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Patellar tendon adaptation in relation to load-intensity and contraction type

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ABSTRACT

Background: Loading leads to tendon adaptation but the influence of load-intensity and contraction type is unclear. Clinicians need to be aware of the type and intensity of loading required for tendon adaptation when prescribing exercise. The aim of this study was to investigate the influence of contraction type and load-intensity on patellar tendon mechanical properties.

Method: Load intensity was determined using the 1 repetition maximum (RM) on a resistance exercise device at baseline and fortnightly intervals in four randomly allocated groups of healthy, young males: (1) control (no training); (2) concentric (80% of concentric–eccentric 1RM, 4×7–8); (3) standard load eccentric only (80% of concentric-eccentric 1RM, 4×12–15 repetitions) and (4) high load eccentric (80% of eccentric 1RM, 4×7–8 repetitions). Participants exercised three times a week for 12 weeks on a leg extension machine. Knee extension maximum torque, patellar tendon CSA and length were measured with dynamometry and ultrasound imaging. Patellar tendon force, stress and strain were calculated at 25%, 50%, 75% and 100% of maximum torque during isometric knee extension contractions, and stiffness and modulus at torque intervals of 50–75% and 75–100%. Within group and between group differences in CSA, force, elongation, stress, strain, stiffness and modulus were investigated. The same day reliability of patellar tendon measures was established with a subset of eight participants.

Results: Patellar tendon modulus increased in all exercise groups compared with the control group ($p < 0.05$) at 50–75% of maximal voluntary isometric contraction (MVIC), but only in the high eccentric group compared with the control group at 75–100% of MVIC ($p < 0.05$). The only other group difference in tendon properties was a significantly greater increase in maximum force in the high eccentric compared with the control group ($p < 0.05$). Five repetition maximum increased in all groups but the increase was significantly greater in the high load eccentric compared with the other exercise groups ($p < 0.05$).

Conclusion: Load at different intensity levels and contraction types increased patellar tendon modulus whereas muscle strength seems to respond more to load-intensity. High load eccentric was, however, the only group to have significantly greater increase in force, stiffness and modulus (at the highest torque levels) compared with the control group. The effects and clinical applicability of high load interventions needs to be investigated further.

1. Introduction

Tendon is a fibrous connective tissue with a high tensile strength that functions to transfer load from muscle to bone. Some tendons have an additional function in storing and releasing mechanical load during stretch-shortening cycle activities such as running, jumping and throwing (Birch, 2007). This tendon function serves to improve performance and increase efficiency of human movement (Fukashiro et al., 2006). A paradox is that tendons that are designed for storing and releasing energy also succumb to tendon overload injury, or tendinopathy. For example, the patellar tendon stores and releases high levels of energy during jumping and this probably contributes to the high prevalence (up to 50%) of patellar tendinopathy among elite volleyball players (Lian et al., 1996; Malliaras and Cook, 2006).

The gold standard for managing Achilles and patellar tendinopathy, two of the most common lower limb tendinopathies, are

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eccentric muscle contractions applied as a regular training programme over a number of months. Recent reviews have advocated this form of muscle training based on current evidence as a first line treatment for these injuries (Gaida and Cook, 2011; Kingma et al., 2007). Little is known about the mechanisms explaining eccentric muscle training efficacy but there are reports of improved tendon structure (e.g. including reversal of pathology (Ohberg et al., 2004)) and improved muscle strength (Alfredson et al., 1998; Kongsgaard et al., 2009), although reports of improved tendon structure are not universal (de Jonge et al., 2010; Petersen et al., 2007). Pathological tendons may have reduced stiffness (Arya and Kulig, 2010; Child et al., 2010), so restoring this property may improve musculotendinous function and reduce recurrence.

Tendon is able to remodel its material and structural properties in response to increased levels of loading. Several authors have shown increased stiffness and in some cases an increase in cross sectional area (CSA) in response to chronic tendon loading (Arampatzis et al., 2007; Burgess et al., 2007; Kongsgaard et al., 2007; Kubo et al., 2007; Magnusson et al., 2008; Reeves et al., 2003). Maximizing tendon strain seems to be important in enabling tendon adaptation. Arampatzis et al. (2007) compared maximal isometric voluntary contraction (MVIC) producing either 2.5–3.0% or 4.5–5.0% strain performed four times per week over 14 weeks and found that only the 'high-strain' group had an increase in Achilles tendon stiffness. A more recent study by the same group showed that the tendon stiffness response was reduced when the strain frequency was increased (from 0.17 to 0.5 Hz) (Arampatzis et al., 2010). Taken together, tendon seems to respond to sustained contractions and greater load intensity, both producing greater strain.

