tendon moment arm

RMS: Root mean square

SD: Standard deviation

US: Ultrasound

VAS: Visual analogue scale

VISA-p: Victorian Institute of Sport Assessment

References

Aström M, Rausing A (1995) Chronic Achilles tendinopathy. A survey of surgical and histopathologic findings. Clin Orthop Relat Res 316:151–164

Bah I, Kwak ST, Chimenti RL et al (2016) Mechanical changes in the Achilles tendon due to insertional Achilles tendinopathy. J Mech Behav Biomed Mater 53:320–328

Baltzopoulos V (1995) A videofuoroscopy method for optical distortion correction and measurement of knee-joint kinematics. Clin Biomech (Bristol Avon) 10:85–92

Couppé C, Kongsgaard M, Aagaard P et al (2013) Diferences in tendon properties in elite badminton players with or without patellar tendinopathy. Scand J Med Sci Sports 23(2):e89–e95

Frohm A, Saartok T, Halvorsen K, Renstrom P (2007) Eccentric treatment for patellar tendinopathy: a prospective randomised shortterm pilot study of two rehabilitation protocols. Br J Sports Med 41:e7

Goncalves-Neto J, Witzel SS, Teodoro WR et al (2002) Changes in collagen matrix composition in human posterior tibial tendon dysfunction. Joint Bone Spine 69(2):189–194

Heales LJ, Lim EC, Hodges PW, Vicenzino B (2014) Sensory and motor defcits exist on the non-injured side of patients with unilateral tendon pain and disability—implications for central nervous system involvement: a systematic review with meta-analysis. Br J Sports Med 48(19):1400–1406

Helland C, Bojsen-Moller J, Raastad T et al (2013) Mechanical properties of the patellar tendon in elite volleyball players with and without patellar tendinopathy. Br J Sports Med 47(13):862–868

Hermens HJ (1999) Commission of the European Communities, SENIAM project. European recommendations for surface electromyography: results of the SENIAM project, 2nd edn. Roessingh Research and Development, Enschede, pp 15–54

Hooley CJ, Cohen RE (1979) A model for the creep behaviour of tendon. Int J Biol Macromol 1(3):123–132

Ireland D, Harrall R, Curry V et al (2001) Multiple changes in gene expression in chronic human Achilles tendinopathy. Matrix Biol 20(3):159–169

Kalebo P, Sward L, Karlsson J, Peterson L (1991) Ultrasonography in the detection of partial patellar ligament ruptures (jumper’s knee). Skeletal Radiol 20:285–289

Khan KM, Bonar F, Desmond PM et al (1996) Patellar tendinosis (jumper’s knee): findings at histopathologic examination, US, and MR imaging. Victorian Institute of Sport Tendon Study Group. Radiology 200:821–827

Kongsgaard M, Kovanen V, Aagaard P et al (2009) Corticosteroid injections, eccentric decline squat training and heavy slow resistance training in patellar tendinopathy. Scand J Med Sci Sports 19(6):790–802

Kongsgaard M, Qvortrup K, Larsen J et al (2010) Fibril morphology and tendon mechanical properties in patellar tendinopathy: effects of heavy slow resistance training. Am J Sports Med 38:749–756

Krevolin JL, Pandy MG, Pearce JC (2004) Moment arm of the patellar tendon in the human knee. J Biomech 37:785–788

Kubo K, Yata H, Kanehisa H, Fukunaga T (2006) Effects of isometric squat training on the tendon stifness and jump performance. Eur J Appl Physiol 96:305–314

Kulig K, Landel R, Chang YJ et al (2013) Patellar tendon morphology in volleyball athletes with and without patellar tendinopathy. Scand J Med Sci Sports 23(2):e81–e88

Lichtwark GA, Wilson AM (2005) In vivo mechanical properties of the human Achilles tendon during one legged hopping. J Exp Biol 208(Pt 24):4715–4725

Lippold OC (1952) The relationship between integrated action potentials in a human muscle and its isometric tension. J Physiol 177:492–499

Mafulli N, Reaper J, Ewen SW, Waterston SW, Barrass V (2006) Chondral metaplasia in calcifc insertional tendinopathy of the achilles tendon. Clin J Sport Med 16(4):329–334

