The Effect of Specific Bioactive Collagen Peptides on Tendon Remodelling during 15 Weeks of Lower Body Resistance Training

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Title page

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THE EFFECT OF SPECIFIC BIOACTIVE COLLAGEN PEPTIDES ON TENDON REMODELLING DURING 15 WEEKS OF LOWER BODY RESISTANCE TRAINING

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COLLAGEN PEPTIDES AND RESISTANCE TRAINING

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Key words

Magnetic resonance imaging
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Young's modulus
Supplementation

Abstract

Purpose: Collagen peptide supplementation has been reported to enhance synthesis rates or growth in a range of musculoskeletal tissues and could enhance tendinous tissue adaptations to resistance training (RT). This double-blind placebo-controlled study aimed to determine if tendinous tissue adaptations, size (patellar tendon cross-sectional area [CSA] and vastus lateralis [VL] aponeurosis area) and mechanical properties (patellar tendon), following 15 weeks of RT could be augmented with collagen peptide (CP) vs. placebo (PLA) supplementation.

Methods: Young healthy recreationally active men were randomized to consume either 15 g of CP (n=19) or PLA (n=20) once every day during a standardized program of lower-body RT (3 times/wk). Measurements pre- and post-RT included: patellar tendon CSA and VL aponeurosis area (via MRI); patellar tendon mechanical properties during isometric knee extension ramp contractions.

Results: No between-group differences were detected for any of the tendinous tissue adaptations to RT (ANOVA group x time, $0.365 \le P \le 0.877$). There were within-group increases in VL aponeurosis area (CP: +10.0%, PLA: +9.4%), patellar tendon stiffness (CP: +17.3% PLA: +20.9%) and Young's Modulus (CP: +17.8%; PLA: +20.6%) in both groups (paired t-tests [all] $P \le 0.007$). There were also within-group decreases in patellar tendon elongation (CP: -10.8%, PLA: -9.6%) and strain (CP: -10.6%, PLA: -8.9%) in both groups (paired t-tests [all] $P \le 0.006$). Whilst no within-group changes in patellar tendon CSA (mean or regional) occurred for CP or PLA, a modest overall time effect (n=39) was observed for mean (+1.4%) and proximal region (+2.4%) patellar tendon CSA (ANOVA, $0.017 \le P \le 0.048$).

Conclusion: In conclusion, CP supplementation did not enhance RT-induced tendinous tissue remodelling (either size or mechanical properties) compared to PLA within a population of healthy young males.

INTRODUCTION

Tendinous tissue properties affect movement by influencing the transmission of force from muscle fibres to the skeleton (1, 2) and are implicated in injury occurrence and prevention. Specifically, stiffer tendons are less susceptible to damage (3) and may provide greater joint stability and reduce loading of passive tissues (4). Therefore, interventions capable of increasing tendinous tissue stiffness have important implications for athletes, patients, and the general population alike. Whilst resistance training (RT) involving sustained high load contractions (≥2 s duration; ≥70% of maximum load) has consistently been shown to increase tendon (5, 6) and aponeurosis-tendon unit (7, 8) stiffness, the potential for nutritional supplementation to augment the tendinous tissue remodelling observed with RT has received very limited attention.

Bioactive peptides are defined as peptide fragments with 2–45 amino acid residues that have a positive effect on bodily functions and/or health (9, 10). Previously, ingested peptides and proteins were believed to be digested down to their constituent amino acids within the human gut. However, evidence now suggests that certain peptides, including collagen, can cross the intestinal epithelium, enter circulation, and ultimately exert a range of systemic physiological effects (11–13). Collagen peptide (CP) supplementation has been reported to enhance synthesis rates or growth in a range of musculoskeletal tissues (cartilage (14); ligament (15); and bone (16)). In the context of RT, the effects of CP supplementation on skeletal muscle has begun to receive some attention, including previous work from our laboratory (17), with reports of augmented muscle function (18, 19), growth (17–20), and/or intrinsic contractile properties (17). However, the influence of collagen supplementation on tendinous tissues has received less attention to date.

Three studies have documented the potential for collagen supplementation to enhance the rehabilitation of injured tendons in response to RT (21–23). However, there remains a critical requirement to identify specific underpinning mechanisms responsible for the augmented musculotendinous tissue adaptations observed when CP supplementation is combined with RT (24). To our knowledge only one randomised control trial has examined the effects of CP supplementation on the size and mechanical properties of tendinous tissue following RT (25), with favourable effects reported for CP vs. placebo supplementation for Achilles tendon cross-sectional area, but not stiffness. However, low resolution ultrasound imaging was used to assess tendon cross-sectional area (CSA) at a single location (rather than high resolution MRI, preferably at multiple locations along the entire length of the tendon), aponeurosis size was not examined, and limited mechanical properties were documented (i.e. excluding elongation, strain [relative elongation] or Young's modulus (25)). Consequently, an investigation using in vivo gold standard imaging techniques to assess both free tendon and aponeurosis size, as well as a complete characterisation of tendon mechanical properties, seems warranted to extend our understanding of the efficacy of CP supplementation for augmenting tendinous tissue adaptations above RT alone.

The purpose of this study was to determine if tendinous tissue adaptations, size (patellar tendon CSA and vastus lateralis [VL] aponeurosis area) and mechanical properties (patellar tendon), following 15 weeks of RT can be augmented with CP vs. placebo (PLA) supplementation. These measurements were secondary outcomes within a larger project examining the musculo-tendinous adaptations to RT with/without CP supplementation (17). We hypothesised that enhanced tendinous tissue size and mechanical property adaptations would be observed with CP vs PLA following RT.

MATERIALS AND METHODS

Participants

Fifty-two healthy young men (aged 18-40 years) with low-moderate levels of recreational physical activity, no prior lower-body injuries, no recent history (>18 months) of RT, and no involvement in regular systematic physical training volunteered for this study and gave their written informed consent. Loughborough University Ethics Review Sub-Committee granted ethical approval (Reference Number: R19-P030). Participants were excluded from study participation if they were unwilling to consume an animal-based protein supplement or had unusual habitual protein intake (i.e. <0.8 g/kg; based on 24 h food intake recall).

Thirteen participants withdrew from the study because of: a change to personal circumstances (x4); lack of RT enjoyment (x3); non-attendance (x2); or discomfort of one or both knees (x4). Participant withdrawals occurred as follows: 4 in weeks 1-5, 5 in weeks 6-10, 4 in weeks 11-15 of the intervention. Thirty-nine participants completed the intervention period and no side-effects of either supplement were reported. Isometric knee extension maximum strength of the dominant leg and body mass, recorded in familiarisation sessions, allowed participants to be pair-matched and then randomly assigned to either CP or PLA supplementation (CP group n= 19; PLA group: n= 20).

Overview

This study was a single-centre randomised double-blind control trial with per-protocol analysis. Participants first completed a familiarisation session including all tasks to be performed in the main measurement sessions. Main measurement sessions involving unilateral assessments of the dominant leg (as determined from leg preference for kicking a ball) were completed in duplicate both pre (two sessions, 3–5 days apart and before the first training session) and post (two sessions, 2–3 days after the final training session and 2–3 days later) 15 weeks of RT. Torque was recorded during isometric knee extension maximum voluntary contractions (MVCs); isometric knee extension ramp contractions; and isometric knee flexion MVCs (completed in this order). Hamstring surface electromyography (EMG) was recorded during isometric knee extension and flexion MVCs and ramp contractions for the purposes of estimating patellar tendon forces during knee extension ramp contractions. Patellar tendon elongation during isometric knee extension ramp contractions was recorded using 2-D ultrasonography scanning (Fig. 1). Prior to main measurement sessions participants were required to avoid caffeine consumption for 6 h. The time of pre and post main measurement sessions was standardised within each participant to ensure consistent testing times, all sessions were conducted between 12:00-20:00 h.

Musculoskeletal imaging of the dominant thigh and knee was also conducted pre- (5-7 days prior to the first training session) and post-RT (3–5 days after the final training session). T1 weighted MRI scans were used to assess VL aponeurosis area, mean and regional patellar tendon cross-sectional area (CSA), and patellar tendon moment arm. Scan time of day was standardised within participants, who were instructed to eat and drink normally and avoid strenuous exercise and alcohol consumption for 36 h before all measurement sessions.

During the 15-week intervention period all participants completed a lower-body RT programme three times per week (i.e. 45 sessions) that primarily targeted the quadriceps, and secondarily the hamstrings and gluteus maximus. Participants also consumed either 15g of CP or PLA supplements once per day during the intervention period (i.e. 105 daily doses) and were instructed to maintain their habitual physical activity and usual diet throughout the study.

Habitual Physical Activity and Dietary Assessment

The International Physical Activity Questionnaire (IPAQ, short format (26)) was administered twice throughout the study: ~3 weeks prior to the start of the intervention, and in the final week of the intervention. A 3-day (2 weekdays, 1 weekend day) weighed food and fluid intake diary was completed by all participants at two time points during the study (weeks 3 and 13 of the intervention) to estimate habitual energy and macronutrient intake. One trained investigator analysed food and fluid intake diaries and used manual entry for any product not available in the software (Version 5.0, Nutritics). One participant was excluded from the food and fluid intake diary analysis after failing to accurately complete their diary, hence the CP group data for this measure is *n*=18.