Most clinical eccentric training studies use a dosage of three sets of 15 repetitions and load is progressed in order to induce pain (Alfredson et al., 1998). There is evidence that tendinopathy patients may benefit from higher load intensities such as 6RM (Konsggaard et al., 2009), but it is unknown whether the magnitude of the load or contraction type are predominant factors responsible for tendon adaptation and whether this explains some of the improved pain and function outcomes in some tendinopathy studies. The aim of this study was to investigate tendon adaptation to: (1) eccentric loading of different magnitudes, and (2) different contraction types (concentric or eccentric) at a similar magnitude, in healthy tendons.

2. Method

Thirty-eight healthy male volunteers were recruited from staff and students at Queen Mary, University of London. Men between 18 and 35 years old were recruited as load response may deteriorate with age (Reeves et al., 2004). Potential participants were excluded if they weight trained regularly or had any lower limb pain that may interfere with the interventions and tests in this study. The study was approved by the Queen Mary University of London, Research Ethics Committee.

2.1. Pre-testing

Participants' age, height, weight, weight training history (yes/no and how long ago they stopped) and activity level were recorded with a questionnaire. Knee girth (at the joint line), was measured. Weight and skinfolds were also measured at the end of the training period. Ultrasound imaging appearance (presence or absence of gray scale abnormality or Doppler signal) was assessed at baseline.

2.2. Exercise interventions

Participants were randomly allocated to one of four groups: (1) control (no exercise); (2) concentric training (80% of concentric–eccentric 1RM, 4×7–8); (3) standard load eccentric training (80% of concentric-eccentric 1RM, 4×12–15 repetitions) and (4) higher load eccentric training (80% of eccentric 1RM, 4×7–8 repetitions). In the eccentric groups, participants lifted the weight with two legs and performed the lowering phase with their left leg (thereby minimizing the influence of any concentric contraction). In the concentric group participants lifted the weight with one leg and lowered with two (thereby minimizing the role of any eccentric contraction). The training was therefore predominantly eccentric or concentric, but there was a small component of the other contraction type in each.

Participants selected a group number from an opaque envelope and were stratified based on activity ($<$ or $>$ 3 h of running and jumping activity per week). At baseline and once per fortnight the relevant 5RM was tested (eccentric for high load eccentric and concentric-eccentric for concentric and standard load eccentric group). 5RM was converted to 1RM (Brzycki, 1993) and used to set load intensity for the following fortnight. The concentric-only and standard load eccentric-only training was performed at 80% of concentric–eccentric 1RM whilst the higher load eccentric-only training was performed at 80% of eccentric 1RM. Participants exercised to fatigue which was typically 12–15 repetitions for the standard load eccentric and 7–8 repetitions for the higher load eccentric and concentric groups. Fatigue was defined as difficulty with, or an inability to complete the last 2–3 repetitions of at least the third and fourth set. The control group was asked to refrain from any weight training during the study period. Both exercise groups performed their exercise on a leg extension machine (SL-153 leg extension, Johnson Fitness, Taiwan) three times per week for 12 weeks. The duration of each eccentric lowering phase was standardized to 5 s using a metronome and knee extensions were performed in a range between 0° and 90° knee flexion.

Exercise technique and pain during training (yes/no during each session) were assessed every fortnight. Compliance was monitored closely as all participants trained in the Centre for Sports and Exercise Medicine, Queen Mary, using the same leg extension machine. Participants marked off each session they completed on a training register. At the end of the study compliance (% of sessions completed) was calculated. Participants were contacted by phone and/or email if they were falling behind in their sessions for any given week (i.e. by Tuesday if they had not performed any training during that working week) and a training time arranged. The lead researcher (PM) regularly organized to meet participants during the weekend so they could make up training they had missed.

