Received: 14 September 2023 | Revised: 12 December 2023 | Accepted: 18 December 2023

DOI: 10.1111/sms.14555

ORIGINAL ARTICLE

WILEY

Personalized tendon loading reduces muscle-tendon imbalances in male adolescent elite athletes

Theresa Domroes[1,2] | Kolja Weidlich[1,2] | Sebastian Bohm[1,2] | Falk Mersmann[1,2] | Adamantios Arampatzis[1,2]

[1]Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany

[2]Berlin School of Movement Science, Humboldt-Universität zu Berlin, Berlin, Germany

Correspondence
Adamantios Arampatzis, Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Philippstr 13, Haus 11, 10115 Berlin, Germany.
Email: a.arampatzis@hu-berlin.de

Funding information
German Federal Institute of Sport Science

Abstract

An imbalanced adaptation of muscle strength and tendon stiffness in response to training may increase tendon strain (i.e., the mechanical demand on the tendon) and consequently tendon injury risk. This study investigated if personalized tendon loading inducing tendon strain within the effective range for adaptation (4.5%–6.5%) can reduce musculotendinous imbalances in male adolescent handball athletes (15–16 years). At four measurement time points during a competitive season, we assessed knee extensor muscle strength and patellar tendon mechanical properties using dynamometry and ultrasonography and estimated the tendon's structural integrity with a peak spatial frequency (PSF) analysis of proximal tendon ultrasound scans. A control group ($n=13$) followed their usual training routine, an intervention group ($n=13$) integrated tendon exercises into their training (3x/week for ~31 weeks) with a personalized intensity corresponding to an average of ~6.2% tendon strain. We found a significant time by group interaction ($p<0.005$) for knee extensor muscle strength and normalized patellar tendon stiffness with significant increases over time only in the intervention group ($p<0.001$). There were no group differences or time-dependent changes in patellar tendon strain during maximum voluntary contractions or PSF. At the individual level, the intervention group demonstrated lower fluctuations of maximum patellar tendon strain during the season ($p=0.005$) and a descriptively lower frequency of athletes with high-level tendon strain (≥9%). The findings suggest that the personalized tendon loading program reduced muscle-tendon imbalances in male adolescent athletes, which may provide new opportunities for tendon injury prevention.

KEYWORDS
adaptation, overuse, tendinopathy, tendon training, youth athletes

1 | INTRODUCTION

A well-coordinated interplay of muscle and tendon is essential for an effective execution of various movements in sports and daily life.[1–3] While muscles generate the necessary forces, tendons enable the storage and return of elastic strain energy during movement.[3,4] Tendon elasticity further influences the muscle's operating length and velocity and hence the force-length-velocity and power-velocity potential as well as the efficiency-velocity relationship of the muscle.[1,5,6] On the other hand, tendons are quite susceptible to overuse injuries and there is a high prevalence of tendinopathies in adult as well as youth athletes.[7–9]

One underlying factor for tendon overuse may be imbalances in the changes of muscle strength and tendon mechanical properties.[10] If the force generating capacity of the muscle increases without concomitant increases in the respective tendon stiffness, this results in increased tendon strain. Though the exact strain level for tendon failure is unknown in vivo, it seems to be quite constant across tendons.[11] Therefore, any increase in tendon operating strain increases the mechanical demand on the tendon tissue and reduces the tendon safety factor (i.e., ratio of operating tendon strain to ultimate tendon strain). Accordingly, it has been shown in vitro that the initial level of tendon strain during static and cyclic loading was the best predictor of time or cycles to failure[12] and that tissue damage and catabolic processes outweigh tissue repair mechanisms at continuous cyclic loading with tendon strain levels as high as 9%.[13] In vivo, imbalances between muscle strength and tendon stiffness have been observed in athletes from child- to adulthood,[14–18] resulting in high frequencies of increased tendon strain levels (i.e., an increased mechanical demand on the tendon) as well as high fluctuations of tendon strain during a season. Thereby, an inverse relationship between tendon strain and the structural integrity of the proximal patellar tendon was reported for male adolescent athletes, indicating a local disorganization of the collagenous structure in tendons that are subjected to high tendon strain.[19,20] Further, we could recently demonstrate in a prospective longitudinal study that the risk for developing tendon pain is increased 2.3-fold in athletes with tendon strain levels ≥9% during maximum effort muscle contractions.[21] Considering that tendinopathies constitute a considerable burden for athletic populations and that their prevalence seems to increase from child- to adulthood,[8,9] early preventive approaches to reduce the mechanical demand on the tendon may have the potential to reduce tendon injury risk and to restore a well-coordinated interaction between muscle and tendon in athletes. This may be achieved by introducing exercises into the training routine that counteract musculotendinous imbalances by promoting a more homogenous adaptation of muscle strength and tendon stiffness. In case of increased tendon strain, this would specifically entail loading programs that primarily target tendon adaptation.

While muscles are able to adapt to a variety of mechanical and metabolic stimuli,[22] it seems that tendon adaptation requires a certain strain magnitude. In vitro findings suggest that a mechanical over-stimulation as well as an under-stimulation of tendon tissue may induce catabolic processes and matrix deterioration and that there only exists a certain strain range (i.e., a "sweet spot" of tendon strain magnitude) in between that can induce net anabolic processes in the tendon.[13,23] A series of systematic in vivo intervention studies demonstrated that cyclic loading of the tendon with a strain magnitude between 4.5% and 6.5% caused improvements of tendon mechanical properties, while no improvements were observed at ~3% of strain.[24–26] This tendon strain range was mostly achieved at 90% of isometric maximum voluntary contractions (MVC). This may, however, not apply to all individuals. Especially in populations with a high prevalence of musculotendinous imbalances, there exists a high variability in tendon strain during MVCs or one repetition maximum (1RM) loading, so that tendon exercises at the same load relative to the MVC or 1RM may result in tendon strain outside the effective region for tendon adaptation.[27,28] Tendon exercises at high strain above the "sweet spot" region may thereby even have harmful consequences for the tendon (i.e., increase the risk for tendinopathy).[21] Accordingly, a prescription of exercise load based on an MVC or 1RM alone does not seem to be accurate enough to specifically promote tendon adaptation, particularly in athletes with musculotendinous imbalances, as these affect the relationship between an MVC or 1RM and tendon strain.[27,28] A load prescription that considers the individual tendon strain during loading is consequently an innovative approach for targeted tendon adaptation, which has to our knowledge not been investigated in vivo before. With this approach, individuals with high maximum tendon strain (i.e., muscle-tendon imbalances) would train at lower relative intensities (e.g., a lower percentage of MVC or 1RM) to reach the "sweet spot" for tendon adaptation, so that it can be expected that tendon adaptation is promoted to a higher extent compared to muscle adaptation, which would in turn reduce musculotendinous imbalances. In individuals with lower maximum tendon strain (i.e., without muscle-tendon imbalances) on the other hand, the higher training intensities are presumably suitable to induce a balanced adaptation of both muscle and tendon.[27]

Therefore, the aim of the current study was to investigate the effects of a tendon strain-based personalized loading program on patellar tendon adaptation, muscle-tendon imbalances and tendon micromorphological structure during a competitive season in male adolescent elite handball athletes, as it has been previously shown that musculotendinous imbalances are quite common in this population.[18,29] We hypothesized that fluctuations of patellar tendon strain over the season as an indicator for individual imbalances in the adaptation of muscle and tendon will be lower in the intervention group in comparison to the control group.