Magnusson SP, Hansen P, Kjaer M (2003) Tendon properties in relation to muscular activity and physical training. Scand J Med Sci Sports 13(4):211–223

Magnusson SP, Langberg H, Kjaer M (2010) The pathogenesis of tendinopathy: balancing the response to loading. Nat Rev Rheumatol 6:262–268

Malliaras P, Kamal B, Nowell A et al (2013) Patellar tendon adaptation in relation to load-intensity and contraction type. J Biomech 46(11):1893–1899

Purdam CR, Cook JL, Hopper DH, Khan KM, VIS Tendon Study Group (2003) Discriminative ability of functional loading tests for adolescent jumper’s knee. Phys Ther Sport 4(1):3–9

Reeves ND, Maganaris CN, Narici MV (2003) Efect of strength training on human patella tendon mechanical properties of older individuals. J Physiol 548:971–981

Seynnes OR, Erskine RM, Maganaris CN et al (2009) Training induced changes in structural and mechanical properties of the patellar tendon are related to muscle hypertrophy but not to strength gains. J Appl Physiol 107(2):523–530

Seynnes OR, Bojsen-Møller J, Albracht K et al (2015) Ultrasound based testing of tendon mechanical properties: a critical evaluation. J Appl Physiol 118(2):133–141

Visentini PJ, Khan KM, Cook JL et al (1998) The VISA score: an index of severity of symptoms in patients with jumper's knee (patellar tendinosis). Victorian Institute of Sport Tendon Study Group. J Sci Med Sport 1(1):22–28

Zwerver J, Bredeweg SW, van den Akker-Scheek I (2011) Prevalence of jumper's knee among nonelite athletes from different sports: a cross-sectional survey. Am J Sports Med 39(9):1984–1988

Table 1 Subject characteristics

	Subject with patellar tendinopathy (*N* = 34)	**Healthy subjects (*N* = 13)**	***P* value**
Age (year)	22.2 ± 3.7	24.9 ± 6.0	0.13
Height (cm)	180.1 ± 6.4	179.0 ± 5.5	0.60
Weight (kg)	74.7 ± 6.8	73.1 ± 7.8	0.50
BMI (Kg m^{-2})	23.1 ± 2.1	22.8 ± 1.8	0.69
Training (h/week)	5.5 ± 2.4	5.8 ± 1.9	0.72
Duration of symptoms (number of months)	32.6 ± 25.0	–	–
Maximal intensity of self-perceived pain in past 7 days	6.7 ± 1.8	–	–
VISA-p score	55.9 ± 10.4	–	–
Unilateral/bilateral symptom	16:18	–	–

BMI body mass index, VISA-p Victorian Institute of Sport Assessment—patellar

Table 2 Mechanical properties

	Subject with patellar tendinopathy (*N* = 34)	**Healthy subjects (*N* = 13)**	***P* value**
Tendon length (mm)	49.4 ± 5.2	47.5 ± 5.3	0.28
Tendon elongation (mm)	5.0 ± 1.9	6.3 ± 1.9	0.03
Tendon strain (%)	10.4 ± 4.0	13.4 ± 4.2	0.03
Maximum tendon force (N)	14,158 ± 4832	15,038 ± 2363	0.53
Tendon stiffness (Nmm^{-1})	3266 ± 1767	2677 ± 1156	0.27

Table 3 Correlation between tendon mechanical properties, pain, and function

	Maximal intensity of self-perceived pain in the past 7 days	**Pain during the single-legged declined-squat test**	**VISA-p score**
Tendon strain	$r = -0.37$ $P = 0.03$	$r = -0.37$ $P = 0.03$	$r = 0.18$ $P = 0.32$
Tendon stiffness	$r = 0.27$ $P = 0.12$	$r = 0.30$ $P = 0.09$	$r = -0.04$ $P = 0.84$
Tendon maximal force	$r = -0.15$ $P = 0.40$	$r = -0.25$ $P = 0.15$	$r = 0.21$ $P = 0.23$

Figure 1 In vivo tendon mechanical property examination using ultrasonography and dynamometry