2.3. Measurement of knee extension and flexion torque

Participants were seated comfortably in the dynamometer (Isocom, Eurokinetics, UK), with the knee in 90° flexion. The axis of the knee and dynamometer were aligned and straps were positioned at the hip and thigh. All testing and interventions were performed on the participants left leg only. Torque was measured during three maximal isometric knee flexion trials. Participants then performed a maximal isometric knee extension contraction that lasted for 5 s and were instructed to gradually increase to peak torque over the first second. Five preconditioning contractions were performed, including two maximal, and 25%, 50%, 75% of maximal. This was designed to bring tendon stiffness to a steady state for reproducibility and allowed participants practice at maintaining submaximal contractions accurately.

Following the preconditioning trials, two sets of four trials were performed at 25%, 50%, 75% and 100% of MVIC, in random order. If the torque was not stable in the final 3 s of a particular trial (visual inspection of plotted data from dynamometer) the trial was repeated. Sixty seconds rest was allowed between each trial.

2.4. Measurement of surface electromyography

Co-contraction of the antagonist was estimated so that total patellar force (that attributed to both agonist and antagonist contraction) could be calculated. Biceps femoris muscle surface electromyography (sEMG) was measured during flexion MVIC and this relationship was used to estimate antagonist (hamstring) torque based on biceps femoris sEMG during extension MVIC. To achieve this sEMG was measured from biceps femoris muscle during knee extension as well as during maximal and submaximal knee flexion contractions. EMG was recorded via wireless surface electromyography (sEMG) (Telemyo 2400T G2, Noraxon, USA). The skin was prepared and Ag/AgCl electrodes placed over the biceps femoris according to standard SENIAM guidelines (Freriks and Hermens, 2000), with an inter-electrode distance of 20 mm. Surface EMG signals were sampled at 1500 Hz, pre-amplified and band-pass filtered between 10 and 500 Hz, prior to export to excel for post-processing.

2.5. Ultrasound imaging measures of tendon elongation, CSA and length

In vivo measurement of patellar tendon elongation was performed with ultrasound imaging, using a 7.5 MHz linear array transducer (Voluson-i, GE Medical Systems, Milwaukee, USA). The lead researcher who has postgraduate training in ultrasound imaging performed all ultrasound imaging. Prior to imaging an echo-absorptive marker (a thin aluminium strip) was placed across the patellar tendon, 1 cm below the inferior patella pole (Fig. 1). The transducer was placed in the sagittal plane over the proximal part of the patellar tendon and measured patellar tendon elongation during each trial. During MVIC any proximal movement of the inferior patellar pole away from the line cast by the marker indicated patellar tendon elongation (Fig. 2) and was subsequently measured by digitizing video recordings of each contraction (ImageJ, U.S. National Institutes of Health, Bethesda, Maryland). Patellar tendon length (inferior patella pole to tibial tuberosity) and CSA (at 50% of tendon length) were also measured. An average of two measures was used for each. Knee extension movement during the MVIC was measured with an electronic inclinometer placed along the anterior tibia. Trials were discarded if movement was greater than 10° this would overestimate tendon elongation.

Fig. 1. Placement of the echo-absorptive marker.

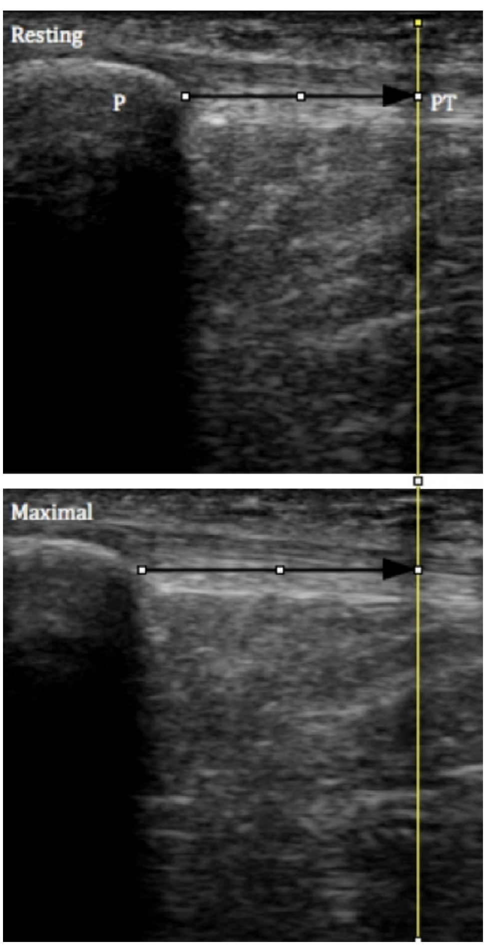

Fig. 2. Sagittal plane ultrasound image showing echo-absorptive marker (draw over with yellow line), patella (P) and patellar tendon (PT) in the resting and maximally contracted positions. The black shows the measurement taken in each position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.6. Re-test

At 12-weeks follow-up tendon CSA, length, patellar tendon elongation, knee flexion and extension torque and weight were re-measured using identical methods. Participants were asked whether they had undertaken any other weight training or changed their sports activity level during the study period.