2 | METHODS

2.1 | Participants and experimental design

To investigate the effects of a personalized tendon exercise intervention, we recruited male adolescent elite handball players (aged 15–16 years) for a control and an intervention group. The necessary sample size was calculated in a power analysis (G*Power, version 3.1.9.7). Based on a large effect (d = 1.4), which we observed previously for pre-post changes in tendon stiffness after a non-personalized tendon exercise intervention in adolescent athletes,[20] and a power of 0.9, we calculated a sample size of eight per group. Considering a potential drop-out, 15 participants were recruited for the control group. In the following season, 13 athletes from the same team (i.e., same age group), including four athletes that already participated in the control group, were recruited for the intervention group. All participants had a weekly training duration of at least 10 h (approx. 60% handball specific training, 40% strength and athletic training; excluding competition). Exclusion criteria were any neurological or musculoskeletal impairments of the lower extremity. Participants with patellar tendon pain were included if maximum voluntary muscle strength testing was possible. All participants and their legal guardians gave written informed consent to the experimental procedures, which were approved by the ethics committee of the Humboldt-Universität zu Berlin (ref. no. HU-KSBF-EK_2020_0005).

The control group received only their sport-specific training, while the intervention group integrated a personalized tendon loading program into their regular training. In both groups, knee extensor muscle strength, patellar tendon mechanical properties and micromorphology as well as the prevalence of tendon pain and disability were assessed at four measurement time points during a competitive season (M1, M2 and M3: in-season; M4: transition period). The exact time span between measurements differed between groups and individuals due to constraints in the scheduling of the measurements (e.g., holidays, training camps, tournaments) with on average 12, 13, and 10 weeks between measurements in the control group and 14, 14, and 6 weeks in the intervention group. The training intervention started approximately 3 weeks after M1 so that the intervention duration was on average 31 weeks. All measurements were performed on the dominant leg, which was defined as the leg used to kick a ball. Biological maturity of the participants was predicted as the years to peak height velocity (PHV) using age and sitting height in the recalibrated prediction equation suggested by Moore et al.[30] The prevalence of patellar tendon pain and pain-related disability was assessed with the validated German version of the VISA-P questionnaire[31] considering the symptoms of the past 2 weeks. Participants were categorized as symptomatic with a score ≤ 87 points, as this represents the minimum clinically important difference[31] from the maximum score of 100 points.

Two participants of the control group were excluded from the study due to unavoidable movement artifacts in the ultrasound recordings of the tendon, which did not allow an accurate analysis of tendon properties. One participant of the intervention group did not participate in M2, one participant of each group did not participate in M3 and M4, leading to a total of 50 observations in the control group and 49 observations in the intervention group.

2.2 | Assessment of tendon micromorphology

The assessment of tendon micromorphology was based on a spatial frequency analysis of ultrasound recordings of the proximal part of the patellar tendon. The ultrasound recordings took place prior to the measurement of muscle strength and tendon mechanical properties to avoid the influence of possible acute loading-related responses. The participants were positioned supine with their knee flexed to 90° (measured with a goniometer), as tendon slack is commonly removed in this angle, while strain induced by passively generated forces is still low.[19]

Two short sequences were captured with an ultrasound probe (ultrasound system: MyLab60; Esaote, Genova, Italy; probe: linear array LA523, 13 MHz, depth: 3.0 cm) placed over the patellar tendon parallel to its longitudinal axis below the most distal apex of the patella. Images were analyzed with a custom-written MATLAB interface (version R2016a; MathWorks, Natick, MA, United States). A polygonal region of interest (ROI) was defined, spanning from the deep insertion of the patella to the central portion of the tendon with a length of 40% of the tendon's rest length (measured as described below) and a height that covered the full thickness of the tendon. All 32 × 32 pixel kernels contained within the ROI were analyzed as suggested by

Bashford and colleagues.[32] In short, a 2D Fast Fourier transform and a high-pass filter with a radial frequency response and half-power cutoff frequency of 1.23 mm^{-1} were applied. The filtered kernels were zero padded in both directions to a size of 128 × 128 pixels to increase frequency resolution. The distance of the peak spatial frequency (PSF) to the spectral origin in the frequency spectrum of all analyzed kernels was averaged and the mean PSF of both recorded trials was then used for further analysis. Thereby, low PSF values represent a more isotropic speckle pattern in the ultrasound images, indicating a low packing density and alignment of the collagen bundles as is common for tendinopathic tendons.[32]

2.3 | Assessment of knee extensor muscle strength

Muscle strength of the knee extensors was assessed as the maximum knee extension moment during isometric MVCs using a custom-built mobile measurement system (Figure 1). After a self-selected warm-up which included submaximal and five maximal jumps, the participants were fixed in a seated position with a nonelastic belt with a trunk angle of about 90°. A force sensor (2 kN; Biovision, Wehrheim, Germany) in series with a non-elastic rope was attached with a strap to the participants' lower shank. The rope was adjusted so that the force sensor was aligned in the direction of force application perpendicular to the shank and that the knee joint angle reached 60° during contractions (0° represents full knee extension; measured with a goniometer), as this is approximately the optimal angle for maximum force generation of the knee extensors.[33] Ten submaximal isometric knee extension contractions with increasing effort served as additional warm-up, familiarization and preconditioning of the tendon. Afterwards, the participants performed two MVCs with 2–3 min rest between trials. Force data was recorded with a custom-written MATLAB interface (version R2016a) at 200 Hz and filtered with a second-order Butterworth filter with a cutoff frequency of 6 Hz. Subsequently, a moving average filter with a window size of 50 ms was used for the determination of maximum force values. The recorded force was then multiplied with the lever arm of the applied force (i.e., distance from the lateral epicondyle to the middle of the strap around the shank) to get the knee joint moment, which was corrected for moments of gravity based on the data provided by Dempster[34] for the estimation of the mass and center of mass of the foot and shank. The MVC-trial with the highest moment was then used for further analysis.

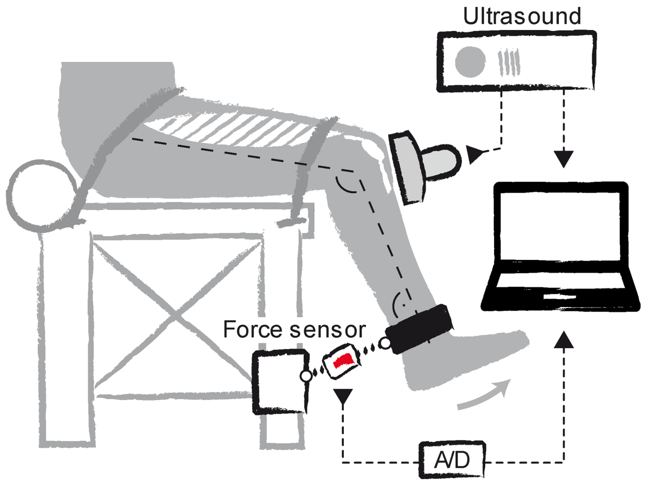

FIGURE 1 Mobile measurement system. The force generated during isometric knee extensions at 60° knee joint angle (0° represents full knee extension) was recorded with a force sensor. To obtain the forces acting on the tendon, measured forces were multiplied with the lever arm of the applied force (i.e., distance from the lateral epicondyle to the middle of the strap around the shank), corrected for moments of gravity and divided by the patellar tendon moment arm (based on anthropometry). Patellar tendon elongation during contractions was captured with ultrasound and time synchronized with a manually released 5 Volt trigger signal.

