This is the accepted version of an article published by Lippincott Williams & Wilkins in Clinical Journal of Sport Medicine. To access the final edited and published work see https://www.doi.org/10.1097/JSM.0000000000000562.

Title:

Changes on Tendon Stiffness and Clinical Outcomes in Athletes Are Associated With Patellar Tendinopathy After Eccentric Exercise

Lee, Wai-Chun PhD*; Ng, Gabriel Yin-Fat PhD*; Zhang, Zhi-Jie PhD†; Malliaras, Peter PhD‡; Masci, Lorenzo MD§; Fu, Siu-Ngor PhD*

*Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong SAR, China;

†Department of Physical Therapy, Luoyang Orthopedic Hospital of Henan Province, Luoyang, Henan, China;

‡Faculty of Medicine, Nursing and Health Sciences, Monash University, Clayton, Victoria, Australia; and

§Pure Sports Medicine, London, United Kingdom.

Abstract

Objective:

Eccentric exercise is commonly used as a form of loading exercise for individuals with patellar tendinopathy. This study investigated the change of mechanical properties and clinical outcomes and their interrelationships after a 12-week single-legged decline-board exercise with and without extracorporeal shockwave therapy (ESWT).

Design:

Randomized controlled trial.

Setting:

Outpatient clinic of a university.

Participants:

Thirty-four male in-season athletes with patellar tendinopathy for more than 3 months were randomized into exercise and combined groups.

Interventions:

The exercise group received a 12-week single-legged decline-squat exercise, and the combined group performed an identical exercise program in addition to a weekly session of ESWT in the initial 6 weeks.

Main Outcome Measures:

Tendon stiffness and strain were examined using ultrasonography and dynamometry. Visual analog scale and Victoria Institute of Sports Assessment-patella (VISA-p) score were used to assess pain and dysfunction. These parameters were measured at pre-intervention and post-intervention.

Results:

Significant time effect but no significant group effect on the outcome measures; significant reduction in tendon stiffness ($P = 0.02$) and increase in tendon strain ($P = 0.00$); and reduction of intensity of pain ($P = 0.00$) and dysfunction ($P = 0.00$) were observed. Significant correlations between changes in tendon stiffness and VISA-p score ($\rho = -0.58$, $P = 0.05$); alteration in tendon strain, pain intensity ($\rho = -0.63$, $P = 0.03$); and VISA-p score ($\rho = 0.60$, $P = 0.04$) were detected after the exercise program.

Conclusions:

Eccentric exercise-induced modulation on tendon mechanical properties and clinical symptoms are associated in athletes with patellar tendinopathy.

INTRODUCTION

Patellar tendinopathy is common among athletes in jumping sports and is characterized by pain and dysfunction during jumping and landing. Eccentric exercise is one of the commonly used physiotherapeutic interventions for tendinopathy.1 Pain reduction has been reported after an eccentric exercise program,2–6 and enhancement of tendon strain exceeding its habitual use is one of the proposed treatment mechanisms.7

The patellar tendon is an energy-storing tendon that not only transmits muscle-derived forces that produce joint motion8,9 but also stores and releases energy like a spring, which has the potential to enhance power and efficiency.10,11 During eccentric exercise, the cyclic loading and unloading provides a mechanical stimulus that may result in tendon remodeling,12 including modulation of tendon stiffness. Indeed, an increase in tendon stiffness was detected after heavy-load isotonic (both concentric–eccentric and eccentric isolated) contraction in healthy individuals.13 In pathologic patellar tendons, nonsignificant reduction in tendon stiffness after eccentric decline squat (6%) and heavy slow resistance training (11%) have been reported among subjects aged between 18 and 50 years.4 In younger subjects with a mean age of 33, the same research group reported a significant reduction in tendon stiffness after a heavy slow resistance training program.14 There is a need to investigate the effects of eccentric exercise on the tendon mechanical properties in athletes in jumping sports who are more prone to have patellar tendinopathy. Whether the change in tendon stiffness is associated with tendon pain or dysfunction is unknown. Such information may be helpful in the management of patellar tendinopathy.

Extracorporeal shockwave therapy (ESWT) is another physiotherapeutic intervention for tendinopathic tendon. Wang et al15 compared ESWT with conservative management including medication, conventional physiotherapy, and exercise in subjects with patellar tendinopathy. The authors reported that ESWT has better results on pain and Victoria Institute of Sports Assessment-patella (VISA-p) functional score than other conservative management. Taunton et al16 also found better improvement in the ESWT group when compared with a sham group at postintervention. Regarding tendon properties, shockwaves induce direct mechanical perturbation to the treated tissue, which has been proposed to lead to tendon repair and remodeling.17 Increased ultimate tensile loading has been reported in animal studies after ESWT.18–20

It seems that both eccentric exercise and ESWT may influence pain and could also influence tendon mechanics. A question therefore arises as to whether ESWT might enhance adaptation of tendon mechanical properties when coupled with eccentric exercise. Combining exercise and ESWT is common in clinical practice and has been shown to be more effective than exercise alone among subjects with Achilles tendinopathy21 but not in subjects with patellar tendinopathy.22 Whether or not there may be additional benefits from combining ESWT with exercise for subjects with patellar tendinopathy is one of the questions to be explored.