2.7. Calculation of patellar tendon force, stiffness and material properties

Patellar tendon force was calculated using the moment equilibrium equation. Total torque was given by the sum of the knee extensor and estimated knee flexor torque and was divided by the patellar tendon moment arm. The patellar tendon moment arm length was estimated by a fixed value for this anatomical parameter (44.7 mm) taken from previous studies (Baltzopoulos, 1995; Krevolin et al., 2004). Knee girth was measured to test the validity of assuming a constant tendon moment arm length for all participants. Knee girth did not differ significantly between the groups ($p > 0.05$, Table 1), indicating that the estimate of patellar tendon moment arm was equally valid for each group. Patellar tendon stiffness (change in force divided by change in elongation, N mm^{-1}) was calculated between the higher torque intervals of 50–75% and 75–100% of maximal torque, as this is most relevant to patellar tendon injury in running and jumping athletes. Tendon modulus (MPa) was calculated at the same torque intervals by multiplying the stiffness value by the ratio of tendon length to CSA. Stress (force divided by CSA) and strain (elongation divided by tendon length) were calculated at each tendon force interval.

2.8. Measurement reliability

Reliability of measuring tendon elongation and calculating stiffness were assessed among a subset of eight participants. Intra-rater reliability was assessed for tendon elongation at 25%, 50%, 75% and 100% of MVIC and subsequent calculation of stiffness at each torque interval. Two trials were recorded at each intensity and then this was repeated after a 30 min rest during which participants were taken out of the dynamometer chair. Intra-rater reliability was estimated using interclass correlation coefficients for tendon elongation (0.88, 95% CI = 0.60–0.98) and tendon modulus (0.96, 95% CI = 0.81–0.99). The typical error was 0.40 mm (95% CI = 0.26–0.89) for elongation and 138.3 MPa (95% CI = 89.1–304.4) for modulus.

2.9. Data processing

Tendon elongation, sEMG and torque measures were manually synchronized for each recording after a 3 s count down, and each trial recorded for 5 s. For each measure the final 3 s of each trial were used in analyses. Excel was used to calculate the root mean square sEMG and mean torque over this period. Tendon CSA, length and elongation were measured from digitized ultrasound images by a single assessor who was blind to group allocation.

2.10. Statistical analysis

Statistical analysis was performed using SPSS (version 18.0, SPSS Inc., Chicago, Il). Baseline characteristics were compared using factorial ANOVA (age, height, weight, knee girth, compliance, 5RM, maximum torque, force, elongation, CSA, stress, strain, stiffness, modulus) and Chi-square (activity). Within group change and difference between the groups in change scores was investigated (5RM, maximum torque, force, elongation, CSA, stress, strain, stiffness, modulus) using

Table 1
Baseline characteristics for each group.

	Control	Concentric	Eccentric standard	Eccentric high
Number	9	9	10	10
Age (yr)	26 (4.1)	29 (5.1)	28 (4.6)	27 (3.8)
Height (cm)	177 (6.9)	179 (9.0)	179 (7.5)	177 (8.3)
Weight (kg)	73 (6.5)	79 (14.5)	76 (12)	75 (6.3)
Knee girth (cm)	36 (1.3)	38 (2.9)	37 (2.6)	37 (1.6)
Compliance (% sessions)		89 (7.0)	87 (5.1)	89 (6.2)
Activity (hours of sport/week)				
Standard (> 3 h/week)	2 (22%)	4 (44%)	5 (50%)	5 (50%)
High (≤3 h/week)	7 (78%)	5 (56%)	5 (50%)	5 (50%)

Note: frequency/proportion shown for activity and compliance; mean (SD) for all other variables repeated measures *t*-tests and factorial ANOVA, respectively. Significant factorial ANOVA findings were investigated further with the Student Newman–Keuls post hoc test. The relationship between stiffness and modulus at baseline and follow up was investigated (Pearson's correlation). The proportion of training sessions in which participants reported pain was compared across the three exercise groups (Chi-square test). The alpha level was set at 0.05.