Resistance Training

All participants completed the same supervised, undulating periodised (~12 repetition [RM] to ~6RM), progressive lower-body RT programme 3 times per week (typically Monday, Wednesday, Friday) during the 15-week intervention period, as described elsewhere (17). Briefly, each session was fully supervised by the investigators and involved three isoinertial (constant load) exercises (2-4 sets with each, 4 sets from week 7 onwards), in the following order: unilateral knee extension (TechnoGym, Selection Leg Extension; Bracknell, UK) commencing with the dominant leg and alternating sets between legs; bilateral knee flexion (Life Fitness, Seated Leg Curl SL40; Cambridgeshire, UK); bilateral leg press (Watson Gym Equipment, 45° Leg Press, Somerset, UK). Two minutes of recovery separated sets with the same leg/legs. Participants took 2 s seconds to lift and 2 s to lower the weight during each exercise. Progressive overload was achieved by increasing load if all specified repetitions in the penultimate set of an exercise were completed. Bilateral warm-up sets were completed prior to unilateral knee extension and bilateral knee flexion (same number of repetitions at~50% of the load for the first main set).

Supplementation

Participants consumed 15 g of collagen peptides (CP; 10 g of ‘Bodybalance’ [mean molecular weight ~3.5 kDa] and 5 g of ‘Tendoforte’ [~2.0 kDa], Gelita AG) or placebo (PLA; 15 g of maltodextrin) dissolved in water once daily for 15 weeks. The CP supplement consisted of two subtly different products with an identical amino acid composition, as previously detailed (17), but different mean molecular weights which may maximise the absorption and bioactive properties (27). Both supplements were provided in identical pre-packaged sachets (except supplement code) thereby blinding both participants and investigators. Sachets were emptied into opaque shaker bottles, 350 ml of water added, and shaken vigorously prior to consumption. Investigators (RT days) or participants (non-RT days) prepared the supplements and supplements were consumed either immediately post RT or mid-afternoon on non-RT days. Regular instruction not to eat or drink anything, except water within 1 h of supplement consumption was provided. Four sachets were provided each week for participants to consume on non-RT days and participants were required to return empty sachets from the previous week, and sign that they had consumed each sachet on a non-RT day during the prior week.

Isometric dynamometer, Torque and EMG Recordings

Isometric knee extension and flexion contractions were conducted with participants seated on an adjustable rigid custom-made isometric dynamometer (see Fig. 1A) that allowed for consistent individualised positioning. Knee and hip joint angles during isometric knee extension and flexion contractions were 104° and 126° (180° = anatomical reference position), respectively. Waist, shoulder and lower thigh restraints were tightly fastened to prevent extraneous bodily movement during contraction. Knee extension and flexion force were measured with a low noise S-beam strain gauge (Force Logic, Swallowfield, UK) mounted to the dynamometer perpendicular to, and either posterior (knee extension) or anterior (knee flexion) to the tibia. The strain gauge was positioned and secured at ~15% of tibial length above the medial malleolus with a reinforced canvas webbing ankle strap (35 mm width).

The strain gauge signal was amplified (x370) and sampled at 2,000 Hz with an external A/D converter (Micro 1401; CED Ltd., Cambridge, UK) and recorded with Spike 2 software (CED Ltd., Cambridge, UK). Prior to analysis, force data were low-pass filtered at 500 Hz with a fourth-order zero-lag Butterworth filter (28), gravity corrected via subtraction of baseline force (i.e. passive limb weight), and then multiplied by lever length (the distance from the knee joint space to the centre of the ankle strap) to calculate torque.

To facilitate calculation of tendon force, surface EMG was wirelessly recorded from the lateral and medial hamstrings (Trigno; Delsys Inc., Boston, MA) during knee extension ramp contractions and knee flexion MVCs. The skin beneath the sensors was prepared (shaved, abraded, and cleansed with 70% ethanol) before individual single differential (bipolar configuration) Trigno Standard EMG sensors were attached (using adhesive interfaces) over the lateral (LH) and medial (MH) hamstrings at 45% of thigh length above the popliteal fossa. Sensors were placed parallel to the presumed orientation of the underlying fibres. EMG signals were amplified at source (x300; 20 to 450-Hz bandwidth) before further amplification (overall effective gain, x909). EMG signals were sampled at 2,000 Hz via the same A/D converter and computer software used to record the force signal, enabling data synchronization. Prior to analysis, EMG signals were corrected for the 48-ms delay inherent to the Trigno EMG system.

Isometric Knee Extension and Flexion Maximum Voluntary Contractions.

Following incremental isometric knee extension or flexion warm-up contractions of the dominant leg (5 s per contraction, 3 x 50%, 3 x 75%, and 1 x 90% of perceived maximum) participants performed 3-4 MVCs. Prior to MVCs, participants received instruction to “push as hard as possible” (extension) or “pull as hard as possible” (flexion) for 3–5 s, with ≥30 s rest between each effort. Real-time biofeedback was provided, via a computer monitor positioned in front of the participant displaying the torque-time curve, with the greatest knee extension or flexion torque obtained within that session marked with a horizontal cursor. The greatest instantaneous torque achieved during any MVC within the measurement session was defined as knee extensor or flexor isometric maximum voluntary torque (MVT). Hamstrings root-mean-square (RMS) EMG amplitude of both sensors was measured during a 500-ms epoch surrounding both knee extension and flexion MVT (250 ms either side). The within-participant between-day reliability (CV_W) for knee extension and knee flexion MVT were 5.0%, and 6.9% respectively (n=39).

Recordings during Isometric Knee Extension Ramp Contractions to assess Patella Tendon Stiffness.

Patellar tendon elongation (imaged with ultrasound) was synchronously recorded alongside knee extension torque, hamstrings EMG, and sagittal plane video of the knee joint during isometric knee extension ramp contractions of the dominant leg in order to derive patellar tendon stiffness measures (Fig. 1A and B). Earlier maximum knee extensor strength assessments were considered suitable to precondition the tendinous tissues prior to stiffness measurements (29). Prior to the start of each ramp contraction a target constant gradient torque trace (35 $Nm.s^{-1}$ loading rate from 0 to 100%MVT; Fig. 1B) was displayed on a computer monitor in front of the participant. From 5 seconds prior to the start of the contraction the participant’s real-time torque-time trace was overlaid on top of the target trace on the computer screen, thereby providing feedback, and the participant was instructed to match the target trajectory as closely as possible during all ramp contractions. Prescribed ramp contraction duration at pre- and post-test was 6.4 ± 1.3 s and 7.7 ± 1.5 s and 6.6 ± 1.1 s and 8.0 ± 1.3 s for the CP and PLA groups, respectively.

Two sub-maximum practice ramp contractions up to ~50%MVT were completed prior to five maximum ramp contractions, holding the prescribed trajectory for as long as possible (i.e. as close to 100% MVT as possible). Of the 5 maximum ramp contractions, the three ramps with the highest torque were selected for analysis, providing participants had closely matched the prescribed loading rate and osteotendon attachments (patella tendon stiffness) displacement were clearly visible in the ultrasound recordings (see below), in which case measurements were averaged across these three contractions.

A linear array ultrasound probe (92 mm EUP-L53L, B-mode, 10 MHz scanning frequency, 32 Hz sampling frequency; ultrasound machine: EUB-8500; Hitachi Medical Systems UK Ltd, Northamptonshire, UK) was held firmly (i.e. manually) over the anterior aspect of the knee to image the entire length of the patella tendon during isometric knee extension ramp contractions. The probe was aligned longitudinal to the patellar tendon so that the apex of the patella and the insertion of the posterior tendon fibres at the tibia could be visualized at rest and throughout each ramp contraction. All ultrasound recordings during ramp contractions allowed visualization of the osteotendinous attachments at both ends of the patellar tendon (see Fig. 1C for example images).

Knee-joint angles during ramp contractions were derived from sagittal plane video recordings (HC-V110; Panasonic Corporation, Osaka, Japan). The camera was mounted on a tripod (0.9 m height) positioned perpendicular (2 m) to the dynamometer. An S-video/composite to USB video converter (VCAP302, ClimaxDigital, Spennymoor, UK) and Spike video recorder software (CED Ltd., Cambridge, UK), allowed synchronous recordings of video outputs (from the ultrasound machine and the video camera at 25 Hz) alongside torque and EMG data.

Measurement of Tendinous Tissue Elongation and Tendon Force during the ramp contractions

The video recordings of patellar tendon elongation (from ultrasound) and knee-joint displacement during the ramp contractions were analysed off-line by tracking specific anatomical landmarks frame-by-frame using public domain semi-automated video analysis software (Tracker, version 5.0.6; www.physlets.org/tracker/). Longitudinal displacement of osteotendon attachments, at the patella apex and the tibial insertion, allowed patellar tendon elongation to be determined (Fig. 1C). Knee joint angle was measured as the angle between visible markers placed on the greater trochanter, lateral knee-joint space and lateral malleolus, and during ramp contractions changed by 3 ± 1°. Under passive movement conditions patellar tendon elongation was considered negligible (8).