This study aimed to (1) compare the effect of 12 weeks of single-legged eccentric decline squat exercise as a single intervention and combined with ESWT on patellar tendon stiffness, tendon strain, pain and function; and to (2) investigate the association between the change in tendon stiffness, pain and function after the interventions. We hypothesized that eccentric exercise combined with ESWT would not induce more changes in tendon stiffness, tendon strain, pain, and function than eccentric exercise alone. The change in tendon stiffness and strain might associate with the improvement in pain and function.

METHODS

Subject Recruitment

Thirty-four subjects with patellar tendinopathy were recruited from local competitive volleyball, basketball, and handball teams. Sample size was calculated based on a pilot study on 12 subjects. The effect size for between-intervention groups difference on tendon strain was 0.92. Taking Alpha at 5% and power at 80%, the estimated sample size should be 20 subjects per group.

Within 18 months, 43 subjects were recruited. Nine of these improved, and the severity of dysfunction was lower than the inclusion criteria (VISA-p score more than 80), and so were therefore excluded from the study. The final number of subjects included was 34.

A diagnosis of patellar tendinopathy was defined as pain at the inferior pole of the patella during or after training for at least 3 months, tenderness at the inferior pole of the patella with palpation, pain during or after activity that was equal or greater than 2 of the 11-point Visual analog scale (VAS), a Victorian Institute of Sport Assessment-patella (VISA-p) score less than 80 of 100, and the presence of proximal patellar tendon thickening and hypoechoic regions on ultrasound examination.23 A physiotherapist with 15 years of experience in musculoskeletal disorders performed diagnostic screening. Subjects were excluded if they had signs of patellofemoral pain syndrome (parapatellar region pain without ultrasound change on tendon), fat pad irritation, meniscal injury, osteoarthritis, rheumatoid arthritis, infection, a history of lower limb fracture, inflammatory myopathy, previous patellar tendon cortisone injection, or other interventions for patellar tendinopathy within 3 months. For subjects with bilateral patellar tendinopathy, the more symptomatic side (based on the intensity of self-perceived pain) was selected for analysis.

Ethics Statement

The study was approved by the Human Subjects Ethics sub-committee of the administrating institution, and all participants provided their written informed consent before the study. All procedures adhered to the Declaration of Helsinki.

In Vivo Tendon Mechanical Properties Assessment Using Ultrasonography and Dynamometry

The procedure was adopted from the protocols described by Kubo et al24 and Reeves et al.25 An isokinetic dynamometer (HUMAC NORM; Cybex, International Inc, Rosemont, Illinios) was used to capture the torque output during maximum isometric knee extension at 90 degrees of knee flexion (full extension = 0 degrees). Subjects sat with the knee joint axis aligned against the dynamometer axis of rotation. Torque signals were converted at a sampling rate of 1000 Hz (LabView8.6; National Instruments, Austin, Texas). An ultrasound 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 ultrasound probe was placed on the patellar tendon along its sagittal plane and aligned with the direction of tendon fibers. An echo-absorptive external marker was used to demarcate the midpoint of the patellar tendon. Ultrasound images were captured at a rate of 10 Hz. Hamstring muscle activity was captured using surface electromyography (EMG) sensors with 10-mm interelectrode distance (DE-2.1 single differential detection; Delsys, Natick, Massachusetts). Sensors were placed on clean, shaved, and previously abraded skin at a site corresponding to the midpoint of the length between the ischial tuberosity and lateral epicondyle of the tibia, with reference to the guideline of SENIAM European recommendations for surface EMG.26 The reference electrode was placed at the bony point of the lateral malleolus of the ipsilateral ankle. Electromyography data were synchronized with the dynamometer and stored for off-ine analysis.

All subjects participated in 2 assessment sessions. The first session aimed for probe adjustment and subjects' familiarization with the procedures. Each subject performed a standardized warm-up with 5-minute low-intensity exercise on a stationary bike and 2 sets of 5 repetitions of 15-second static stretching of quadriceps and hamstrings were performed before testing. This was followed by 4 to 7 smoothly ramped knee isometric extensions with visual feedback using a torque gauge with 90-second rest in between. Adjustment of anchor point or straps was performed to ensure the placement of probe within the proximal patellar tendon region, while the subject was performing the isometric contraction. In the second session, a similar procedure was performed using 4 contractions with ramped knee extension to maximal effort together with patellar tendon ultrasound imaging. Each contraction lasted for 10 seconds. In our pilot study, we found that it was easier to track the change of tendon length during the 10 second ramp-up contraction with shorter (ie, 5 seconds contraction) time. Good repeatability of tendon strain and stiffness were reported with this approach.27 The same testing procedures were conducted after the treatment interventions.

Calculation of Tendon Strain and Stiffness

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. The 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, tendon length between the apex of the patella with respect to the echo-absorptive external marker was measured during the ramped quadriceps contraction.13 The change in tendon length was defined as deformation (d).