3. Results

There was no significant difference in demographic factors (age, height, activity) and exercise compliance between the groups at baseline ($p>0.05$, Table 1). All participants were pain-free at the start of the study. There was no significant difference in the number of training sessions in which pain was reported in each group (1.3–2.0%, $\chi^2=0.1$, $p=0.72$). One subject in each exercise group had anterior knee pain during the isokinetic follow up testing. Removing this subject from the analysis did not change the findings.

3.1. Stiffness and modulus

Force-elongation and stress–strain increased in a curvilinear fashion in all three exercise groups and curves shifted to the left after training (Figs. 3 and 4). There was no significant difference in modulus at 50–75% and 75–100% MVIC between the groups at baseline ($p>0.05$). Initial stiffness did not predict change in stiffness in the entire cohort ($p>0.05$), so small group differences initially in force-elongation and stress–strain relationships are unlikely to have influenced patellar tendon adaptation to load. Change in modulus was not different between the concentric and standard eccentric (Fig. 3) or the standard and high load eccentric groups (Fig. 4) at 50–75% and 75–100% MVIC ($p>0.05$). Change in modulus was greater in the exercise groups compared with the control groups at 50–75% (control = −3.4%, concentric = +80.8%, standard eccentric = 59.4%, high eccentric = 87.3%, $p<0.05$, Table 2), however, only the high eccentric group was significantly greater than controls at 75–100% of maximum torque (control = +2.5%, concentric = +70.6%, standard eccentric = 59.4%, high eccentric = +84.3%, $p<0.05$, Table 2).

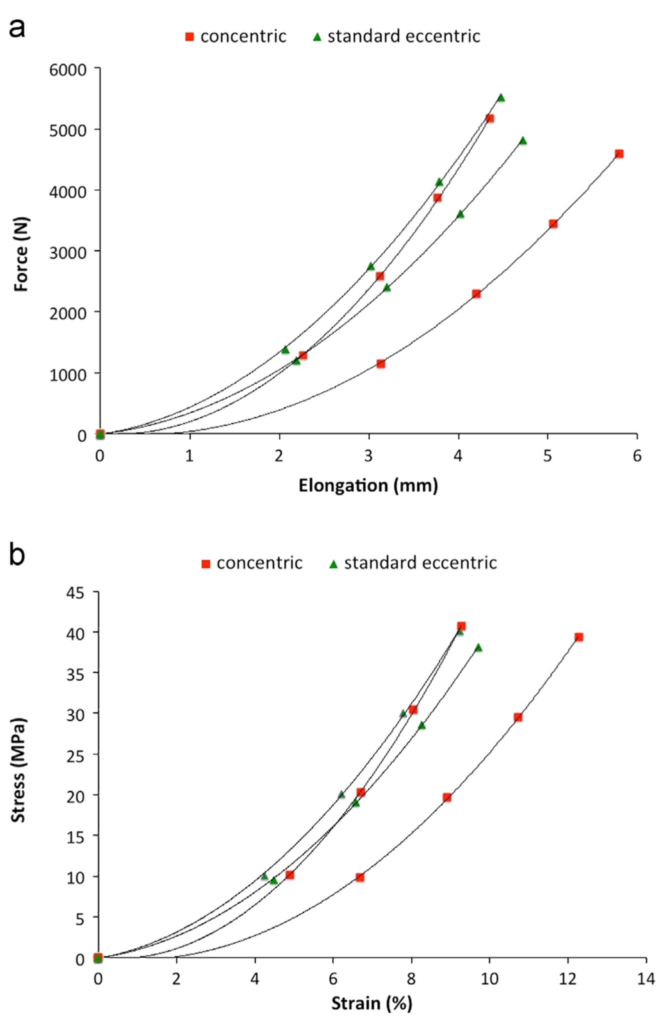

Fig. 3. Pre and post force-elongation (a) and stress–strain (b) curves comparing eccentric and concentric loading (post intervention curves have shifted to the left).