Patellar tendon force during each of the three selected ramp contractions was calculated as total knee extensor torque (external knee extensor torque + estimated antagonist torque) divided by estimated patellar tendon moment arm length during ramp contraction (m). Antagonist torque during isometric knee extension ramp contractions was estimated by normalising RMS EMG amplitude (50 ms moving window) from the hamstrings (LH and MH) sensors to RMS EMG from the corresponding sensors at knee flexion MVT, before multiplying mean normalised antagonist EMG amplitude by knee flexor MVT (assuming a linear relationship between EMG amplitude and knee flexion torque). Torque and EMG amplitude were down sampled to 25 Hz during analysis to equate the sampling rate of the ultrasound video recording. Direct measures of patellar tendon moment arm length at rest were obtained from MRI scanning (see below). Due to constraints in the size of the knee coil, sagittal plane images were acquired at a relatively extended knee-joint angle (143 ± 5°: 180° = full extension) compared to the joint angle during isometric knee extension ramp contractions (104 ± 2°). Patellar tendon moment arm length measured with MRI was therefore corrected to the knee-joint angle during each ramp contraction using previously published data fitted with a quadratic function (30).

Calculation of Patella Tendon Stiffness measures during the ramp contractions

Patellar tendon elongation was plotted separately against total tendon force for each of the three ramp contractions and fitted with a second-order polynomial function (forced through zero). The polynomial functions of patellar tendon elongation during each ramp contraction were then used to derive elongation at 5% increments of pre-RT maximum voluntary tendon force, before averaging the 3 contractions, thereby producing a mean patellar tendon force-elongation relationship for the patellar tendon for each measurement session.

To standardise comparisons between pre and post intervention measurements, within each participant, patellar tendon stiffness for each measurement session was calculated as the slope of the patellar tendon force-elongation curve over a consistent absolute tendon force range, specifically 70-80% of pre-RT maximum voluntary patellar tendon force. Stiffness/modulus measures derived over the highest attainable tendon force/stress range (e.g. 70-80% of pre-RT maximum voluntary patellar tendon force) have previously been recommended and are considered reliable (29, 31, 32). Patellar tendon stress and strain were calculated from the mean patellar tendon force-elongation relationship values for each measurement session. Stress was quantified by dividing patellar tendon force by mean patellar tendon cross-sectional area (either the pre- or post-RT measurement, see below). Patellar tendon strain was calculated as tendon elongation as a percentage of resting tendon length. Resting patellar tendon length was measured as the mean distance between the patella apex and tibial insertion prior to contraction for the three selected ramp contractions. Subsequently, the stress-strain relationship was plotted and Young's modulus calculated over a stress range that corresponded to 70–80% of pre-RT maximum tendon stress (maximum tendon force /

cross-sectional area). All measures of tendon mechanical properties were averaged across the two sessions conducted pre and post intervention. The within-participant between-day reliability of patellar tendon stiffness and elongation were 11.9% and 8.7%, respectively (n=39).

MRI scan and analysis

Vastus lateralis aponeurosis size. Participants sat quietly for 15 min prior to MRI scans (3.0T Discovery MR750w, GE Healthcare, Chicago, IL, USA). T1-weighted axial and coronal plane MRI scans of the dominant thigh (between the anterior superior iliac spine to the lateral tibial condyle) were conducted with participants supine, arms resting across the chest, hip and knee joints extended, and the ankle at ~90°. Using a receiver 8-channel whole-body coil, axial (time of repetition/time to echo 600/8.35 ms; image matrix 512 × 512; field of view 260 mm × 260 mm; pixel size 0.508 mm × 0.508 mm; slice thickness 5 mm; inter-slice gap 0 mm) and coronal (time of repetition/time to echo 600/8.53 ms; image matrix 256 × 256, field of view 450 mm × 450 mm, pixel size 1.76 mm × 1.76 mm, slice thickness 5 mm, inter-slice gap 0 mm) images were acquired in two overlapping blocks for both axial and coronal scans. Synchronisation of coronal and axial plane scans permitted the objective alignment of axial blocks during analysis (Horos, version 3.3.6, www.thehorosproject.org).

The deep aponeurosis of the VL muscle was defined as the visible dark black segment between the VL and VI muscles in the axial thigh MRI images (Fig. 2). The transverse length (cm) of the black segment was defined as VL aponeurosis width, and was traced manually on every third image (i.e. every 1.5 cm), starting in the most distal image where the aponeurosis was visible. The measures of aponeurosis width were plotted against aponeurosis length (Fig. 2E). A 1000 point cubic spline curve (GraphPad Prism 8; GraphPad Software) was fitted to the plot of VL aponeurosis width vs. aponeurosis length and the VL aponeurosis area was calculated as the area under the spline curve.

Patellar tendon cross-sectional area and moment arm. A lower extremity knee coil was then used to acquire knee joint axial images for patella tendon analysis (time of repetition/time to echo 600/9.83 ms; image matrix 512 × 512, field of view 160 mm x 160 mm, pixel size 0.313 mm × 0.313 mm, slice thickness 2 mm, inter-slice gap 0 mm) and sagittal images for determination of moment arm (image matrix 512 × 512, field of view 160 mm × 160 mm, pixel size 0.313 mm × 0.313 mm, slice thickness 2 mm, inter-slice gap = 0 mm). A wedge-shaped foam block was positioned under the knee to obtain the most flexed knee-joint angle (143 ± 5°, 180° = full extension) possible within the constraints of the knee coil. The knee was scanned in as flexed position as possible to minimise the correction required to calculate the moment arm at the knee joint angle of the knee extension MVCs (see above). Contiguous sagittal images of the knee joint were acquired between the medial and lateral tibial condyles. A phantom (15 ml centrifuge tube; Globe Scientific Inc., New Jersey, USA) containing a 1.0% $CuSO_4$ (Copper [II] sulphate, 98%, pure, anhydrous; Acros Organics, New Jersey, USA) solution was secured longitudinally and ~2 cm medial to the patellar tendon with transpore tape to allow standardisation of pre and post contrast settings during patellar tendon CSA analysis (Fig. 3).

Patellar tendon CSA was measured in every contiguous axial image along the tendon's length (i.e. from the first image where the patella was not visible to the last image before the tibial insertion) using Horos software (version 3.3.6, www.thehorosproject.org). The brightness and contrast settings (i.e. window level [WL] and window width [WW] within the Horos software) of these images was first standardised relative to the $CuSO_4$ phantom. Specifically, the axial patellar tendon image mid-way along the tendon was viewed with the NIH (National Institute of Health) colour scale applied and brightness and contrast adjusted until a circular region of interest (0.25 cm^2 area) positioned in the centre of the phantom was entirely a standardised green colour. The NIH colour scheme was then removed to return to grayscale with brightness and contrast settings still fixed relative to the $CuSO_4$ phantom. The zoom level was set to 900% for all images, and a convolution filter (sharpen 5 x 5) applied to sharpen the images, before manually outlining the patellar tendon perimeter in every image along the length of the tendon (Fig. 3). Along the length of each patellar tendon 20 ± 3 images were segmented (mean ± SD across all participants). Mean tendon CSA was the average of all the measured images along the tendon's length. Additionally, three regional tendon CSA measurements were calculated as the mean of measured images within the proximal, mid, and distal thirds of tendon length, respectively. Patellar tendon moment arm length was measured from the sagittal plane knee images as the perpendicular distance from the line of action of the patellar tendon to the tibio-femoral contact point in the image closest to 40% of the distance between the most lateral (0%) and medial (100%) points of the femoral condyles as determined from synchronised axial images (33, 34).

Reliability. In a pilot trial of nine healthy young men with repeated MRI scans (5-14 days apart) using the above protocol and analysis we found mean within-participant between-day reliability (i.e. within-participant coefficient of variation, CV_W; [SD ÷ mean] x 100) of patellar tendon mean CSA, patellar tendon moment arm and VL aponeurosis area to be 1.9%, 1.3%, and 4.1%, respectively.

Statistical Analysis

All data were anonymized prior to analysis to blind investigators to participant identity and supplement group allocation, and patellar tendon axial images (for CSA measurements) were also anonymised for measurement time point, prior to analysis. Data normality was assessed using the Shapiro-Wilk test. The majority of variables were normally distributed at pre-RT (61% or 11 out of 18 variables) when both groups were pooled. For the seven not normally distributed variables the Box-Cox transformation technique was applied and normality of transformed data was subsequently confirmed with the Shapiro-Wilk test before proceeding with parametric statistical tests. Therefore, parametric statistics were used across all variables. Within-group changes over time were assessed with paired t tests. Group x time effects were assessed with two-way repeated measures ANOVA and main effects of time are also reported. Statistical significance was defined as $P<0.05$ and statistical analysis was completed using SPSS version 27. All data are presented as mean ± standard deviation unless otherwise indicated. Between-group effect size (ES) was calculated using percentage change data as previously described (35) and classified as: <0.20 = "trivial," 0.20–0.49 = "small," 0.50–0.80 = "moderate," or >0.80 = "large". An ES to represent the main effect of time was also calculated for the overall sample (*n*=39) as: [difference between pre-RT mean and post-RT mean] ÷ pre-RT SD, and classified using the same system as between-group ES. Duplicate measurement sessions conducted pre- and post-RT were used to assess between-day reliability of strength and mechanical property measurements.

RESULTS

Group Characteristics at Baseline, Dietary assessment and body mass.