Estimation of muscle cocontraction of hamstrings during ramped quadriceps contraction was performed by analyzing the EMG signals captured on the biceps femoris (BF) during the action. The raw EMG signal was preamplified (×10000, Bagnoli Handheld system; Delsys) and filtered using high- and low-pass filters set at 10 and 500 Hz, respectively. To determine the level of antagonist coactivation 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, 2 maximal knee isometric flexion contractions with 5 seconds each were performed at the position studied. The RMS BF muscle EMG activity was measured at the time point of maximal torque over 500 ms time period and was then normalized for a 1-second time period. The average of the 2 values of EMG–torque ratio was used for analysis. The antagonist torque, Tant, 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.28

Tendon force was calculated as follows—F = (Tob + Tant)/PMA, where F is the isometric tendon force, Tob is the observed isometric knee extensor torque, Tant is the antagonist (BF) cocontraction torque, and PMA is the patellar tendon moment arm estimated by a fixed value (44.7 mm) for the knee joint angle of 90 degrees taken from the study by Baltzopoulos.29 After determining the maximal deformation for the 4 ramped contractions, the 2 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 the greatest common force and averaged. Tendon deformation (d) at intervals of 10% of the common maximal force in these 2 attempts was measured. Force–deformation curves (F-d curve) were fitted with second-order polynomial fit, with R2 $\geqslant$ 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 original length (d/L) at maximal contraction force and expressed as a percentage.

Tendon-Related Pain and Dysfunction

Each subject rated their maximal pain during activity in the past 7 days using VAS on a 10-cm continuous line marked “no pain” on one end and “worst pain” on the other end. The VISA-p questionnaire, a reliable and valid disease-specific outcome measure, was used to assess pain and dysfunction.30 Six questions are related to pain and 2 questions are related to function, and the outcome is scored from 0 (maximal pain and minimum function) to 100 (no pain and full function).

Interventions

Subjects with patellar tendinopathy were randomly assigned to exercise or combined groups. They were told to maintain their standard loading in sports activities throughout the intervention period. The Consolidated Standards of Reporting Trials (CONSORT) diagram for the study is displayed in Figure 1.

Eccentric Exercise Programme

All subjects performed a 12-week single-legged eccentric decline squat exercise.31 The exercise involved standing on the painful leg on a 25 degrees decline board and maintaining an upright trunk while slowly squatting down to the point of pain (in 2 seconds). The starting position was then resumed using the other leg or the arms for subjects with bilateral symptoms. If the intensity of pain was less than 4 to 5 of 10 of the VAS, a 5-kg weight was added on a backpack. If the pain was more than 6 to 7 of 10, a decrease in the weight was suggested. Three sets of 15 repetitions were performed per session, twice a day. Subjects were required to fill in an exercise log (sets, repetitions, and frequency per day) and to return it to the researchers at each follow-up session.

Extracorporeal Shockwave Therapy

Sham or focused ESWT (Minilith SL1; Storz Medical, Tägerwilen, Switzerland) was delivered to the most tender region of the proximal patellar tendon with the knee positioned at 30 degrees of flexion. The location was determined by palpation and guided by subjects' feedback. The treatment intensity was increased from 0.08 mJ/mm2 to the level that subject could maximally tolerate. Thereafter, 1500 shocks were delivered at 4 Hz.32 For the sham intervention, 1500 shocks with an intensity below 0.08 mJ/mm2 were delivered at 4 Hz, and at this dosage subjects did not report any pain. Extracorporeal shockwave therapy was delivered weekly over the initial 6 weeks of the exercise program. Subjects were asked not to have any other treatment for their patellar tendinopathy during the study period.

Statistical Analysis

Statistical analyses were performed using SPSS version 17.0 (SPSS Inc, Chicago, Ilinios). Demographic data were compared between the exercise and the combined groups (independent t tests or Mann–Whitney U if data were not normally distributed). Two-way repeated analysis of variance was conducted with time (before and after) as within-subject factors and intervention (exercise or combined) as between-subject factors and the affected side (unilateral and bilateral) as a covariate. The dependent variables were tendon force, resting length, deformation, stiffness, strain, maximal self-perceived pain in the past 7 days, and VISA-p score. The intention-to-treat principle with the last observation carried forward was used for missing data. Spearman correlation tests were used to explore possible relationships between percentage changes (before and after) in tendon stiffness, strain, intensity of tendon pain, and VISA-P scores in the exercise and combined groups. Statistical significance was set at P value of $\leqslant 0.05$.

RESULTS

Thirty-four subjects entered into the program. One subject dropped out of the combined group, and 3 subjects dropped out of the exercise group. Drop-outs reported that they were not available to attend the sessions. One in each group was lost for postintervention evaluation. There were no significant differences in demographic data between the combined and exercise groups, although there was a trend for older age in the exercise group (Table 1).

Tendon Stiffness and Tendon Strain

Significant main effect for time but not group or group × time interaction was detected for tendon stiffness and tendon strain (Table 2). The mean baselines of tendon stiffness were 3544 ± 1820 N/mm for the exercise group and 3342 ± 1836 N/mm for the combined group. Both groups reduced over time to 3108 ± 2031 N/mm and 2363 ± 1402 N/mm, respectively. There was a significant increase on tendon strain from 10.6 ± 4.0% to 12.8 ± 5.4% in the exercise group and from 9.9 ± 4.3% to 13.3 ± 5.4% in the combined group ($P = 0.01$). No significant change in maximum tendon force and resting length and deformation was detected ($P > 0.05$).