2.4 | Assessment of tendon mechanical properties

The force-elongation relationship of the patellar tendon was determined by recording tendon elongation with ultrasound (MyLab60; Esaote, Genova, Italy) during five isometric ramp contractions in the same setup used for the MVCs. During the contractions, the participants received visual feedback to increase effort steadily from rest to maximum within 5 s. Tendon elongation was recorded by fixing a 10 cm ultrasound probe (probe: LA923, 7.5 MHz; 25 Hz image frequency) over the longitudinal axis of the patellar tendon with a modified knee brace. A manually released 5 Volt trigger signal was used to synchronize the ultrasound and force data. The displacement of the deep insertion of the tendon at the patellar apex and the tibial tuberosity in the ultrasound images was tracked with a semi-automatic tracking software (Tracker Video Analysis and Modeling Tool V. 5.1.5; Open Source Physics, Aptos, CA, United States) to determine tendon elongation. Tendon rest length was determined from the ultrasound images as the length of the slack tendon prior to the onset of the contraction (i.e., in a relaxed state at 60° knee joint angle). It was measured with a spline fit through the deep insertion marks and two additional points along the border of the tendon and averaged for all five trials. The forces acting on the tendon were obtained by dividing the knee joint moment by the patellar tendon moment arm which was estimated based on anthropometry[14] and adjusted to the knee joint angle with the data reported by Herzog and Read.[35] The force-elongation relationship for each single ramp trial was saved as piecewise-linear polynomial function in MATLAB (version R2019b; "interp1" function with "pp" option), using all the measured data of the respective ramp as input. To achieve a high reliability and observer independence,[36] we averaged the five force-elongation curves. Therefore, at each measured data point, all single ramp trials were evaluated using their respective piecewise-linear polynomials and then averaged (using the "fncmb" function in MATLAB). The resulting mean piecewise-linear polynomial was evaluated up to 80% of maximum tendon force (i.e., the force calculated from the highest MVC trial of each participant), as this was the highest relative force all participants were capable of achieving during the ramp contractions. Finally, a second-order polynomial fit passing through zero was applied to the averaged patellar tendon force-elongation data points. Patellar tendon stiffness was calculated from this polynomial function as the quotient between 50% and 80% of the maximum tendon force. Tendon stiffness was further normalized by multiplying it with the tendon rest length. Accordingly, normalized tendon stiffness represents the slope of the tendon force-strain relationship. Maximum tendon strain was calculated by extrapolating tendon elongation to the maximum tendon force based on the polynomial fit of the force-elongation curve and dividing it by tendon rest length.

2.5 | Tendon exercise intervention

The participants in the intervention group received an exercise program which was designed to provide an evidence-based effective strain magnitude (i.e., 4.5%–6.5% tendon strain[24,25]) for tendon adaptation. Accordingly, the training load was personalized for each participant based on their maximum patellar tendon strain during MVCs (calculated as described above). With the simplified assumption of a linear relationship between tendon force and elongation, we determined the relative force needed for each participant to induce 5.5% of tendon strain. The maximum relative training load was limited to 90% of maximum force to ensure an accurate execution of the training protocol. This means that all participants who would, according to our calculation, need a training intensity above 90% MVC to reach 5.5% tendon strain (i.e., participants with maximum tendon strain ≤6.1%), also trained at 90% of their MVC, which has been shown to be an adequate stimulus for the balanced adaptation of both muscle and tendon.[24,25]

To ensure an adequate transferability of the strain values determined in the experimental setup and the strain achieved during training, isometric knee extensions were performed in a training device similar to the experimental setup (Figure 2A). Therefore, a non-elastic band was fixed to the lower shank and adjusted so that the knee joint angle reached 60° during contractions. A digital scale mounted in series with the band served to monitor the training load. For the determination of the personalized training load to reach the target patellar tendon strain, every participant performed an MVC in the training device. From the maximum load recorded in the training device and the prescribed relative loading intensity (i.e., % MVC), the absolute load to be applied during training was then determined for each participant individually. Both MVCs, in the measurement system and training device, were performed at the same knee joint angle, therefore we assumed similar muscle forces and tendon strain. Based

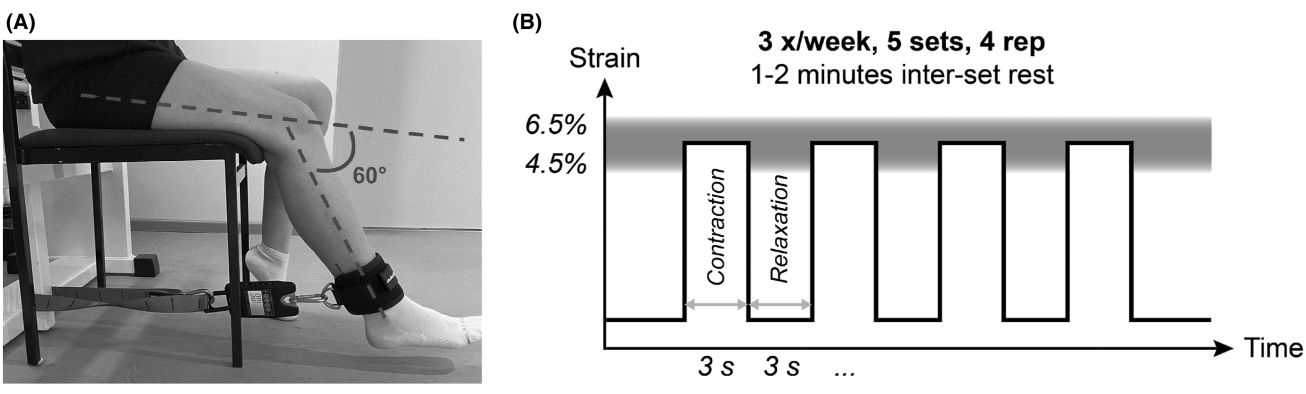

FIGURE 2 (A) Training set-up and (B) loading profile for the personalized tendon exercises. Isometric knee extension contractions were conducted at 60° knee joint angle (0° represents full knee extension). The individual load was controlled with a digital scale fixed to an adjustable non-elastic band. Training load was prescribed individually from an MVC performed in the training device, that was adjusted every 2 weeks, and the relative load determined based on tendon strain at the four measurement time points and two additional measurements (~7-week intervals).

on the most effective loading protocol for the tendon from our earlier systematic research,[24–26] the training consisted of five sets of four isometric knee extension contractions at the individual training load with a contraction duration of 3 s (Figure 2B). The participants were instructed to train both legs with the same relative load and to complete the training three times per week. The training frequency was chosen since we found in previous intervention studies with adolescent athletes that tendon exercises performed three times per week elicited significant adaptations of tendon stiffness,[20] while no systematic changes of tendon stiffness were observed with training two times per week.[29]

To account for strength adaptations during the training period, a new MVC was recorded in the training device every 2 weeks. With regards to possible changes in tendon mechanical properties, we additionally determined tendon strain (during three isometric ramp contractions) at an interval of about 7 weeks between the regular measurement time points to adjust the prescribed training load accordingly. Since M3 and M4 were only 6 weeks apart in the intervention group, these intermediate measurements were performed between M1, M2 and M3, respectively.

2.6 | Statistics

A linear mixed-effects model was formulated using the *nlme* package in RStudio (version 4.1.2; RStudio, PBC, Boston, MA, United States) with group-specific y-intercept, slope and variance of the residuals to analyze time- and group-dependent changes. The advantage of linear mixed models is that they can handle missing data and are robust against violations of the normality assumption,[37] which was not given for age, body height, body mass, and tendon rest length according to the Shapiro–Wilk test applied to the normalized residuals. The model equation was

$$y_{ij} = \beta_0 + \beta_1 t_{ij} + g_i \beta_2 + g_i \beta_3 t_{ij} + b_{0i} + b_{1i} t_{ij} + r_{ij} \quad (1)$$