Age (CP 27.0 ± 5.0 y; PLA 24.4 ± 3.2 y), height (CP 1.79 ± 0.09 m; PLA 1.80 ± 0.08 m), body mass (CP 73.3 ± 12.0 kg; PLA 75.8 ± 11.5 kg), and habitual physical activity (IPAQ; CP 2067 ± 1377 MET-min/wk; PLA Pre 2220 ± 1542 MET-min/wk) did not differ-between groups at pre (unpaired t-test, $0.051 \leq P \leq 0.746$). Patellar tendon mean CSA, stiffness, elongation, and length, as well as knee extension and flexion MVT, did not differ between groups pre-RT (unpaired t-test, $0.091 \leq P \leq 0.813$). No between group differences in habitual energy or macronutrient intake relative to body mass occurred (unpaired t-test, 0.237≤P≤0.430). After accounting for supplementation there were no differences between-groups for total energy or carbohydrate intake relative to body mass (unpaired t-test, 0.244≤P≤0.755), but protein intake relative to body mass was greater for CP than PLA (P=0.026). Full dietary assessment results are reported elsewhere (17). There were within-group increases in body mass for both the CP (paired t-test, P<0.001; Pre 73.3 ± 12.0; Post 75.4 ± 12.0 kg) and PLA (P=0.016; Pre 75.8 ± 11.5; Post 76.7 ± 10.0 kg) group, although no group x time interaction occurred (ANOVA, P=0.155, ES=0.48 "Small"). There was a time effect for body mass (ANOVA P<0.001; ES=0.013 "Trivial").

Maximum Strength

As reported elsewhere (17), knee extension MVT (CP +21.4 ± 7.8%; PLA +21.7 ± 10.7%) and knee flexion MVT (CP +23.3 ± 15.4%; PLA +21.3 ± 17.6%) increased from pre to post within both groups (paired t-test, [all] P<0.001). There were effects of time on both strength measures (ANOVA [both] P<0.001; 0.77≤ES≤1.10 from "Moderate" to "Large"), but no group x time interactions were observed (ANOVA, 0.596≤P≤0.671; 0.03≤ES≤0.12 [both] "Trivial") for knee extension or flexion MVT.

Tendinous tissue morphology

Patellar tendon mean CSA (CP +1.1 ± 3.2%; PLA +1.7 ± 3.7%) and region specific CSA (Proximal CSA: CP +2.5 ± 5.7%; PLA +2.3 ± 5.7%. Mid CSA: CP +0.3 ± 4.8%; PLA +1.6 ± 4.8%. Distal CSA: CP +0.4 ± 2.4%; PLA +1.3 ± 3.5%), did not increase from pre to post within either group (paired t-test, 0.088≤P≤0.894; Table 1). There were no group x time interactions (0.365≤P<0.877; 0.03≤ES≤0.28 from "Trivial" to "Small"; Table 1) for patellar tendon mean (Fig. 4A and B) or region-specific CSA. Time effects were observed for patellar tendon mean and proximal CSA measures (ANOVA, 0.017≤P≤0.048; 0.09≤ES≤0.13 [both]

"Trivial") but not mid or distal CSA (0.085≤P<0.475; 0.05≤ES≤0.06 [both] "Trivial"). Patellar tendon length did not change from pre- to post-RT within either group (CP +0.5 ± 2.1%; PLA +0.1 ± 1.3%; paired t-test, [both] P≥0.308) and did not display a group x time interaction (ANOVA, P=0.491; ES=0.23 "Small"). No time effects were observed for patellar tendon length (ANOVA, P=0.276; ES=0.03 "Trivial").

VL aponeurosis area (CP +10.0 ± 8.5%; PLA +9.4 ± 10.0%; paired t-test, [both] P≤0.001) and maximum width (CP +6.4 ± 5.7%; PLA +7.6 ± 9.1%; [both] P≤0.001) increased from pre- to post-RT within both groups (Table 1). No group x time interactions (ANOVA, 0.697≤P≤0.798; 0.07≤ES≤0.16 [both] "Trivial") were observed for either VL aponeurosis area (Fig. 4C and D) or maximum width. Time effects were observed for both VL aponeurosis area and maximum width (ANOVA, [both] P<0.001; 0.47≤ES≤0.49 [both] "Small").

Patellar tendon mechanical properties

Patellar tendon stiffness (CP +17.3 ± 23.5%; PLA +20.9 ± 22.0%; paired t-test, 0.001≤P≤0.007) and Young's modulus (+17.8 ± 24.9%; PLA +20.6 ± 22.9%; 0.001≤P≤0.007) increased from pre- to post-RT within both groups (Table 1). Group x time interactions did not occur for patellar tendon stiffness (ANOVA, P=0.613; ES=0.16 "Trivial"; Fig. 5A and B) or Young's modulus (P=0.837; ES=0.12 "Trivial"; Fig. 5C and D), although there were time effects for both patellar tendon stiffness and Young's modulus (ANOVA, [both] P<0.001; 0.40≤ES≤0.50 from "Small" to "Moderate").

From pre- to post-RT there were decreases in both groups for patellar tendon elongation at 80% pre-RT maximum voluntary tendon force (CP -10.8 ± 13.2%; PLA -9.6 ± 13.2%; paired t-test, [both] P≤0.005; Fig. 6) and patellar strain (relative elongation) at 80% pre-RT maximum voluntary tendon force (determined from patellar tendon stress-strain relationships; CP -10.6 ± 14.2%; PLA -8.9 ± 14.0%; [both] P≤0.006; Table 1). No group x time interactions were observed ($0.775 \leq P \leq 0.827$; $0.09 \leq ES \leq 0.12$ [both] “Trivial”; Table 1) for patellar tendon elongation or strain. Time effects occurred for both patellar tendon elongation and strain (ANOVA, [both] $P<0.001$; $0.61 \leq ES \leq 0.65$ [both] “Moderate”).

DISCUSSION

The aim of this study was to determine if tendinous tissue adaptations, size (patellar tendon and VL aponeurosis) and mechanical properties (patellar tendon), following 15 weeks of lower-body RT can be augmented with CP supplementation compared to a placebo. In direct contradiction to our hypothesis, CP supplementation did not enhance RT-induced tendinous tissue size or mechanical property adaptations of healthy young males. Pre- to post-RT changes in patellar tendon mechanical properties (i.e. increased stiffness/Young’s Modulus [+17.3 to +20.9%], decreased elongation/strain [-8.9 to -10.8%]), and increases in VL aponeurosis size [+6.4 to 10.0%] were observed within each group (paired t-test) and when both groups were pooled together (ANOVA time effect). Whilst no within-group changes in patellar tendon CSA (mean or regional) occurred for the CP or PLA groups, a modest overall time effect (n=39) was observed for mean (+1.4%) and proximal (+2.4%) patellar tendon CSA. Critically however, no between-group differences were detected for any measured variables. The findings of this study suggest the addition of CP supplementation to a RT intervention offers no additional benefit for remodelling tendinous tissue size or mechanical properties within an asymptomatic young male population.

Tendinous tissue morphology

Patellar tendon size (CSA) did not change in either group after RT, with no between group interaction effect, and therefore was unresponsive to CP supplementation. The results of the present investigation are contrary to the findings of a recent study where the addition of daily collagen peptide supplementation (5 g/day) during 14 weeks of RT was reported to induce a 2.3-fold larger increase in Achilles tendon CSA, compared to a placebo group (+11.0% vs. +4.7%; (25)). Whilst the distinct effects of collagen peptide supplementation on tendon growth between our study and this previous investigation could be due to the different tendons measured, methodological differences could also be a factor. Specifically, Jerger et al (25) only measured tendon CSA at one location along the length of the Achilles tendon using low resolution ultrasonographic imaging which has previously been reported to be inaccurate, unreliable, and lacking the prerequisite sensitivity to detect clinically relevant or intervention-induced changes in tendon CSA (36, 37). The methods used in the current study involved more thorough procedures (i.e. contiguous 2 mm thick high resolution, pixel size 0.313 mm × 0.313 mm, MR images, along the entire length of the tendon and use of a phantom to control for the variable contrast in MR images) that were highly reliable (within-participant CVw 1.9% for mean tendon CSA). With the thorough methods of the present investigation there was no indication of any group x time interaction effects for tendon CSA measurements ($P \geq 0.365$; $ES \leq 0.28$). Thus, it seems unlikely that CP supplementation facilitates/enhances patellar tendon hypertrophy.

Moreover, irrespective of supplementation the possibility of tendon hypertrophy in response to RT has been the subject of conflicting reports (e.g., small, but significant hypertrophy, (34); no hypertrophy, (38)). In the current study, whilst there were no within-group effects of RT, when both groups were considered together the small increases in mean patellar tendon (+1.4%) and proximal (+2.4%) CSA were found to be significant (i.e. ANOVA main effect of time). This contrasts with our previous longitudinal study that found no evidence of tendon hypertrophy with RT (12 weeks of RT; (8)). The significant tendon hypertrophy found within the current study, despite the small magnitude of the changes (<2.5%; $ES \leq 0.13$ "Trivial") was perhaps because of the relatively large number of participants for a tendon hypertrophy investigation (*n*=39) the high precision of the measurements (CV_W 1.9%), and the relatively long duration of the RT (15 weeks). Overall, the current findings indicate that a small significant increase in tendon size may be detectable with rigorous methods.