Clinical Outcomes

Similarly, a significant main effect for time but not group or group × time interaction was detected for maximum self-perceived pain in the past 7 days ($P = 0.000$) and for VISA-P score ($P = 0.000$). Self-perceived pain over 7 days reduced by 49% (from 6.6 ± 2.0 to 3.2 ± 2.5 in the exercise group and from 6.7 ± 1.9 to 3.9 ± 1.9 in the combined group). The VISA-p score improved by 35% (from 57.4 ± 8.3 to 77.3 ± 12.6 in the exercise group and from 55.1 ± 12.9 to 72.9 ± 14.3 in the combined group).

Association Between Percentage Changes in Tendon Mechanical Properties and Clinical Outcomes

Table 3 highlights correlation coefficients between the percentage changes in tendon stiffness, tendon strain, tendon pain, and VISA-P scores when analyses were conducted on individual treatment groups. In the exercise group, there was a correlation between the percentage change in tendon stiffness and VISA-P scores ($\rho = -0.58$, $P = 0.05$). Greater reduction in tendon stiffness was associated with greater improvement in VISA-P score (Figure 2A). A trend of correlation between the percentage change in tendon stiffness and pain ($\rho = 0.55$, $P = 0.07$; Figure 2B) was observed. Also, percentage change in tendon strain was associated with VISA-P score ($\rho = 0.60$, $P = 0.04$; Figure 2C) and self-perceived pain ($\rho = -0.63$, $P = 0.03$; Figure 2D). When the outlier (percentage change in strain greater than 3 SD of the group mean) was excluded, percentage change in tendon strain was associated with VISA-P score ($\rho = 0.58$, $P = 0.06$) and self-perceived pain ($\rho = -0.66$, $P = 0.03$). Increase in the tendon strain was significantly associated with a reduction in the intensity of self-perceived pain and a trend in improvement in VISA-P score. In the combined group, there was no significant correlation between the changes in tendon stiffness, tendon strain, and the intensity of pain or function.

DISCUSSION

The main aim of this study was to explore the effects of eccentric exercise on tendon mechanical properties and its correlation with clinical outcomes. Findings from this study indicated that tendon stiffness reduced and strain increased after 12 weeks of eccentric exercise among in-season athletes with patellar tendinopathy. Increase in tendon strain was not enhanced by the addition of ESWT. More importantly, modulations of tendon mechanical properties were related to improvement in pain and dysfunction.

After a 12-week eccentric exercise either as a single program or combined with ESWT, tendon stiffness significantly reduced by ∼15%. There is only one previous study reporting a nonsignificant reduction in tendon stiffness after a program of eccentric exercise on subjects with patellar tendinopathy.4 Of the 12 subjects who completed 3 sets of 15 slow repetitions of eccentric unilateral squats on a 25-degree decline board twice daily for 12 consecutive weeks, reduction in tendon stiffness by ∼6% was reported. The seemingly greater increase in tendon stiffness in our study may be explained by the factor of age (relatively younger in our study) or the progressive nature of the loading program (increment of amount of load during the eccentric exercise program was specified in our study). The same research group later reported a decrease in tendon stiffness (by ∼9%) after 12 weeks of heavy slow resistance training program in subjects with patellar tendinopathy but not in healthy subjects (by ∼1% only).14 Nevertheless, Malliaras et al13 observed an increase in tendon stiffness and modulus after 12 weeks of eccentric exercise, concentric–eccentric, and standard eccentric exercises when compared with no training. Langberg et al33 found that the effect of exercise on collagen synthesis was different in healthy and pathological tendons. It seems that tendon adaptation may be different between healthy and pathological tendons. To determine whether the reductions of tendon stiffness in our study is a genuine observation (an opposite response of what had been reported in healthy tendons), correlations of the changes in tendon stiffness and strain with clinical outcomes were conducted.

What are the mechanisms that may explain the reduction of tendon stiffness and increase of strain after eccentric exercise program? Rees et al12 proposed that exercise results in mechanical stimulus, which may facilitate tendon remodeling. In addition, a transient change in tendon hydration state was reported in Achilles tendons after cross-country running.34 The authors proposed that such changes might relate to water exudation and collagen realignment. Ho and Kulig35 demonstrated similar reductions in tendon hydration state in the patellar tendon with or without tendinopathic changes. Whether our observation of change in tendon stiffness and strain is associated with a change in hydration state or realignment of newly formed fibres requires further investigation. The change of mechanical properties or pain severity could possibly be due to the fact that the subjects reduced the load or weight used during the exercise program. However, all subjects reported that they only increased or kept the load (cuff weight used during the eccentric exercise program) in the follow-up sessions. Also, they remained active in sports at the same level throughout the intervention period. Therefore, no case of “unloading” presented itself in this study.