where i is the index for participant, j is the index for the measurement session, $g_i = 0$ in the control group and 1 in the intervention group, t_{ij} is the time point (in weeks) for the measurement session j of the participant i, β_0 is the y-intercept constant for the control group, β_1 is the slope constant for the control group, β_2 is the y-intercept constant for the difference between control and intervention group, β_3 is the slope constant for the difference between control and intervention group, b_{0i} is the participant-specific y-intercept (random effect), b_{1i} is the participant-specific slope (random effect), and r_{ij} is the residual. Accordingly, the terms including g equal zero in the control group and β_0 and β_1 represent the respective constants for intercept and slope. In the intervention group, $\beta_0 + \beta_2$ and $\beta_1 + \beta_3$ represent the constants for intercept and slope, respectively. This allows testing of the significance of changes over time in the control group (slope constant β_1), baseline differences between groups (intercept constant β_2), and group differences in time-dependent changes (slope constant β_3; henceforth referred to as time by group interaction). Additionally, we tested separately for the intervention group if the slope differed significantly from zero. Note that age was only tested for baseline differences. To account for individual and group differences in the time span between measurements, the time points of the measurements were coded in weeks for each participant individually. As the inclusion of random effects in the linear mixed-effects model accounts for individual differences in intercept and slope, the residuals of the model can be used as a measure of individual fluctuations of muscle and tendon properties over time. Hence, we determined the estimated standard deviations of the residuals of the linear mixed model for the contextually relevant parameters. To assess group differences in the standard deviation of the residuals, we formulated two linear mixed models according to equation 1. One model assumed homogeneity of the residual variance (no group differences) while the other model allowed for group differences in the residual variance. These two models were then compared by a likelihood ratio test. From differences in this model comparison, it can then be inferred whether the standard deviation of the residuals differed between groups. To investigate whether there exists an association between initial tendon strain levels and changes in tendon stiffness, the correlation of maximum tendon strain at M1 and relative changes in normalized tendon stiffness from M1 to M4 was analyzed for both groups separately using the Pearson correlation coefficient (r). The significance level for all statistical tests was set to $\alpha = 0.05$.

3 | RESULTS

There were no significant baseline differences between groups in age ($p = 0.464$), biological maturity (estimated as offset from PHV; $p = 0.530$), body height ($p = 0.433$), and body mass ($p = 0.913$; Table 1). Biological maturity, body height and mass increased significantly over time in the control ($p < 0.001$, $p = 0.011$ and 0.003) and intervention group ($p < 0.001$) with no time by group interaction ($p = 0.328$, 0.565, and 0.154). Average VISA-P scores and the number of symptomatic athletes are shown in Table 1. The percentage of symptomatic athletes during the measurement period ranged from 0% to 38.5% in the control group and 0% to 8.3% in the intervention group. The tendon exercise intensity relative to the individual MVC in the intervention group was on average (mean ± SD)

TABLE 1 Anthropometric data, average VISA-P scores and number of symptomatic athletes for both groups and each measurement time point (M1-4) over a competitive season. Note: The numbers are mean ± standard deviation of the given experimental data. Maturity offset refers to the estimated years to peak height velocity. Symptomatic was defined as VISA-P score ≤ 87.

	Control				Intervention			
	M1 (n = 13)	M2 (n = 13)	M3 (n = 12)	M4 (n = 12)	M1 (n = 13)	M2 (n = 12)	M3 (n = 12)	M4 (n = 12)
Age (years)	16.0 ± 0.6	16.2 ± 0.6	16.5 ± 0.6	16.7 ± 0.6	15.8 ± 0.6	16.2 ± 0.6	16.3 ± 0.5	16.4 ± 0.5
Maturity offset (years)[a,b]	2.45 ± 0.84	2.61 ± 0.79	2.87 ± 0.83	2.97 ± 0.83	2.25 ± 0.65	2.54 ± 0.67	2.70 ± 0.64	2.77 ± 0.71
Body height (cm)[a,b]	186 ± 7	186 ± 7	187 ± 7	187 ± 8	189 ± 8	189 ± 8	189 ± 8	190 ± 9
Body mass (kg)[a,b]	80.4 ± 10.3	81.0 ± 10.2	83.1 ± 10.8	82.5 ± 10.1	80.0 ± 10.6	80.8 ± 11.8	81.8 ± 12.4	82.8 ± 12.2
VISA-P score	97.5 ± 8.9	93.0 ± 9.5	100 ± 0	100 ± 0	100 ± 0	98.5 ± 4.6	100 ± 0	100 ± 0
No. of sympt. athletes	1 (7.6%)	5 (38.5%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (8.3%)	0 (0.0%)	0 (0.0%)

[a]Significant change over time in the control group.

[b]Significant change over time in the intervention group ($p < 0.05$); there was no time by group interaction ($p > 0.05$). Note that age was only tested for baseline differences between groups.

67% ± 11%, 65% ± 8%, and 61% ± 13% for M1, M2, and M3 respectively, with an overall range from 47% to 90%. Based on the experimentally determined force-elongation relationship, this corresponded to a tendon strain during training of 6.1% ± 0.4%, 6.3% ± 0.5%, and 6.2% ± 0.5%, with an overall range from 4.9% to 7.0%.

We found a tendency for a higher maximum knee joint moment in the control group compared to the intervention group at baseline ($p = 0.059$; Figure 3A) as well as a significantly higher knee joint moment normalized to body mass and higher maximum force applied to the tendon in the control group ($p = 0.011$ and $p = 0.031$; Table 2). There were no significant changes of maximum knee joint moment, normalized knee joint moment and maximum tendon force over time in the control group ($p = 0.789$, 0.740 and 0.845), but there was a significant time by group interaction ($p < 0.001$) and significant increases over time in the intervention group in all three parameters ($p < 0.001$).

Patellar tendon stiffness (Table 2) and normalized tendon stiffness (Figure 3B) were significantly higher in the control group at baseline ($p = 0.021$ and 0.015) with no significant time-dependent changes in the control group ($p = 0.414$ and 0.416). There was a significant time by group interaction for both patellar tendon stiffness ($p = 0.002$) and normalized patellar tendon stiffness ($p = 0.002$) and a significant increase over time in the intervention group ($p < 0.001$). Patellar tendon rest length and maximum tendon elongation (Table 2) were not significantly different between groups ($p = 0.953$ and 0.235) and there were no significant changes over time in the control group ($p = 0.628$ and 0.635) or intervention group ($p = 0.102$ and 0.760) and no time by group interaction ($p = 0.623$ and $p = 0.838$). We found no group differences of maximum patellar tendon strain during MVCs ($p = 0.111$; Figure 3C) and PSF ($p = 0.729$; Figure 3D), as well as no changes over time in the control ($p = 0.603$ and 0.883) and intervention group ($p = 0.967$ and 0.364) and no time by group interaction ($p = 0.686$ and 0.637).

The intervention group demonstrated lower fluctuations (residuals) of maximum patellar tendon strain ($p = 0.005$; Figure 3C) during the season. There were no group differences in the fluctuations of maximum knee joint moment ($p = 0.170$, Figure 3A), normalized knee joint moment ($p = 0.187$) and maximum patellar tendon force ($p = 0.159$), as well as normalized patellar tendon stiffness ($p = 0.339$; Figure 3B) and PSF ($p = 0.161$; Figure 3D). Descriptively, the average frequency of athletes with high-level patellar tendon strain (i.e., ≥9%) was lower in the intervention group compared to the control group (27% vs. 42%; Figure 4). Further, we found a significant positive correlation between maximum patellar tendon strain at M1 and relative changes in normalized patellar tendon stiffness from M1 to M4 in the intervention group ($r = 0.619$, $p = 0.032$) but not in the control group ($r = 0.091$, $p = 0.778$; Figure 5).