In support of our findings, there is evidence that RT does not stimulate in-vivo tendon collagen synthesis (39), and healthy adult tendon has been widely suggested to have a limited capacity for adaptation (40). Furthermore, cross-sectional studies employing MRI scanning to compare tendon CSA between resistance-trained (i.e. high load, relatively low loading frequency) and untrained/recreationally active individuals have documented no difference between groups (41, 42). In contrast, cross-sectional MRI studies comparing runners vs. non-runners (43) and asymmetrically loaded legs (lead vs. nonlead legs of elite fencers and badminton athletes (44)) suggest that endurance type activities (i.e., low/moderate loading at relatively high frequency) may stimulate tendon hypertrophy.

VL aponeurosis, an extension of the tendon that runs alongside the muscle, did however show clear evidence for a response to RT in both groups with increases in area and width of 6-10%. Although importantly there was no evidence for any differences between groups in the changes in VL aponeurosis size ($P \geq 0.697$; $ES \leq 0.16$), and therefore there was no apparent effect of CP supplementation on aponeurosis growth. Previous longitudinal evidence reported ambiguous findings for increases in aponeurosis size (8, 45), although these prior studies featured smaller sample sizes and documented less pronounced muscle hypertrophy than the current investigation (17). Therefore, this new aponeurosis evidence appears to clarify that the aponeurosis is adaptable to RT in accordance with a cross-sectional comparison study that found greater aponeurosis area in chronically resistance-trained men (41). However, CP supplementation did not appear to further augment the changes in aponeurosis size after RT.

Patellar tendon mechanical properties

As expected, patellar tendon mechanical properties showed increased absolute stiffness in both groups (high force stiffness, +17 to +21%; elongation ~-10%) primarily due to increased material stiffness (Young's modulus, +18 to +21%; strain, -9 to -11%) rather than any change in tendon CSA. However, there were no differences between groups for the changes in tendon properties (all $P \geq 0.613$ and $ES \leq 0.16$) and thus no evidence that CP supplementation modified these adaptive responses. In agreement with our patellar tendon stiffness findings, changes in Achilles tendon stiffness have also recently been documented to be similar between CP and placebo supplementation groups following 14 weeks of RT (25), although incomplete mechanical properties were reported within this prior study (i.e. elongation, strain and Young's modulus were not reported). The changes in absolute and material stiffness /Young's modulus after RT in the current study are in keeping with extensive previous literature (34, 46) and could be due to changes in patellar tendon intrinsic collagenous structure and/or biochemical composition (e.g., increased collagen content, crosslink density, fibril size; (3, 47). At present evidence for specific alterations in free tendon intrinsic structure/composition after RT in healthy individuals are lacking, and therefore further investigations to uncover the mechanism(s) for the increases in Young's modulus are required. Despite positive outcomes being reported when collagen supplementation has been included in addition to rehabilitative loading of injured tendinous tissue (21–23), there is currently equivocal evidence supporting the inclusion of CP supplements for the enhancement of RT-induced increases in the mechanical properties of healthy tendon. Whereas for injured tendons there appears to be an elevated collagen turnover (48) that may make injured tendons more responsive to nutritional interventions, such as collagen peptides.

Limitations

Whilst careful methodology to assess adaptations in the mechanical properties and size of the patellar tendon and size of the VL aponeurosis were used, it is important to consider the limitations of the present study. Patellar tendon Young's modulus was assessed pre- and post-RT to assess the material stiffness of the tendon, but tendon tissue samples were not acquired to assess the structure and biochemical composition of the tendon. Whilst the applied nature of the RT exercises included within the current investigation mean our results are applicable to real-world RT practices as they offer a less controlled and individually standardised experimental model for assessing tendinous tissue adaptations compared to isometric RT, commonly used in the existing research literature. An overall dropout rate of 25% was observed in the current study which is greater than that reported for supervised RT studies of similar duration (e.g., 12-20%; (49, 50)) but was similar between our two groups (CP= 27%, PLA= 23%). For the measurement of patella tendon force that was subsequently used to calculate patella tendon mechanical properties, antagonist (knee flexor) EMG was used to estimate antagonist torque during knee extension. However, the knee flexors are quite a diverse group of 9 muscles and the current study assessed EMG from only 2 of these muscles which may produce some error in the estimation of antagonist torque. Our assessment of habitual physical activity (IPAQ short form) may have been subject to the influence of social desirability bias but there is no reason to suspect this would have been greater in one group compared to the other. The results of the current study cannot be generalised to individuals experiencing tendon injury or undertaking rehabilitation due to possible ultrastructural, molecular, and biochemical differences between asymptomatic and symptomatic tendons. For example, collagen turnover in healthy adults has been reported to be slow (40) but is elevated in tendinopathic individuals (48). Studies investigating the effects of CP supplementation on tendinous tissue size and mechanical properties in a tendon injury rehabilitation population, alongside function and pain, seem warranted to provide mechanistic support for favourable outcomes reported in the existing research literature.

CONCLUSIONS

In conclusion, CP supplementation did not enhance patellar tendon CSA, VL aponeurosis area, or mechanical property adaptations compared to PLA within a population of healthy recreationally active young males and consequently cannot be advocated as a supplement to augment RT-induced remodelling of healthy tendinous tissue.

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CONFLICT OF INTEREST DISCLOSURE

The authors declare that there is no conflict of interest and that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation

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TABLE CAPTIONS

Table 1. Tendinous tissue morphology, and patellar tendon mechanical properties pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation.

FIGURE CAPTIONS

Fig. 1 Experimental set-up for the determination of patella tendon stiffness measures. Participants were tightly fastened to a rigid isometric knee extension dynamometer (A). Unilateral knee extension torque, video of the knee joint angle (θ), antagonist muscle (medial and lateral hamstring) surface electromyography (EMG) and patellar tendon ultrasound video images were synchronously recorded during isometric knee extension ramp contractions performed at a constant rate (B). Patellar tendon ultrasound images (C) at rest (top) and at peak ramp torque (bottom) indicate the measurement of patellar tendon elongation ($\Delta T + \Delta P$).

Fig. 2 Example axial magnetic resonance images of the thigh with the width of the vastus lateralis (VL) deep aponeurosis manually segmented (in red) at: (A) proximal, (B) mid, and (C) distal locations. (D) Corresponding coronal plane magnetic resonance image indicating location of axial images along the length of the femur and (E) the aponeurosis width-aponeurosis length curve used to derive VL aponeurosis area via fitting a cubic spline curve. VI, vastus intermedius.

Fig. 3 (A) Example sagittal plane magnetic resonance image of the knee at ~50% of the distance between femoral condyles indicating location of example axial plane images within proximal, mid, and distal regions (displayed in B) along the length of the patellar tendon. (i) Axial images display overall cross-section of the knee and (ii) manual segmentation (in green) of the perimeter of the patellar tendon to determine cross-sectional area at 900% zoom. CuSO4, Copper (II) sulphate.

Fig. 4 Patellar tendon mean cross-sectional area (CSA; a and b) and Vastus lateralis (VL) aponeurosis area (c and d) at a group level (top row, mean ± SD) and for individual participants (bottom row) pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. P value is shown for the ANOVA group x time (g x t) interaction. Within-group pre to post effects were determined from paired t-tests and are denoted by: ***P<0.001.

Fig. 5 Patellar tendon stiffness (a and b) and patellar tendon Young's modulus (c and d) at a group level (top row; mean ± SD) and for individual participants (bottom row) pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. P value is shown for the ANOVA group x time (g x t) interaction. Within-group pre to post effects were determined from paired t-tests and are denoted by. *P<0.05, **P<0.01. Pre and post patellar tendon stiffness and Young's modulus were measured between 70-80% of maximum voluntary tendon force at pre and 70-80% of maximum voluntary tendon stress at pre, respectively.

Fig. 6 Patellar tendon force-elongation relationships pre (blue) and post (red) 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. Elongation values are plotted at 5% increments of pre-RT maximum voluntary tendon force (MVTFpre). Data are mean ± SD. Within-group pre to post effects on elongation at 80% of MVTFpre were determined from paired t-tests and are denoted by: **P<0.01.

TABLES

Table 1. Tendinous tissue morphology, and patellar tendon mechanical properties pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation.