3.2. Force, elongation, CSA, stress and strain

There were no baseline differences in CSA, maximum force, elongation, stress and strain values in any group (Table 2, $p>0.05$). There was no significant change in CSA in any group (Table 2, $p>0.05$). Force increased significantly in the two eccentric groups (low eccentric +16%, high eccentric +31%) and stress increased significantly in the high eccentric training group (+24%). The only group difference was a significantly greater change (increase) in force in the high eccentric (+24%) compared with the control group (+4%) (Table 2, $p<0.05$). Elongation (−26%) and strain (−25%) decreased significantly over time in the concentric group (Table 2, $p<0.05$), and there were no significant differences in change in elongation and strain between the groups (Table 2, $p>0.05$).

3.3. Muscle strength

There was no significant difference in RM and maximum torque between the groups at baseline (Table 2, $p>0.05$). 5RM increased in all exercise groups (concentric = +53%; standard eccentric = +61%; high eccentric = +77%; $p<0.01$). Change in 5RM was significantly greater in the high load eccentric group compared with the other exercise groups ($p<0.01$). Maximum torque increased significantly over the training period in the exercise groups (concentric = +18%; standard eccentric = +16%; high eccentric = +23%, $p<0.05$) groups. Change in maximum torque was not significantly different between the groups (Table 2, $p>0.05$).

4. Discussion

Change in patellar tendon stiffness and modulus over the 12-weeks study period was significantly greater for all exercise groups compared with the control group. Increase in modulus was greater in the high load eccentric group (84–87%) compared with the low load eccentric group (59%) but the difference was not significant and this may be partly due to small group sample size in this study. The only group difference was a significantly greater increase in stiffness and modulus at the highest torque interval (75–100%) in the high eccentric compared with control group. Again, this may relate to sample size, but it may also indicate that heavier load eccentric interventions may be more likely to influence stiffness and modulus at higher torque levels. The current findings may have implications for tendinopathy rehabilitation, as patellar tendinopathy is common in sports people who perform high tendon loading activity, such as volleyball and basketball players performing maximal jumps.

Reeves et al. (2003) also found that the magnitude of adaptation in the patellar tendon was greater at higher torque. Reeves et al. (2003) investigated older adults (mean age 67–73 yr) and modulus was generally higher than in the current study, both before (approximately 1.3. vs. 0.5 GPa) and after training (2.2 vs. 0.9 GPa). This may reflect differences in force regions examined. Reeves et al. (2003) examined smaller force regions that would

Table 2
Baseline, follow up and % change scores (SD) for tendon properties and muscle strength.