4 | DISCUSSION

The present study investigated for the first time the effects of a personalized tendon loading program on imbalances of knee extensor muscle strength and patellar tendon mechanical properties as well as patellar tendon micromorphology during a competitive season in male adolescent elite handball athletes. As hypothesized, we found significantly lower fluctuations of maximum patellar tendon strain during MVCs over time in the intervention group compared to the control group that followed their usual training schedule. On a descriptive level, the frequency of athletes with high-level patellar tendon strain (i.e., ≥9%)

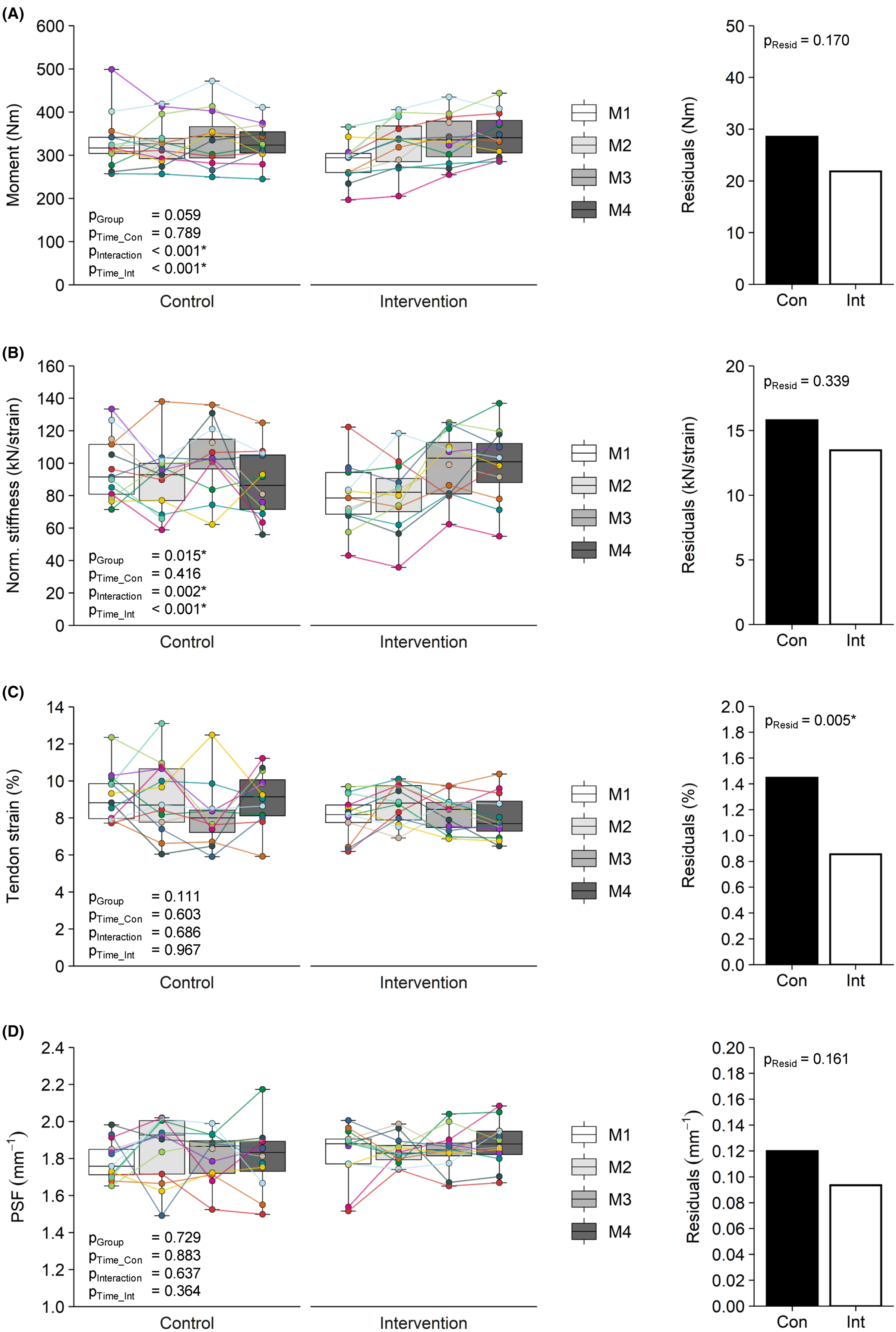
(A)
Moment (Nm)
pGroup = 0.059
pTime_Con = 0.789
pInteraction < 0.001*
pTime_Int < 0.001*
Control
Intervention
M1
M2
M3
M4
Residuals (Nm)
pResid = 0.170
Con
Int
(B)
Norm. stiffness (kN/strain)
pGroup = 0.015*
pTime_Con = 0.416
pInteraction = 0.002*
pTime_Int < 0.001*
Control
Intervention
M1
M2
M3
M4
Residuals (kN/strain)
pResid = 0.339
Con
Int
(C)
Tendon strain (%)
pGroup = 0.111
pTime_Con = 0.603
pInteraction = 0.686
pTime_Int = 0.967
Control
Intervention
M1
M2
M3
M4
Residuals (%)
pResid = 0.005*
Con
Int
(D)
PSF (mm−1)
pGroup = 0.729
pTime_Con = 0.883
pInteraction = 0.637
pTime_Int = 0.364
Control
Intervention
M1
M2
M3
M4
Residuals (mm−1)
pResid = 0.161
Con
Int

FIGURE 3 (A) Maximum resultant knee joint moment, (B) normalized patellar tendon stiffness, (C) maximum patellar tendon strain and (D) peak spatial frequency (PSF) for both groups and each measurement time point (M1-4) over the season. The given experimental data is shown in box plots with individual data depicted in colors. The estimated standard deviation of the residuals of the linear mixed model as a measure of parameter fluctuations over time is shown in the column on the right. The p-values for baseline differences between groups (p_{Group}), changes over time in the control group (p_{Time_Con}), time by group interactions ($p_{Interaction}$), changes over time in the intervention group (p_{Time_Int}) as well as group differences of the standard deviation of the residuals (p_{Resid}) are given. * marks significant p-values (<0.05).

was also lower in the intervention group. Further, knee extensor muscle strength and patellar tendon stiffness increased significantly in the intervention group, but not in the control group. These findings indicate that the integration of individualized patellar tendon exercises into the regular training has the potential to reduce muscle-tendon imbalances in highly trained male adolescent athletes.

In vivo, tendon strain is dependent on the level of force that acts on the tendon and normalized tendon stiffness. As ultimate tendon strain is considered to be quite constant in tendons,[11] tendon strain during maximum effort muscle contractions can serve as a marker for the mechanical demand on the tendon, and high levels of tendon strain reflect imbalances between muscle strength and tendon stiffness.[27] In the current study, maximum patellar tendon strain values during MVCs were on average 8.9% in the control and 8.3% in the intervention group without significant differences between groups. Maximum patellar tendon strain did not change significantly over the eight-month study period in both the control and intervention group. However, the fluctuations of maximum patellar tendon strain during the season were significantly lower in the intervention group, indicating a more balanced adaptation between muscle strength and tendon stiffness at an individual level in this group. Thereby, the overall range of maximum patellar tendon strain was 6.2%–10.4% in the intervention group compared to 5.9%–13.1% in the control group. High fluctuations of tendon strain are indicative for a non-uniform adaptation of muscle strength and tendon stiffness over time that may cause temporarily increased tendon strain. Accordingly, previous studies reported higher fluctuations of tendon strain in athletic populations compared to non-athletic controls[14,16,17] and an increased frequency of high-level tendon strain in athletes.[14,15,17] This is substantiated by the high fluctuations of maximum patellar tendon strain in the control group of the current study. The reduction of these fluctuations in the intervention group indicates that the personalized tendon loading approach is effective in promoting a more homogenous development of muscle strength and tendon stiffness in athletes.

In line with this, we observed a lower average frequency of athletes with high-level patellar tendon strain (i.e., ≥9%) in the intervention group (27%) compared to the control group (42%). Though merely descriptive, this observation coincides with recent findings of our group,[20] where a generic (non-personalized) tendon exercise intervention decreased the number of athletes with high-level patellar tendon strain. It has been shown in vitro that the repeated exposure to high tendon strain increases the risk for tendon injury,[12,13] as mechanical damage and degenerative processes seem to exceed tissue repair mechanisms.[13] Although there is still more in vivo data needed to confirm the exact relationship between tendon strain and tendon degeneration and injury, we recently observed higher patellar tendon strain in future symptomatic athletes compared to athletes that remained asymptomatic as well as a 2.3-fold increased injury risk for athletes with maximum patellar tendon strain ≥9%.[21] Further, we found indications for structural degeneration of the tendon in adolescent athletes who were subjected to high tendon strain.[19,20] Thus, the current findings suggest that the implementation of regular tendon exercises into the training may be an effective preventive measure to reduce tendon overuse injury risk.