	CP		**PLA**		ANOVA Interaction (g x t)	ANOVA time effect
	Pre	Post	Pre	Post		
Aponeurosis morphology:						
VL aponeurosis area (cm^2)	154.4 ± 29.2	169.2 ± 29.6***	157.1 ± 31.0	170.2 ± 30.1***	P=0.697	P<0.001
VL aponeurosis maximum width (cm)	8.9 ± 1.1	9.5 ± 1.2***	9.0 ± 1.3	9.6 ± 1.1**	P=0.798	P<0.001
Patellar tendon morphology:						
Mean CSA, mm^2	93.2 ± 12.8	94.3 ± 13.6	92.7 ± 14.3	94.2 ± 13.9	P=0.622	P=0.048
Proximal region CSA, mm^2	96.4 ± 14.9	98.6 ± 15.6	95.5 ± 16.6	97.5 ± 16.1	P=0.877	P=0.017
Mid region CSA, mm^2	90.8 ± 11.7	91.1 ± 13.2	90.9 ± 14.3	92.2 ± 14.2	P=0.365	P=0.475
Distal region CSA, mm^2	92.5 ± 13.3	92.9 ± 13.4	91.3 ± 15.1	92.3 ± 14.6	P=0.385	P=0.085
Length, mm	48.1 ± 3.8	48.4 ± 3.7	50.8 ± 5.7	50.9 ± 5.6	P=0.491	P=0.276
Patellar tendon properties:						
Stiffness†, $N.mm^{-1}$	1911 ± 631	2153 ± 529**	1863 ± 520	2185 ± 457***	P=0.613	P<0.001
Elongation†, mm	4.06 ± 0.63	3.58 ± 0.53**	4.25 ± 0.76	3.82 ± 0.76**	P=0.827	P<0.001
Young's modulus, GPa	1.01 ± 0.40	1.13 ± 0.33**	1.04 ± 0.35	1.22 ± 0.32**	P=0.837	P<0.001
Strain, %	8.5 ± 1.5	7.5 ± 1.2**	8.4 ± 1.7	7.6 ± 1.1**	P=0.775	P<0.001

Data are mean ± SD. Within-group pre to post effects were determined from paired t-tests and are denoted by: **P<0.01 or ***P<0.001. P values are shown for ANOVA group x time (g x t) interactions and time effects. Patellar tendon CSA was calculated as the mean over all measured images along the length of the tendon (mean CSA) and as the mean of images within each third of the tendon length to derive regional measures of tendon CSA (proximal, mid and distal region CSA). Pre and post patellar tendon stiffness and Young's modulus were measured between 70-80% of maximum voluntary tendon force at pre and 70-80% of maximum voluntary tendon stress at pre, respectively. Pre and post patellar tendon elongation and strain were measured at 80% of maximum voluntary tendon force at pre and 80% of maximum voluntary tendon stress at pre, respectively.

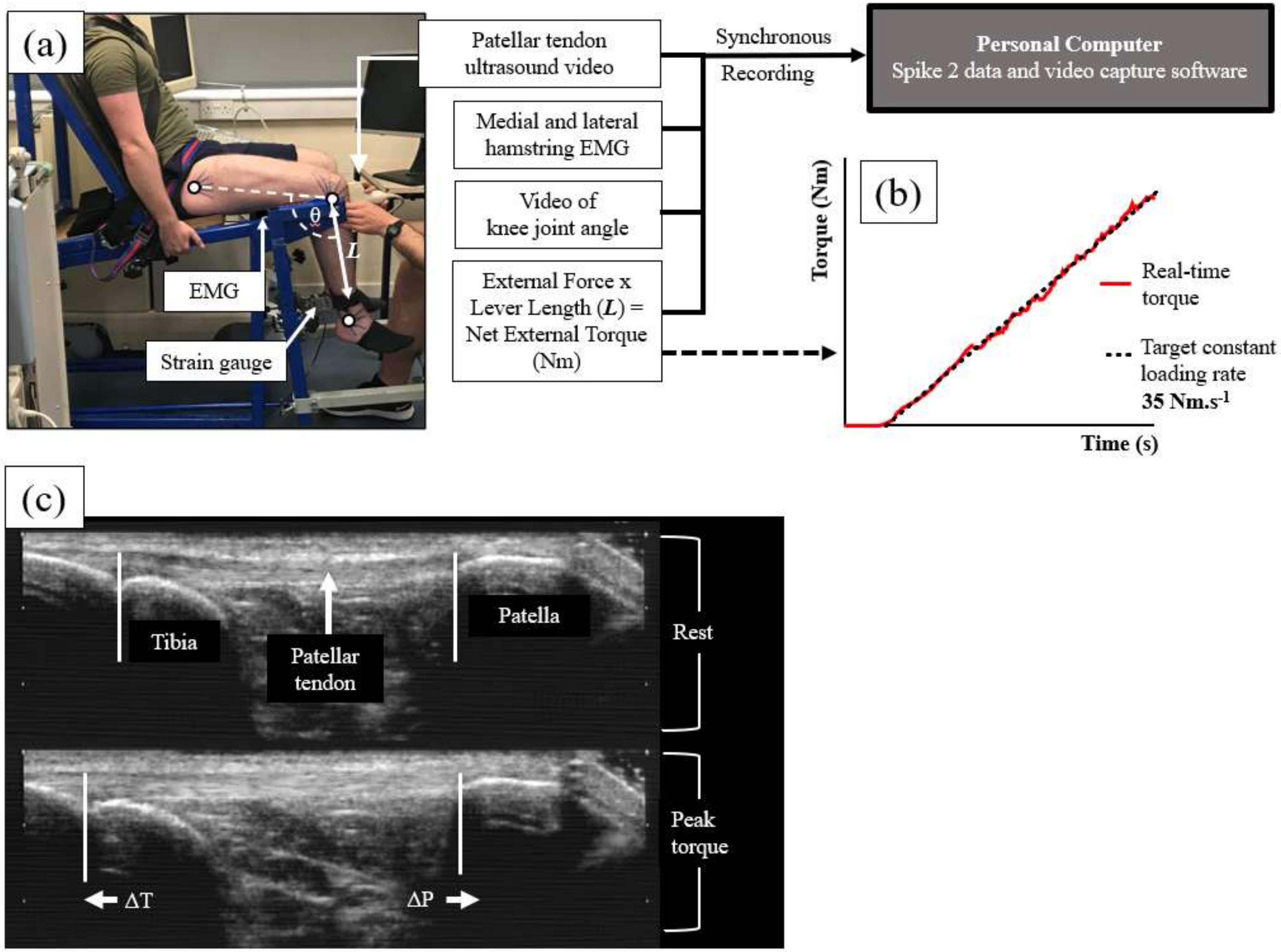

Fig. 1 Experimental set-up for the determination of patella tendon stiffness measures. Participants were tightly fastened to a rigid isometric knee extension dynamometer (A). Unilateral knee extension torque, video of the knee joint angle (θ), antagonist muscle (medial and lateral hamstring) surface electromyography (EMG) and patellar tendon ultrasound video images were synchronously recorded during isometric knee extension ramp contractions performed at a constant rate (B). Patellar tendon ultrasound images (C) at rest (top) and at peak ramp torque (bottom) indicate the measurement of patellar tendon elongation (ΔT + ΔP).