When comparing the effect in the exercise and the combined groups, the change of tendon stiffness was 12% in the former and 29% in the latter, yet this difference was not statistically significant. Extracorporeal shockwave therapy facilitates IL-6, TGF-β1 expression as well as MMP-2 and pro-MMP-9 to stimulate fibroblast activity, type I collagen production, and tissue remodeling.36–38 Improvement in tendon tensile strength has been reported in animal studies using ESWT.18–20 In this study, a similar intensity of ESWT was applied during the initial 6 weeks of the eccentric exercise program. The nonsignificant effect of the combined intervention might relate to great interindividual variability in the response of MMP to ESWT.17 Furthermore, the ESWT was applied to the most painful spot at the proximal part of the tendon (about 5 mm from the inferior pole of the patella), but tendon strain was measured in general in this study. The potential localized effect on tendon strain and stiffness that induced by ESWT might better be assessed using other technology, such as ultrasound elastography.39 This study may be underpowered to show the additional effect of ESWT on tendon mechanical properties. A total of 40 subjects should be required to reach a statistical significance. The project team has recruited potential subjects for 18 months. Data collected could be used as reference for large-scale future studies.

Moderate associations between percentage changes in tendon stiffness and VISA-P scores as well as in tendon strain and intensity of pain were found in subjects receiving an eccentric exercise program. Greater reduction in tendon stiffness was associated with greater improvement on the VISA-P scores, whereas greater increase in tendon strain was associated with greater pain reduction and functional improvement. This is the first study to report a positive association between changes in tendon mechanical properties and clinical outcomes in athletes with patellar tendinopathy after an eccentric exercise program. The reduction in tendon stiffness was associated with better clinical outcomes. As lower tendon stiffness or higher tendon strain implies that the tendon is more extensible, such finding supports the notion that an eccentric exercise program for degenerative tendons may modulate tendon mechanical properties. Higher tendon strain may facilitate the tendon's ability to mechanically buffer the force transmitted through the tendon body during jumping or landing activities, which is one of the primary functions of a tendon.9 Such improvement of extensibility might in turn improve pain thresholds and jumping ability. Indeed, in athletes with patellar tendinopathy, tendon pain levels are correlated to tendon extensibility.27 However, stiffness has been found to be reduced in tendons with Achilles tendinopathy.40,41 It is interesting that such a relationship could not be observed among the combined group. This highlights that other factors may also explain the change in pain and further investigation is indicated.

In this study, tendon stiffness and strain were examined using ultrasound and dynamometry. The measurement method used did not allow localized or regional measurements of specific tendon properties. Methods such as ultrasound elastography are required to explore localized changes. We noted a relatively large variance of tendon force and stiffness among our subjects. Such variance may be due to a wide subject age and limited subject numbers. Narrower subject age and a larger subject size might help to minimize this variance because the measurement technique was reported to have good repeatability.27 Tendon thickness and hypoechoic areas were not recorded in this study. Previous longitudinal studies suggested that there is no significant relationship between ultrasonographic patellar tendon abnormalities and clinical outcome in elite male athletes.42,43 Although Malliaras et al 44 suggested that grey scale ultrasound changes may present different phases of tendon pathology, the tracking was done in nearly half a year, and we are not sure such changes could be detected during our 3-month study period. Future studies may be indicated to track such morphological changes. As the athletes continued to be active in sports at the same level as before and during the intervention, this might be a confounding factor with respect to the effects of the intervention. In addition, because only male participants were recruited, the results cannot be generalized to female population.

CONCLUSIONS

This study concluded that a 12-week eccentric exercise by single-legged decline squat induced significant changes in tendon mechanical properties. A reduction in tendon stiffness, an increase of patellar tendon strain together with reduction in pain, and dysfunction in athletes with patellar tendinopathy were observed. More importantly, the modulation in tendon mechanical properties was related to an improvement in clinical outcomes at the completion of the eccentric exercise program. This observation suggests that modulation of tendon mechanical properties at the affected tendon might be one of the exercise-induced treatment mechanisms for athletes with patellar tendinopathy. Combining exercise and ESWT could not been shown to be more effective than exercise alone among subjects with patellar tendinopathy.

Reference

1. Rodriguez-Merchan EC. The treatment of patellar tendinopathy. J Orthop Traumatol. 2013;14:77–81.

2. Cannell LJ, Taunton JE, Clement DB, et al. A randomised clinical trial of the efficacy of drop squats or leg extension/leg curl exercises to treat clinically diagnosed jumper’s knee in athletes: pilot study. Br J Sports Med. 2001;35:60–64.

3. Jonsson P, Alfredson H. Superior results with eccentric compared to concentric quadriceps training in patients with jumper’s knee: a prospective randomised study. Br J Sports Med. 2005;39:847–850.

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

5. Purdam CR, Jonsson P, Alfredson H, et al. A pilot study of the eccentric decline squat in the management of painful chronic patellar tendinopathy. Br J Sports Med. 2004;38:395–397.

6. Stasinopoulos D, Stasinopoulos I. Comparison of effects of exercise programme, pulsed ultrasound and transverse friction in the treatment of chronic patellar tendinopathy. Clin Rehabil. 2004;18:347–352.

7. Arampatzis A, Peper A, Bierbaum S, et al. Plasticity of human Achilles tendon mechanical and morphological properties in response to cyclic strain. J Biomech. 2010;43:3073–3079.