We observed significant increases in normalized patellar tendon stiffness by on average 28% and maximum knee extension moment by 26% over the season in the intervention group, while both parameters showed no significant changes in the control group (−8% and 1.4%, respectively). It needs to be noted that the groups in the current study were not matched with regard to muscle strength and tendon stiffness at baseline with the intervention group demonstrating on average a 13% lower knee extension moment and 18% lower normalized tendon stiffness. Therefore, it cannot be excluded that other factors besides the tendon exercises contributed to the observed changes in muscle and tendon properties in the intervention group. However, it should be considered that, when examining the individual changes of normalized stiffness (Figure 3B), also all intervention participants with a baseline stiffness within the interquartile range of the control group data demonstrated a clear increase over time. Further, our findings coincide well with earlier reports for the Achilles tendon[24–26] that tendon exercises conducted at tendon strain values between 4.5% and 6.5% and with a long contraction duration are effective in promoting tendon adaptation. This suggests that the adequate strain region for tendon adaptation seems to be similar for the Achilles and patellar tendon and that this also applies to highly trained adolescent athletes. Taken together, our results indicate that

TABLE 2 Maximum resultant knee joint moment normalized to body mass, corresponding force applied to the patellar tendon, patellar tendon stiffness and maximum tendon elongation during maximum isometric knee extension contractions as well as patellar tendon rest length for both groups and each measurement time point (M1-4) over a competitive season. All values are mean ± standard deviation of the given experimental data.

	Control				Intervention			
	M1 ($n=13$)	M2 ($n=13$)	M3 ($n=12$)	M4 ($n=12$)	M1 ($n=13$)	M2 ($n=12$)	M3 ($n=12$)	M4 ($n=12$)
Norm. moment (Nm/kg)[a,b,c]	4.09 ± 0.47	4.08 ± 0.46	4.08 ± 0.46	3.99 ± 0.39	3.60 ± 0.51	4.06 ± 0.49	4.13 ± 0.50	4.22 ± 0.25
Tendon force (N)[a,b,c]	5555 ± 936	5562 ± 763	5703 ± 984	5519 ± 673	4812 ± 709	5484 ± 897	5633 ± 803	5819 ± 689
Tendon stiffness (N/mm)[a,b,c]	1930 ± 360	1802 ± 372	2051 ± 435	1733 ± 374	1593 ± 461	1604 ± 468	1977 ± 363	1989 ± 440
Max. tendon elongation (mm)	4.6 ± 0.8	4.6 ± 1.0	4.1 ± 0.9	4.5 ± 0.8	4.1 ± 0.8	4.4 ± 0.8	4.1 ± 0.6	4.0 ± 0.6
Tendon rest length (mm)	50.3 ± 3.2	50.2 ± 3.1	50.2 ± 3.3	50.1 ± 3.3	50.5 ± 4.8	49.9 ± 5.0	49.9 ± 4.8	50.0 ± 4.9

[a]Significant baseline difference between groups.

[b]Significant time by group interaction.

[c]Significant change over time in the intervention group, $p < 0.05$.

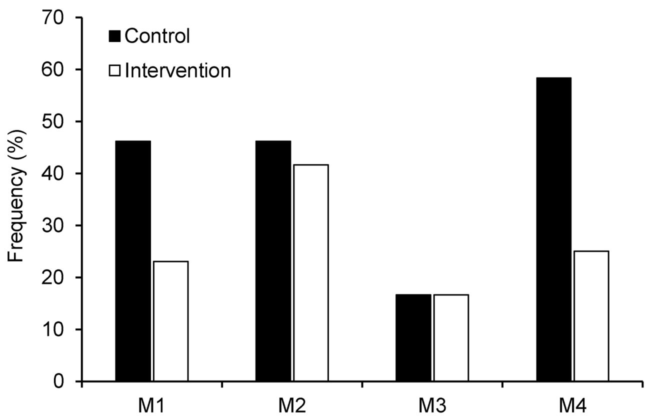

FIGURE 4 Frequency of athletes demonstrating high-level maximum patellar tendon strain (≥9%) for the control (black) and intervention group (white) in the four measurement sessions (M1-4) over the season.

the tendon exercise intervention had a positive effect on muscle and tendon adaptation in general, while at the same time reducing musculotendinous imbalances and fluctuations of maximum patellar tendon strain at an individual level.

Theoretically, tendon strain does not change as long as increases in tendon stiffness are matched by increases in muscle strength and a reduction in tendon strain can only be achieved if increases in tendon stiffness are comparatively higher than increases in muscle strength. Therefore, the observed reduction of the frequency of high-level patellar tendon strain may be attributed to predominant changes of tendon stiffness compared to muscle strength in individuals with high tendon strain values. Interestingly, we found a significant correlation between maximum patellar tendon strain at M1 and relative changes in normalized patellar tendon stiffness in the intervention but not in the control group, which indicates that increases in patellar tendon stiffness were higher in individuals with initially high patellar tendon strain values in the intervention group. These findings are in line with a previous study where a strong correlation between maximum patellar tendon strain at baseline and increases in patellar tendon stiffness was found for male adolescent athletes who performed functional tendon exercises.[20] It can be argued that especially athletes with increased patellar tendon strain and accordingly an increased risk for tendon overuse injuries may benefit from exercise interventions that target tendon adaptation.

While our results indicate that personalized patellar tendon exercises have the potential to individually promote a more balanced adaptation of knee extensor muscle strength and patellar tendon stiffness in male adolescent athletes, some athletes in the intervention group still demonstrated high-level tendon strain (≥9%) during the season and at the end of the intervention (Figure 4). This may partly be explained by interindividual differences in tendon plasticity. Accordingly, Passini and colleagues[38] could for example demonstrate genetically determined differences in the activity of the mechanosensitive ion channel PIEZO1, which influences the adaptation of the tendon to mechanical loading. Further, the training load and content during regular training and competition differed between individuals due to position-specific requirements, participation in multiple teams (e.g., older age group or national team), or injuries not related to the study, which may have influenced differences in muscle and tendon adaptation. However, it needs to be pointed out that peak strain values were never higher than 10.4% in the intervention group while reaching 13.1% in the control group.

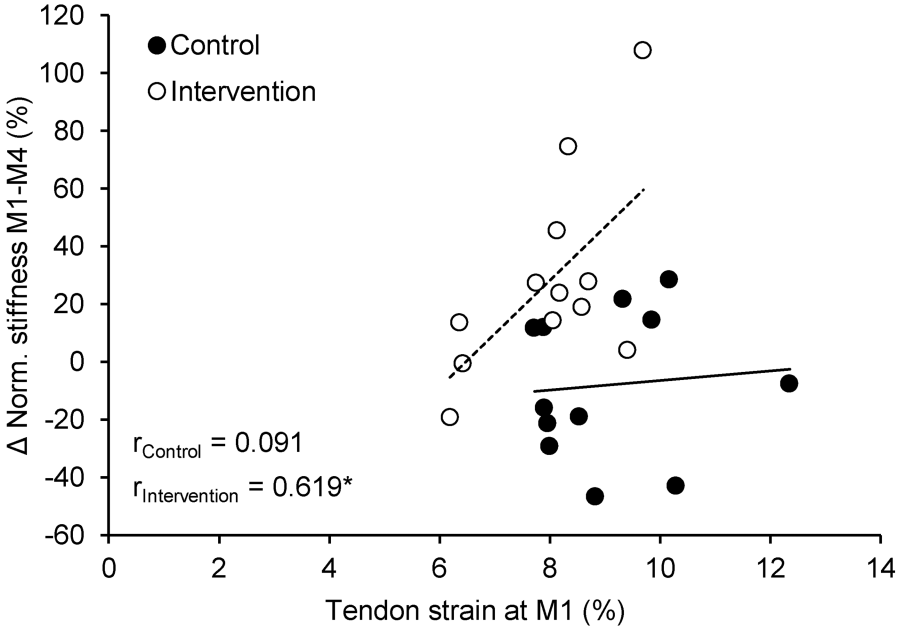

FIGURE 5 Association of maximum patellar tendon strain at the first measurement time point (M1) and the relative changes of normalized patellar tendon stiffness from the first to fourth measurement time point (M1 to M4) for the control (black, solid line) and intervention group (white, dashed line). r Pearson correlation coefficient; * significant association ($p < 0.05$).