	Control			Concentric			Eccentric standard			Eccentric high		
	Pre	Post	% change	Pre	Post	% change	Pre	Post	% change	Pre	Post	% change
Stiffness	1450.9	1370	−3.4	1328.9	2160	80.7	1501.9	2155.9	59.4	1152.9	2138.1	87.3
(Nm) 50–75%	(279.7)	(237.6)	(19.2)	(548.5)	(686)	(82.3)	(598.3)	(713)	(80.5)	(303.2)	(882.1)	(67.7)
Stiffness	1596.7	1585.6	2.5	1560	2338	70.6	1822.1	2536.5	59.4	1386.9	2508.3	84.3
(Nm) 75–100%	(339.6)	(258.6)	(24.8)	(792.6)	(637.8)	(81.8)	(898.3)	(849.8)	(79.7)	(360.2)	(1066.4)	(72)
Modulus (MPa)	634.9	604.2	−3.4	520.1	867.2	80.8	608	870.7	59.4	474.4	853	87.3
50–75%	(127.9)	(141.2)	(19.2)	(163.7)	(279.1)	(82.3)	(274.5)	(287.2)	(80.5)	(165.6)	(318.6)	(67.7)
Modulus (MPa)	698.1	702	2.5	619.9	942.4	70.6	737.4	1021.8	59.4	570.4	1011.2	84.2
75–100%	(157)	(173.2)	(24.8)	(223.4)	(278.8)	(81.8)	(390.2)	(338.6)	(79.7)	(191.2)	(435.8)	(72)
Max. Stress	45.5	46.1	1.9	40.9	44.8	13.6	41.4	46.1	12.9	37.3	45.7	24.4
(MPa)	(7)	(9.4)	(17.5)	(11.9)	(12.3)	(32.9)	(11.5)	(13.2)	(20.2)	(5.9)	(6.2)	(22.3)
Max. Strain	11.7	11.4	2.8	12.3	9.3	−24.9	9.7	9.2	−1.2	11.8	10.3	−10.3
(%)	(3.9)	(2.4)	(25.5)	(2.3)	(3.2)	(17.9)	(2.3)	(2.2)	(29.4)	(3.6)	(3.4)	(27)
Tendon CSA	106.2	108	2.1	112.5	118.1	5.0	116.3	120.5	6.2	113.9	120.5	2.1
(mm^2)	(11.4)	(11)	(7.8)	(5.6)	(8.6)	(7.0)	(8.5)	(19.2)	(8.7)	(18.9)	(19.2)	(7.8)
Force	4778.6	4922.8	3.5	4589.2	5277.1	17.7	4817.2	5512.7	16.2(16.	4211.1	5488.7	30.9
(N)	(581.3)	(814.5)	(16.5)	(1285.8)	(1431.9)	(27.3)	(1491.5)	(1468.7)	5)	(735.6)	(1153.5)	(17.4)
Elongation	5.45	5.2	1.2	5.9	4.4	−25.9	4.8	4.3	−8.4	5.8	4.9	−13.9
(mm)	(1.6)	(1)	(24.2)	(1)	(1.2)	(17.9)	(1.2)	(1.2)	(25.5)	(1.5)	(1.3)	(21.9)
5RM	NA	NA	NA	49.7	74.5	52.7	48.8	75	60.7	57.8	99.6	76.7
(kg)				(13.4)	(14.6)	(17.4)	(15.9)	(16.4)	(27.5)	(8.9)	(11.7)	(37.7)
Torque (Nm)	209.4	225.8	10.1	209.6	242.3	17.6	214.9	245.3	16.2	192	234.5	23.1
	(30.6)	(34.9)	(27.2)	(49.8)	(52.8)	(19.9)	(69.8)	(63.7)	(13.8)	(30.5)	(36.4)	(17.3)

give higher values of stiffness and modulus. Kubo et al. (2005) investigated a younger cohort as in the current study but reported higher patellar tendon stiffness before (approximately 80 vs. 15 Nm) and after (approximately 120 vs. 24 Nm) (Kubo et al., 2005). Different measurement methods are likely to explain the lower stiffness/modulus values in the current study so it is important to compare change in stiffness rather than absolute magnitude. Change in stiffness and modulus was comparable or greater in the current (+59–87%) compared with previous studies (34–60%) (Reeves et al., 2003; Kubo et al., 2005) and this probably reflects the intensity of training (all $>80\%$ 1RM).

The load interventions in the current study were relatively intense, and one issue with transfer into clinical populations is the pain response with loading. The lowest intensity loading was 80% of concentric–eccentric 1RM, and this is higher than the load-intensity used in some patellar tendinopathy clinical studies (Cannell et al., 2001; Jonsson and Alfredson, 2005). Kongsgaard et al. (2010) found that patellar tendon stiffness decreased after 12 weeks of heavy load isotonic training. It is therefore not clear whether increased elastic modulus is a potential mechanism explaining the positive clinical outcomes with patellar tendon eccentric loading and other rehabilitation (Jonsson and Alfredson, 2005; Kongsgaard et al., 2010; Purdam et al., 2004; Visnes et al., 2005; Young et al., 2005). Pathological tendons may take longer to respond, and tendons with more severe pathology on imaging may be less likely to change with loading (Malliaras et al., 2006), including changes in tendon mechanical properties. Eccentric training may be more likely than concentric to have an effect on the nervous system (Fang et al., 2001; Hortobágyi et al., 1996), pain mechanisms or the muscle among clinical populations. It remains to be seen whether more intense interventions among clinical populations are feasible and lead to better long term clinical outcomes.

There are different mechanisms explaining increase in stiffness and elastic modulus and this may depend on contraction type and load-intensity. Only the concentric group had a significant decrease in elongation and strain, even though change in force did not vary between the groups. Concentric contractions involve muscle shortening during which the tendon strains but may not strain as much as it does in eccentric contraction. Morrissey et al. (2011) recently found that Achilles tendon strain increased following 6 weeks of isolated eccentric but not isolated concentric loading with no additional load (i.e. bodyweight only). Further studies are needed to determine whether contraction type has a differential effect on tendon elongation and strain.