8. Alexander RM. Tendon elasticity and muscle function. Comp Biochem Physiol A Mol Integr Physiol. 2002;133:1001–1011.

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

10. Arampatzis A, De Monte G, Karamanidis K, et al: Influence of the muscletendon unit’s mechanical and morphological properties on running economy. J Exp Biol. 2006;209:3345–3357.

11. Kubo K, Tabata T, Ikebukuro T, et al. Effects of mechanical properties of muscle and tendon on performance in long distance runners. Eur J Appl Physiol. 2010;110:507–514.

12. Rees JD, Lichtwark GA, Wolman RL, et al. The mechanism for efficacy of eccentric loading in Achilles tendon injury; an in vivo study in humans. Rheumatology (Oxford). 2008;47:1493–1497.

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

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

15. Wang CJ, Ko JY, Chan YS, et al. Extracorporeal shockwave for chronic patellar tendinopathy. Am J Sports Med. 2007;35:972–978.

16. Taunton KM, Taunton JE, Khan KM. Treatment of patellar tendinopathy with extracorporeal shock wave therapy. B C Med J. 2003;45:500–507.

17. Rosso F, Bonasia DE, Marmotti A, et al. Mechanical stimulation (Pulsed Electromagnetic Fields “PEMF” and Extracorporeal Shock Wave Therapy “ESWT”) and tendon regeneration: a possible alternative. Front Aging Neurosci. 2015;7:211.

18. Hsu RW, Hsu WH, Tai CL, et al. Effect of shock-wave therapy on patellar tendinopathy in a rabbit model. J Orthop Res. 2004;22:221–227.

19. Wang CJ, Wang FS, Yang KD, et al. The effect of shock wave treatment at the tendon-bone interface-an histomorphological and biomechanical study in rabbits. J Orthop Res. 2005;23:274–280.

20. Wang L, Qin L, Lu HB, et al. Extracorporeal shock wave therapy in treatment of delayed bone- tendon healing. Am J Sports Med. 2008;36: 340–347.

21. Rompe JD, Furia J, Maffulli N. Eccentric loading versus eccentric loadingplus shock-wave treatment for midportion achilles tendinopathy: a randomized controlled trial. Am J Sports Med. 2009;37:463–470.

22. Thijs KM, Zwerver J, Backx FJ, et al. Effectiveness of shockwave treatment combined with eccentric training for patellar tendinopathy: a double-blinded randomized study. Clin J Sport Med. 2017;27:89–96.

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

24. Kubo K, Yata H, Kanehisa H, et al. Effects of isometric squat training on the tendon stiffness and jump performance. Eur J Appl Physiol. 2006;96: 305–314.

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

26. Hermens HJ; Commission of the European Communities, SENIAM project. European Recommendations for Surface Electromyography: Results of the SENIAM Project. 2nd ed. Enschede, The Netherlands: Roessingh Research and Development; 1999:15–54.

27. Lee WC, Zhang ZJ, Masci L, et al. Alternations in mechanical properties of the patellar tendon is associated with pain in athletes with patellar tendinopathy. Eur J Appl Physiol. 2017;117:1039–1045.

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

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

30. Visentini PJ, Khan KM, Cook JL, et al. 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. 1998;1: 22–28.

31. Young MA, Cook JL, Purdam CR, et al. Eccentric decline squat protocol offers superior results at 12 months compared with traditional eccentric protocol for patellar tendinopathy in volleyball players. Br J Sports Med. 2005;39:102–105.

32. Vetrano M, Castorina A, Vulpiani MC, et al. Platelet-rich plasma versus focused shock waves in the treatment of jumper’s knee in athletes. Am J Sports Med. 2013;41:795–803.

33. Langberg H, Ellingsgaard H, Madsen T, et al. Eccentric rehabilitation exercise increases peritendinous type I collagen synthesis in humans with Achilles tendinosis. Scand J Med Sci Sport. 2007;17:61–66.

34. Grosse U, Syha R, Gatidis S, et al. MR-based in vivo follow-up study of achilles tendon volume and hydration state after ankle-loading activity. Scand J Med Sci Sports. 2016;26:1200–1208.

35. Ho KY, Kulig K. Changes in water content in response to an acute bout of eccentric loading in a patellar tendon with a history of tendinopathy: a case report. Physiother Theory Pract. 2016;32:566–570.

36. Vetrano M, d’Alessandro F, Torrisi MR, et al. Extracorporeal shock wave therapy promotes cell proliferation and collagen synthesis of primary cultured human tenocytes. Knee Surg Sports Traumatol Arthrosc. 2011; 19:2159–2168.

37. Visco V, Vulpiani MC, Torrisi MR, et al. Experimental studies on the biological effects of extracorporeal shock wave therapy on tendon models. A review of the literature. Muscles Ligaments Tendons J. 2014;4: 357–361.

38. Waugh CM, Morrissey D, Jones E, et al. In vivo biological response to extracorporeal shockwave therapy in human tendinopathy. Eur Cell Mater. 2015;29:268–280; discussion 280.

39. Zhang ZJ, Fu SN. Shear elastic modulus on patellar tendon captured from supersonic shear imaging: correlation with tangent traction modulus computed from material testing system and test-retest reliability. PLoS One. 2013;8:e68216.

40. Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. J Appl Physiol. 2010;108:670–675.