One consequence of the repeated exposure to high-level tendon strain may be the deterioration of the structural integrity of tendinous tissue.[12,13,19] Therefore, we performed a PSF analysis as a marker for the microstructural integrity of the proximal patellar tendon. We found no significant changes of PSF over time, as well as no significant group differences. Low PSF values are indicative for a more disorganized microstructure of the tendon which is characteristic for tendinopathic tendons.[32] Accordingly, PSF values of 1.4–1.8 mm^{-1} (interquartile range) have been reported for the patellar tendon of athletes with tendinopathy and values between 1.7 and 2.0 mm^{-1} for asymptomatic controls.[39] In the current study, the majority of the PSF values (90% of the observations in intervention group and 84% in the control group) falls within the physiological range of healthy tendons. This suggests that most of the participants had no severe impairments of the structural integrity at the proximal patellar tendon, which may explain the absence of group differences or changes over time. Even though we observed a high prevalence of increased tendon strain especially in the control group, it might be conceivable that detectable changes in tendon micromorphology may only manifest with long-term exposure to high-level tendon strain.

One limitation of our study that needs to be pointed out is that we prescribed the same exercise intensity for both legs based on the data derived only from the dominant leg. Due to the time-consuming measurement procedures, we were not able to investigate tendon strain and muscle-tendon adaptation during the season in both legs. Therefore, we cannot exclude that possible asymmetries between the two legs affected the outcomes in the non-dominant leg. While there exists to our knowledge no study on leg asymmetries of tendon mechanical properties in handball players, habitual side-specific loading in fencers and badminton players does not seem to induce systematic differences in maximum tendon strain during MVCs between legs, despite differences in muscle strength and tendon mechanical properties.[40] Nevertheless, a personalized loading for both legs may further improve the adaptational response.

Further, it needs to be mentioned that the identification of muscle-tendon imbalances and the respective exercise prescription required the determination of maximum tendon strain,[27] which was derived from extrapolating tendon elongation to the experimentally assessed maximum tendon force in the current study. This resulted from constraints in the execution of the ramp trials as most of the participants had difficulties reaching their MVC force levels while performing an evenly ramped contraction. We are quite confident that the extrapolation of the data over a small portion of the force-elongation curve (80%–100% MVC) did not affect our main outcomes since the determination of the force-elongation relationship in the current study was relatively robust due to the averaging of five trials. Thereby, the R^2 for the second-order polynomial fit (that was used to extrapolate tendon elongation) was on average >0.98 in every measurement time point and was in no case lower than 0.95, which indicates that the measured data is well reflected by the polynomial. Also, when running the statistical analysis with the tendon strain measured at 80% of maximum tendon force, the main findings were also unchanged. The model comparison, that indicates differences in the standard deviation of the residuals between groups, was also significant ($p=0.002$) and there were no significant changes over time ($p=0.520$) or time by group interaction ($p=0.512$).

In conclusion, this novel tendon exercise approach of personalizing patellar tendon training load to match the strain region for effective tendon adaptation led to increases in knee extensor muscle strength and patellar tendon stiffness and a reduction of muscle-tendon imbalances and high-level tendon strain in highly trained male adolescent athletes. With regards to the injury risk associated with increased tendon strain and the increasing prevalence of tendinopathies with maturation[8,9] this training approach may be a useful tool for the early prevention of tendon overuse injuries.

4.1 | Perspectives

Especially in elite-level sports with a high incidence of tendinopathy, a regular screening of the athletes' muscle-tendon properties might help to identify individuals with an increased risk for tendon overuse injuries and to prescribe preventive personalized tendon exercises. In the current study, we estimated the respective training load from the maximum patellar tendon strain during MVCs. Due to the marked individual differences in maximum patellar tendon strain during the MVCs, the resulting relative training load to reach patellar tendon strain of on average 6.2% during exercises varied highly between individuals (47%–90% of the MVC). The high individual variability in the percentage of MVC for the same target patellar tendon strain emphasizes that the regulation of tendon exercises based on the MVC may be less effective in providing an individually adequate stimulus for tendon adaptation. Individuals with high tendon strain values during MVCs may even be exposed to critically increased tendon strain levels during exercise. Therefore, the current approach of patellar tendon exercises based on an individual experimental assessment of the target patellar tendon strain opens up new opportunities for suitable tendon loading especially in populations with a high prevalence of musculotendinous imbalances.

ACKNOWLEDGMENTS

Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

This study was conducted within the scope of the research project "Resistance Training in Youth Athletes" that was funded by the German Federal Institute of Sport Science (ZMVI1-081901/20–23).

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Theresa Domroes https://orcid.org/0000-0001-9941-6716
Kolja Weidlich https://orcid.org/0000-0002-4398-5773
Sebastian Bohm https://orcid.org/0000-0002-5720-3672
Falk Mersmann https://orcid.org/0000-0001-7180-7109
Adamantios Arampatzis https://orcid.org/0000-0002-4985-0335

REFERENCES

1. Bohm S, Mersmann F, Santuz A, Arampatzis A. Enthalpy efficiency of the soleus muscle contributes to improvements in running economy. *Proc R Soc B*. 2021;288:20202784. doi:10.1098/rspb.2020.2784
2. Krupenevich RL, Beck ON, Sawicki GS, Franz JR. Reduced Achilles tendon stiffness disrupts calf muscle neuromechanics in elderly gait. *Gerontology*. 2022;68(3):241-251. doi:10.1159/000516910
3. Kharazi M, Bohm S, Theodorakis C, Mersmann F, Arampatzis A. Quantifying mechanical loading and elastic strain energy of the human Achilles tendon during walking and running. *Sci Rep*. 2021;11(1):5830. doi:10.1038/s41598-021-84847-w
4. Roberts TJ, Azizi E. Flexible mechanisms: the diverse roles of biological springs in vertebrate movement. *J Exp Biol*. 2011;214(3):353-361. doi:10.1242/jeb.038588
5. Nikolaidou ME, Marzilger R, Bohm S, Mersmann F, Arampatzis A. Operating length and velocity of human M. Vastus lateralis fascicles during vertical jumping. *Royal Soc open Sci*. 2017;4(5):1-15. doi:10.1098/rsos.170185
6. Bohm S, Mersmann F, Santuz A, Schroll A, Arampatzis A. Muscle-specific economy of force generation and efficiency of work production during human running. *Elife*. 2021;10:e67182. doi:10.7554/eLife.67182
7. Lian ØB, Engebretsen L, Bahr R. Prevalence of jumper's knee among elite athletes from different sports: a cross-sectional study. *Am J Sport Med*. 2005;33(4):561-567. doi:10.1177/0363546504270454
8. Simpson M, Rio E, Cook J. At what age do children and adolescents develop lower limb tendon pathology or