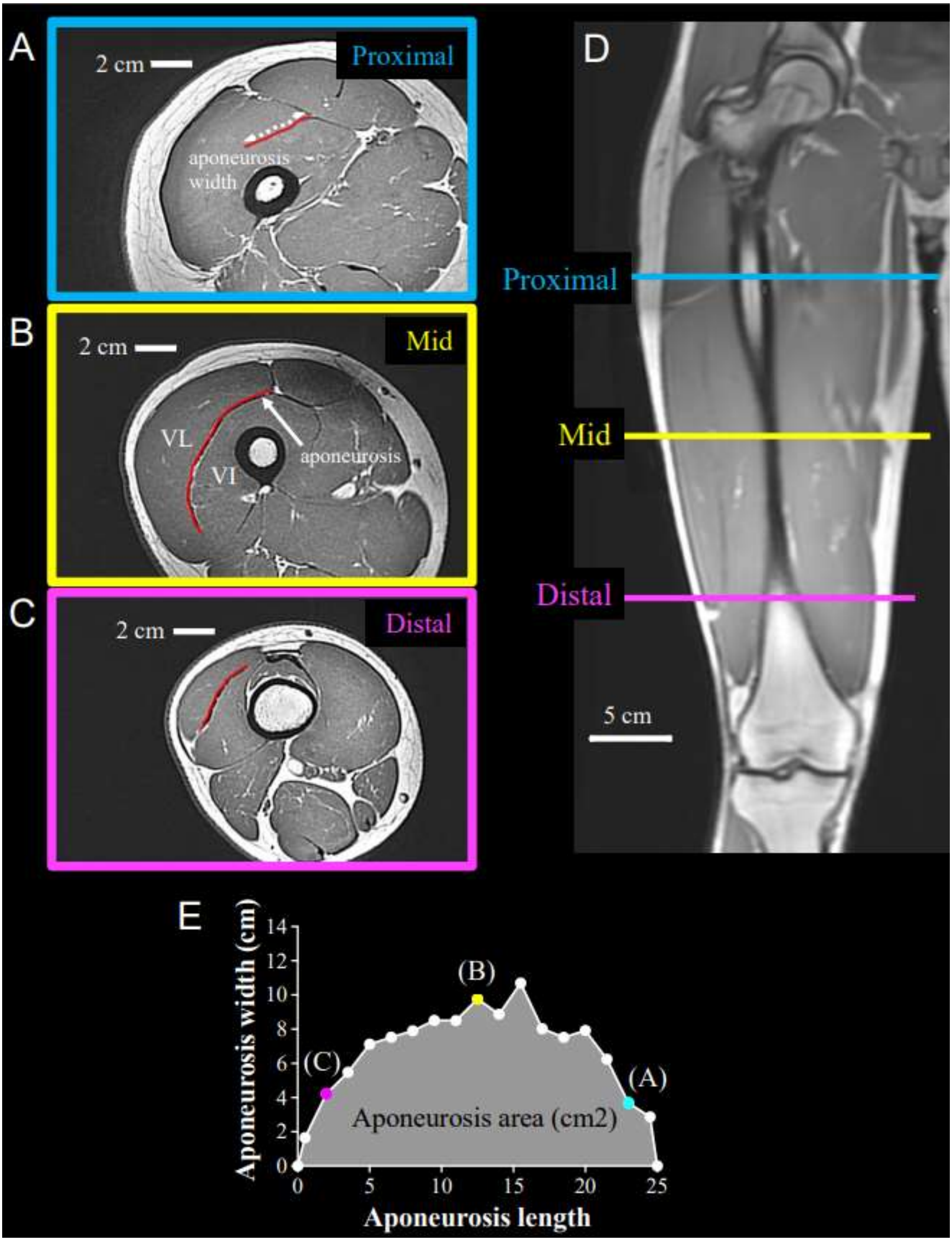

Fig. 2 Example axial magnetic resonance images of the thigh with the width of the vastus lateralis (VL) deep aponeurosis manually segmented (in red) at: (A) proximal, (B) mid, and (C) distal locations. (D) Corresponding coronal plane magnetic resonance image indicating location of axial images along the length of the femur and (E) the aponeurosis width-aponeurosis length curve used to derive VL aponeurosis area via fitting a cubic spline curve. VI, vastus intermedius.

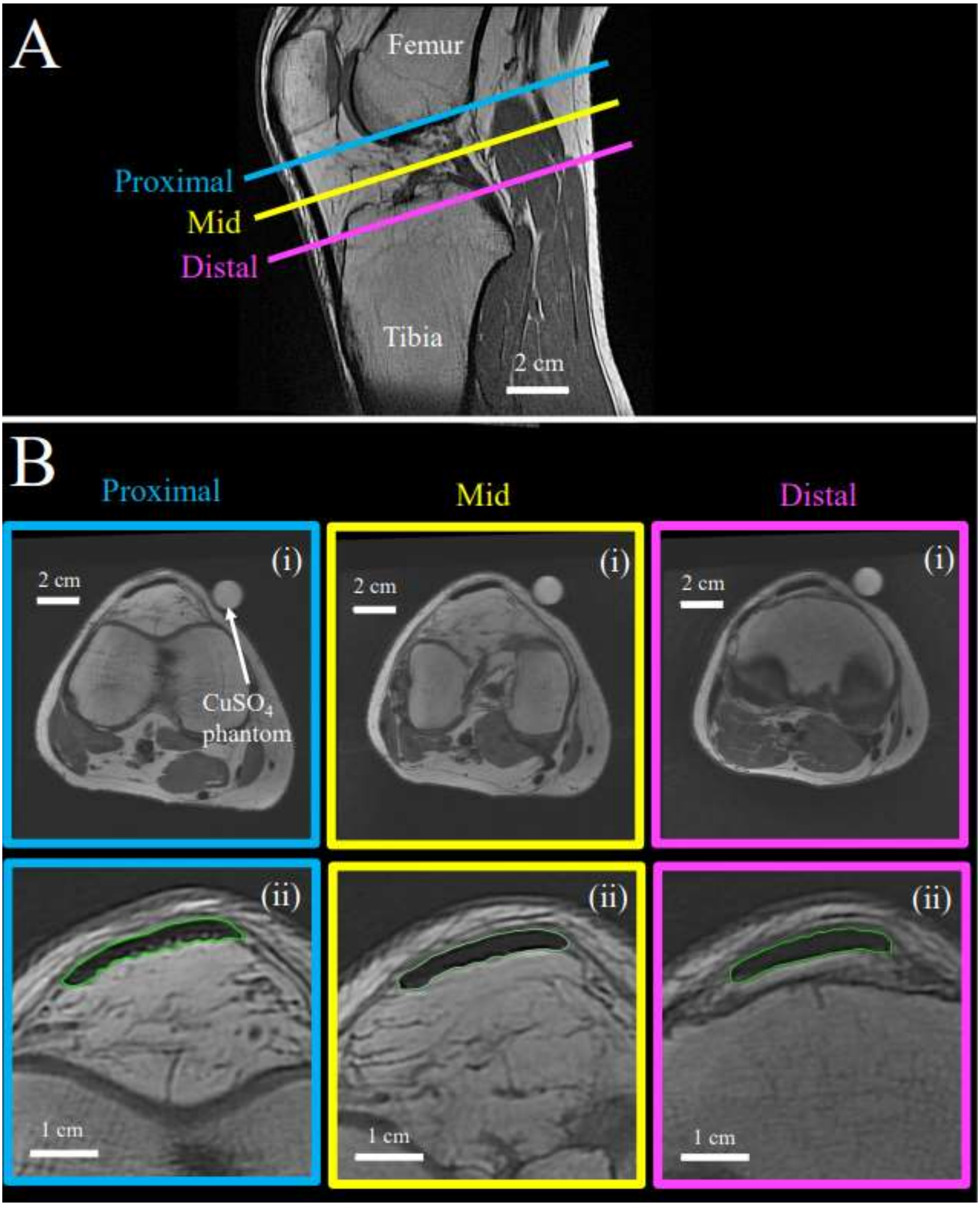

Fig. 3 (A) Example sagittal plane magnetic resonance image of the knee at ~50% of the distance between femoral condyles indicating location of example axial plane images within proximal, mid, and distal regions (displayed in B) along the length of the patellar tendon. (i) Axial images display overall cross-section of the knee and (ii) manual segmentation (in green) of the perimeter of the patellar tendon to determine cross-sectional area at 900% zoom. CuSO4, Copper (II) sulphate.

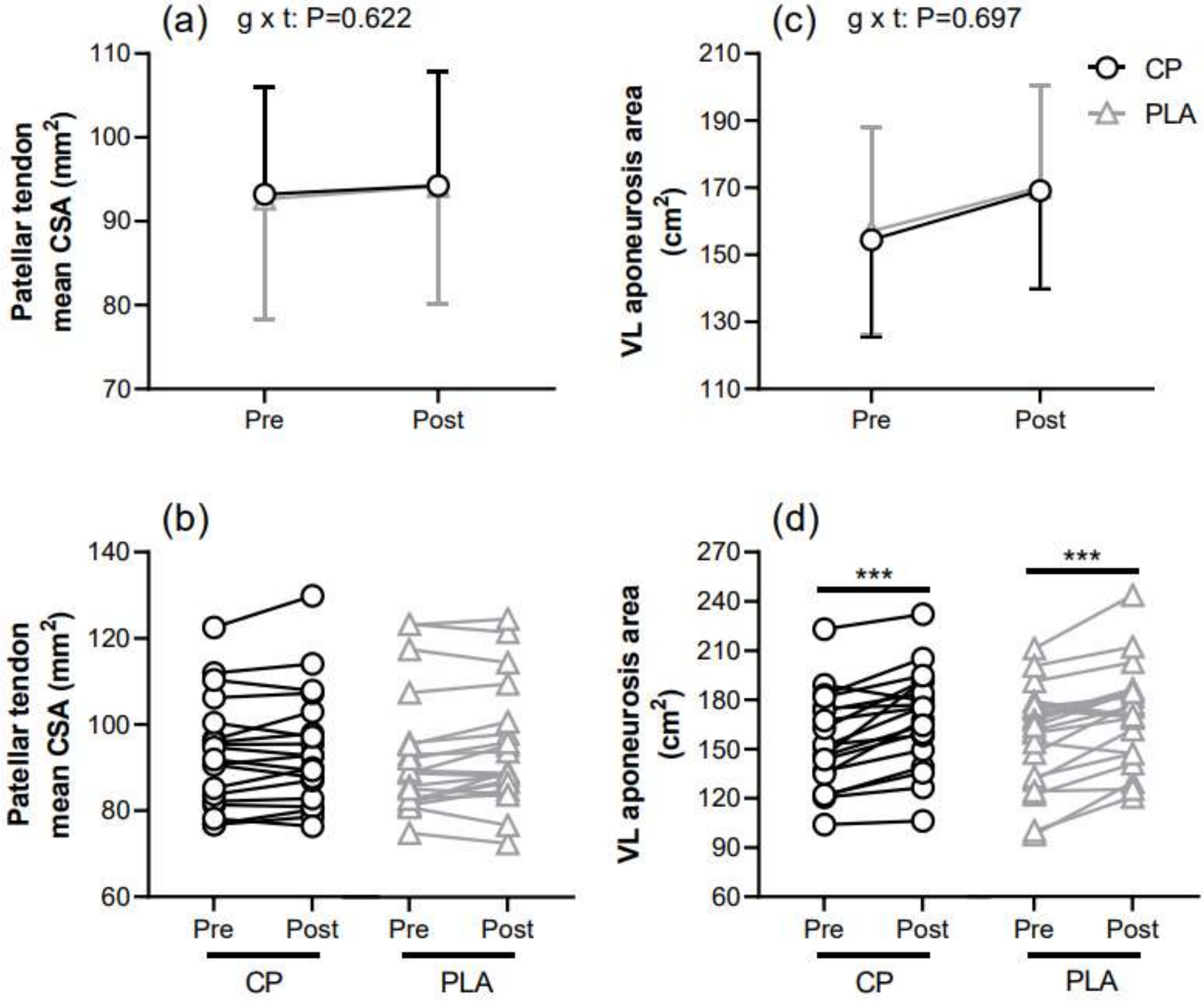

Fig. 4 Patellar tendon mean cross-sectional area (CSA; a and b) and Vastus lateralis (VL) aponeurosis area (c and d) at a group level (top row, mean ± SD) and for individual participants (bottom row) pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. P value is shown for the ANOVA group x time (g x t) interaction. Within-group pre to post effects were determined from paired t-tests and are denoted by: ***P<0.001.