41. Child S, Bryant AL, Clark RA, et al. Mechanical properties of the Achilles tendon aponeurosis are altered in athletes with achilles tendinopathy. Am J Sports Med. 2010;38:1885–1893.

42. Cook JL, Khan KM, Kiss ZS, et al. Asymptomatic hypoechoic regions on patellar tendon ultrasound: a 4-year clinical and ultrasound follow up of 46 tendons. Scand J Med Sci Sports. 2001;11:321–327.

43. Cook JL, Khan KM, Kiss ZS, et al. Prospective imaging study of asymptomatic patellar tendinopathy in elite junior basketball players. J Ultrasound Med. 2000;19:473–479.

44. Malliaras P, Purdam C, Maffulli N, et al. Temporal sequence of greyscale ultrasound changes and their relationship with neovascularity and pain in the patellar tendon. Br J Sports Med. 2010;44:944–947.

Table 1. Demographic Data

	Exercise group (n=14)	Combined group (n=16)	p
Age, yr	24.1 ± 4.6	21.1 ± 2.2	0.09
BMI, kg/m^2	23.1 ± 2.7	22.9 ± 1.5	0.85
No. of hours on sports training, h/wk	5.4 ± 2.0	5.5 ± 2.3	0.82
Duration of symptoms, mo	31.5 ± 30.0	35.6 ± 22.4	0.38
Unilateral/bilateral symptom	6:8	8:8	0.73
Maximum self-perseived pain in the past 7d	6.6 ± 2.0	6.7 ± 1.9	0.90
VISA-P score	57.4 ± 8.2	55.1 ± 12.9	0.56

BMI, body mass index.

Table 2. Tendon Force and Mechanical Properties

	Exercise group (n=14)		Combined group (n=16)		p
	Pre	Post	Pre	Post	
Force, N	15457 ± 5181	15235 ± 4851	14047 ± 4011	13141 ± 2647	0.98
Resting length, mm	48.0 ± 6.0	48.1 ± 5.9	50.2 ± 4.5	50.7 ± 4.7	0.70
Deformation, mm	5.0 ± 1.9	6.0 ± 2.3	5.0 ± 2.1	6.7 ± 2.5	0.10
Stiffness, N/mm	3544 ± 1820	3108 ± 2031	3342 ± 1836	2363 ± 1402	0.02
Strain, %	10.6 ± 4.0	12.8 ± 5.4	9.9 ± 4.3	13.3 ± 5.4	0.01

P value represents main time effect.

Table3 Correlation Coefficients Between Percentage Changes in Tendon Mechanical Properties and Clinical Outcomes

	Exercise group		Combined group	
	Pain score	VISA-P	Pain score	VISA-P
Tendon stiffness	0.55 (p=0.07)	-0.58 (p=0.05)	0.01 (p=0.98)	0.37 (p=0.17)
Tendon strain	-0.63 (p=0.03)	0.60 (p=0.04)	0.01 (p=0.98)	-0.40 (p=0.13)