tendinopathy? A systematic review and meta-analysis. *Sports Med*. 2016;46(4):545-557. doi:10.1007/s40279-015-0438-0
9. Florit D, Pedret C, Casals M, Malliaras P, Sugimoto D, Rodas G. Incidence of tendinopathy in team sports in a multidisciplinary sports club over 8 seasons. *J Sports Sci Med*. 2019;18(4):780-788.
10. Mersmann F, Bohm S, Arampatzis A. Imbalances in the development of muscle and tendon as risk factor for tendinopathies in youth athletes: a review of current evidence and concepts of prevention. *Front Physiol*. 2017;8:1-18. doi:10.3389/fphys.2017.00987
11. LaCroix AS, Duenwald-Kuehl SE, Lakes RS, Vanderby R. Relationship between tendon stiffness and failure: a meta-analysis. *J Appl Physiol*. 2013;115(1):43-51. doi:10.1152/japplphysiol.01449.2012
12. Wren TAL, Lindsey DP, Beaupré GS, Carter DR. Effects of creep and cyclic loading on the mechanical properties and failure of human Achilles tendons. *Ann Biomed Eng*. 2003;31(6):710-717. doi:10.1114/1.1569267
13. Wang T, Lin Z, Day RE, et al. Programmable mechanical stimulation influences tendon homeostasis in a bioreactor system. *Biotechnol Bioeng*. 2013;110(5):1495-1507. doi:10.1002/bit.24809
14. Mersmann F, Bohm S, Schroll A, Marzilger R, Arampatzis A. Athletic training affects the uniformity of muscle and tendon adaptation during adolescence. *J Appl Physiol*. 2016;121(4):893-899. doi:10.1152/japplphysiol.00493.2016
15. Charcharis G, Mersmann F, Bohm S, Arampatzis A. Morphological and mechanical properties of the quadriceps femoris muscle-tendon unit from adolescence to adulthood: effects of age and athletic training. *Front Physiol*. 2019;10(August):1-12. doi:10.3389/fphys.2019.01082
16. Karamanidis K, Epro G. Monitoring muscle-tendon adaptation over several years of athletic training and competition in elite track and field jumpers. *Front Physiol*. 2020;11:1-13. doi:10.3389/fphys.2020.607544
17. Pentidis N, Mersmann F, Bohm S, et al. Development of muscle–tendon adaptation in preadolescent gymnasts and untrained peers: a 12-month longitudinal study. *Med Sci Sports Exerc*. 2021;53(12):2565-2576. doi:10.1249/mss.0000000000002742
18. Domroes T, Weidlich K, Bohm S, Arampatzis A, Mersmann F. Effect of sex on muscle–tendon imbalances and tendon micromorphology in adolescent athletes—a longitudinal consideration. *Scand Med Sci Sports*. 2023;33(12):2561-2572. doi:10.1111/sms.14483
19. Mersmann F, Pentidis N, Tsai MS, Schroll A, Arampatzis A. Patellar tendon strain associates to tendon structural abnormalities in adolescent athletes. *Front Physiol*. 2019;10(JUL):1-10. doi:10.3389/fphys.2019.00963
20. Mersmann F, Domroes T, Pentidis N, et al. Prevention of strain-induced impairments of patellar tendon micromorphology in adolescent athletes. *Scandinavian J Med and Sci Sport*. 2021;31(8):1708-1718. doi:10.1111/sms.13979
21. Mersmann F, Domroes T, Tsai MS, et al. Longitudinal evidence for high-level patellar tendon strain as a risk factor for tendinopathy in adolescent athletes. *Sports Medicine - Open*. 2023;9(1):83. doi:10.1186/s40798-023-00627-y
22. Duchateau J, Stragier S, Baudry S, Carpentier A. Strength training: in search of optimal strategies to maximize neuromuscular performance. *Exerc Sport Sci Rev*. 2021;49(1):2-14. doi:10.1249/JES.0000000000000234
23. Pizzolato C, Lloyd DG, Zheng MH, et al. Finding the sweet spot via personalised Achilles tendon training: the future is within reach. *Br J Sports Med*. 2019;53(1):11-12. doi:10.1136/bjsports-2018-099020
24. Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J Exp Biol*. 2007;210(15):2743-2753. doi:10.1242/jeb.003814
25. Arampatzis A, Peper A, Bierbaum S, Albracht K. Plasticity of human Achilles tendon mechanical and morphological properties in response to cyclic strain. *J Biomech*. 2010;43(16):3073-3079. doi:10.1016/j.jbiomech.2010.08.014
26. Bohm S, Mersmann F, Tettke M, Kraft M, Arampatzis A. Human Achilles tendon plasticity in response to cyclic strain: effect of rate and duration. *J Exp Biol*. 2014;217(22):4010-4017. doi:10.1242/jeb.112268
27. Arampatzis A, Mersmann F, Bohm S. Individualized muscle-tendon assessment and training. *Front Physiol*. 2020;11(June):1-7. doi:10.3389/fphys.2020.00723
28. Weidlich K, Mersmann F, Domroes T, Schroll A, Bohm S, Arampatzis A. Quantification of patellar tendon strain and opportunities for personalized tendon loading during back squats. *Sci Rep*. 2023;13(1):8661. doi:10.1038/s41598-023-35441-9
29. Mersmann F, Laube G, Marzilger R, Bohm S, Schroll A, Arampatzis A. A functional high-load exercise intervention for the patellar tendon reduces tendon pain prevalence during a competitive season in adolescent handball players. *Front Physiol*. 2021;12(March):282. doi:10.3389/fphys.2021.626225
30. Moore SA, McKay HA, Macdonald H, et al. Enhancing a somatic maturity prediction model. *Med Sci Sports Exerc*. 2015;47(8):1755-1764. doi:10.1249/MSS.0000000000000588
31. Lohrer H, Nauck T. Cross-cultural adaptation and validation of the VISA-P questionnaire for German-speaking patients with patellar tendinopathy. *J Ortho SportsPhy Therapy*. 2011;41(3):180-190. doi:10.2519/jospt.2011.3354
32. Bashford GR, Tomsen N, Arya S, Burnfield JM, Kulig K. Tendinopathy discrimination by use of spatial frequency parameters in ultrasound b-mode images. *IEEE Trans Med Imaging*. 2008;27(5):608-615. doi:10.1109/TMI.2007.912389
33. Herzog W, Abrahamse SK, ter Keurs HEDJ. Theoretical determination of force-length relations of intact human skeletal muscles using the cross-bridge model. *Pflügers Arch Euro J Physiol*. 1990;416(1–2):113-119. doi:10.1007/BF00370231
34. Dempster WT. *Space Requirements of the Seated Operator: Geometrical, Kinematic, and Mechanical Aspects of the Body with Special Referece to the Limbs*. Wright-Patterson Air Force Base; 1955.
35. Herzog W, Read LJ. Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *J Anat*. 1993;182:213-230.
36. Schulze F, Mersmann F, Bohm S, Arampatzis A. A wide number of trials is required to achieve acceptable reliability for measurement patellar tendon elongation in vivo. *Gait Posture*. 2012;35(2):334-338. doi:10.1016/j.gaitpost.2011.09.107
37. Jacqmin-Gadda H, Sibillot S, Proust C, Molina JM, Thiébaut R. Robustness of the linear mixed model to misspecified error distribution. *Computational Stat Data Anal*. 2007;51(10):5142-5154. doi:10.1016/j.csda.2006.05.021
38. Passini FS, Jaeger PK, Saab AS, et al. Shear-stress sensing by PIEZO1 regulates tendon stiffness in rodents and

influences jumping performance in humans. *Nature Biomed Eng*. 2021;5:1457-1471. doi:10.1038/s41551-021-00716-x
39. Kulig K, Landel R, Chang YJ, et al. Patellar tendon morphology in volleyball athletes with and without patellar tendinopathy. *Scand J Med Sci Sport*. 2013;23(2):81-88. doi:10.1111/sms.12021
40. Couppé C, Svensson RB, Skovlund SV, et al. Habitual side-specific loading leads to structural, mechanical, and compositional changes in the patellar tendon of young and senior lifelong male athletes. *J Appl Physiol*. 2021;131(4):1187-1199. doi:10.1152/japplphysiol.00202.2021

How to cite this article: Domroes T, Weidlich K, Bohm S, Mersmann F, Arampatzis A. Personalized tendon loading reduces muscle-tendon imbalances in male adolescent elite athletes. *Scand J Med Sci Sports*. 2024;34:e14555. doi:10.1111/sms.14555