Only the high load eccentric group had a significantly greater increase in tendon stress compared to the control group. This suggests that in line with previous work (Arampatzis et al., 2007), changes in material properties (stiffness, modulus) in the high load eccentric group were related to load-intensity. The high load eccentric group, who exercised at the highest load intensity of any group, also had the greatest increase in MVIC and 5RM and it is well known that load-intensity is a stimulus for muscle strength adaptations (Roig et al., 2009). These findings support a load dependent change in muscle and tendon properties following loading but this needs to be investigated further in clinical populations with tendinopathy. Importantly, it needs to be determined whether clinical populations will respond in a similar way and how symptoms will influence potential load intensity.

Patellar tendon CSA did not change significantly in any exercise group over the 12 weeks study period, indicating that increased stiffness and modulus were primarily related to change in material rather than structural properties. Material properties may have improved via several mechanisms, including increased collagen packing density, alterations in crimp angle, or even increased water content (Michna and Hartmann, 1989; Woo et al., 1980; Wood et al., 1988).

Strain was higher and modulus lower than other studies in the literature for the same tendon (Kongsgaard et al., 2010; Reeves et al., 2003) and this may be related to increased knee rotation (up to 10) during MVIC into knee extension. CSA may have been more accurately measured with MRI but this could not be accessed for this study. Although training was mostly concentric or eccentric, participants performed the other contraction mode bilateral to return to the weight to the starting position. This means our contraction type intervention was not pure but it was pragmatic and would be suitable in a clinical environment. Another limitation of this study was the small group sample size and limited power, for example, +39% change in modulus in the standard load eccentric group was not significantly different to a +1% change in the control group.

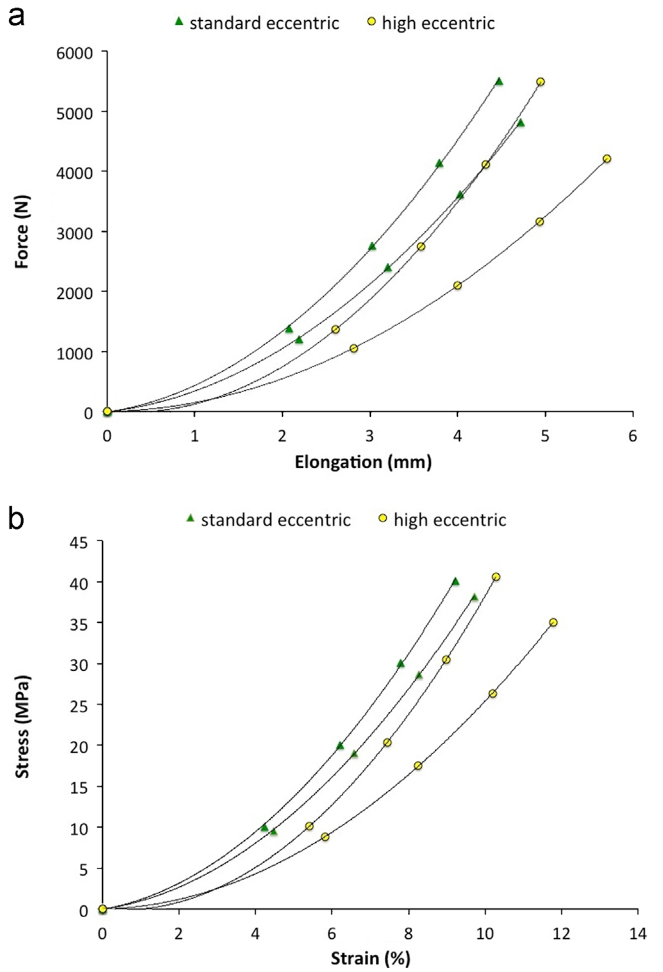

Fig. 4. Pre and post force-elongation (a) and stress–strain (b) curves comparing low and high eccentric loading. (post intervention curves have shifted to the left).

5. Conclusion

Patellar tendon modulus responds to loading at or above 80% of concentric 1RM. Only the high load eccentric group had significantly greater increase in force, stiffness and modulus compared to the control group, so high load eccentric contractions need to be investigated in a clinical population to determine its applicability and efficacy. Among young healthy men the mechanism for adaptation of patellar tendon modulus may be different depending on contraction type and load intensity.

Conflict of interest statement

None of the authors have any conflict of interest to declare.

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