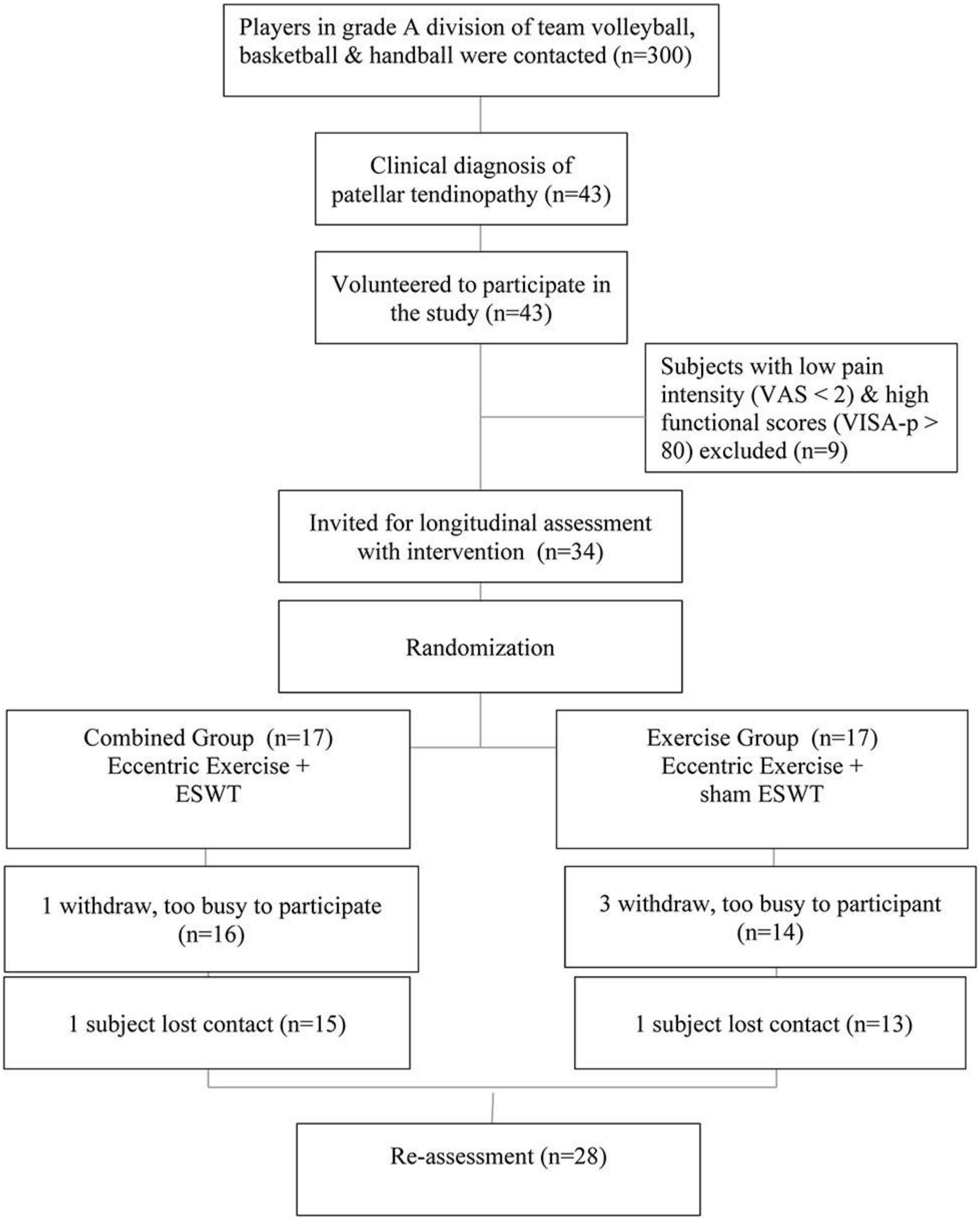

Figure 1. CONSORT diagram showing the flow of participants through the study. ESWT, extracorporeal shockwave therapy; VAS, visual analog scale.

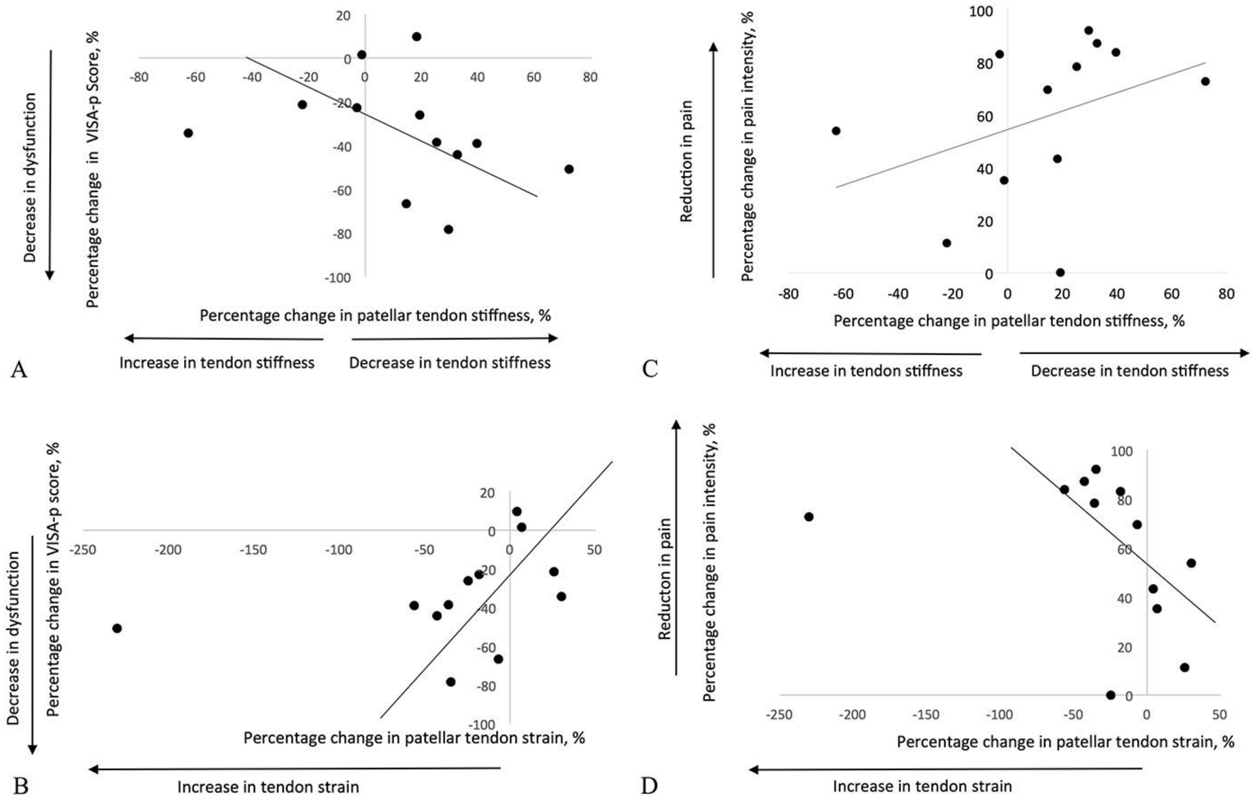

Figure 2. Scatter plots between percentage changes in tendon stiffness with VISA-p scores (A) and intensity of pain (B); percentage changes in tendon strain with VISA-p scores (C) and intensity of pain (D).