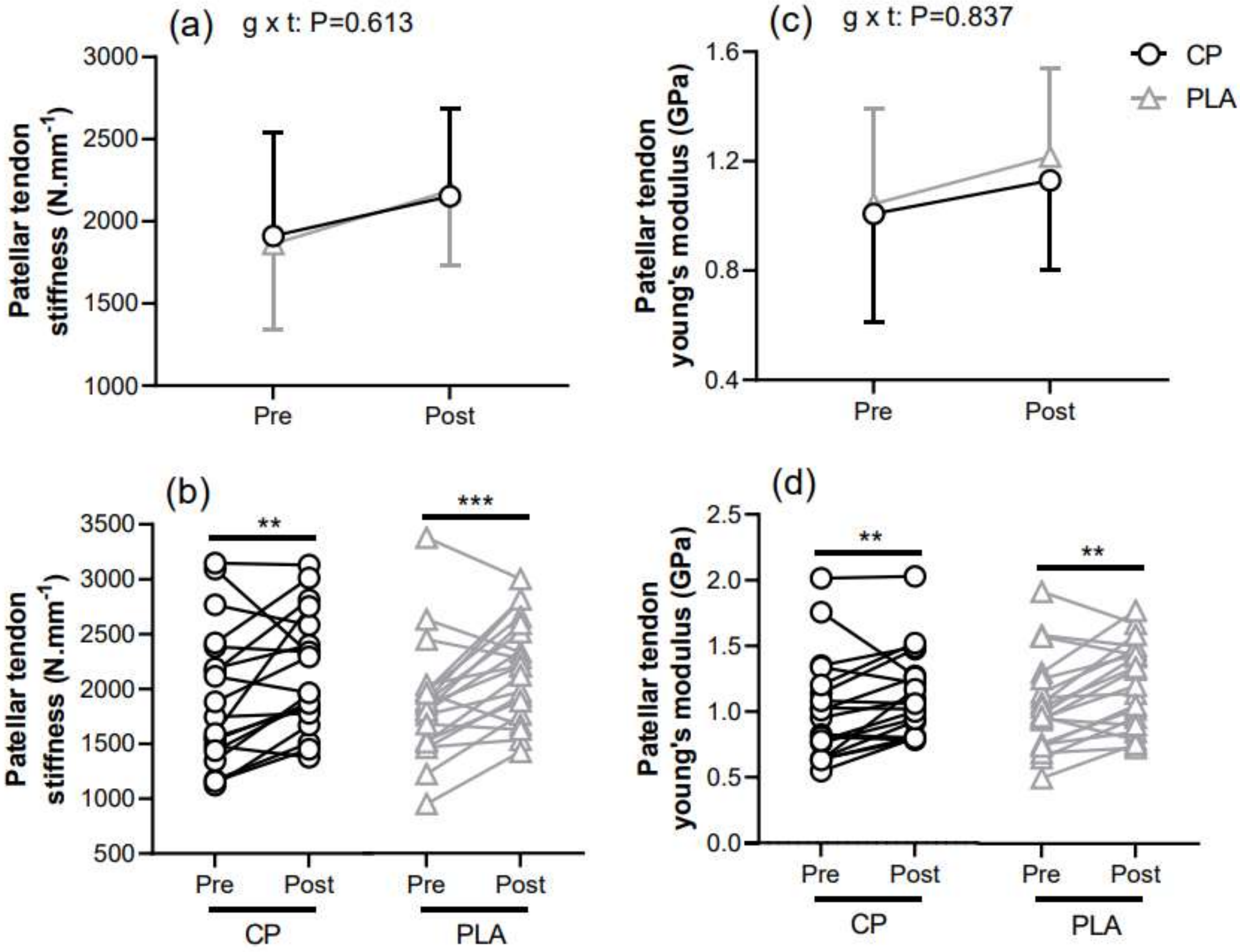

Fig. 5 Patellar tendon stiffness (a and b) and patellar tendon Young's modulus (c and d) at a group level (top row; mean ± SD) and for individual participants (bottom row) pre and post 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. P value is shown for the ANOVA group x time (g x t) interaction. Within-group pre to post effects were determined from paired t-tests and are denoted by. *P<0.05, **P<0.01. Pre and post patellar tendon stiffness and Young's modulus were measured between 70-80% of maximum voluntary tendon force at pre and 70-80% of maximum voluntary tendon stress at pre, respectively.

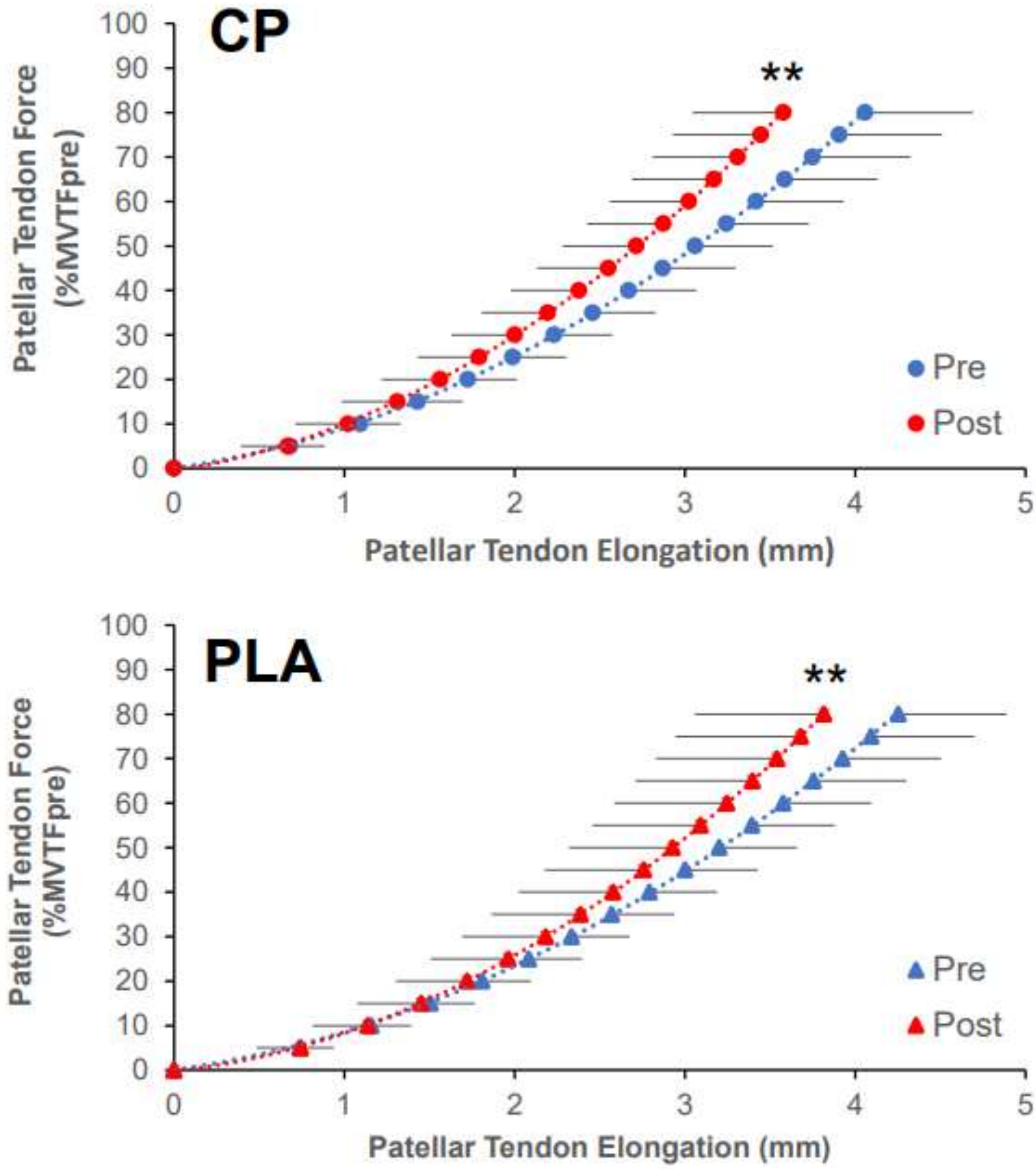

Fig. 6 Patellar tendon force-elongation relationships pre (blue) and post (red) 15 weeks of lower-body resistance training, with collagen peptides (CP, *n*=19) or placebo (PLA, *n*=20) supplementation. Elongation values are plotted at 5% increments of pre-RT maximum voluntary tendon force (MVTFpre). Data are mean ± SD. Within-group pre to post effects on elongation at 80% of MVTFpre were determined from paired t-tests and are denoted by: **P<0.01.