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Low-load blood flow restriction and high-load resistance training induce comparable changes in patellar tendon properties

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ABSTRACT

Introduction: Low-load resistance training with blood flow restriction (LL-BFR) has emerged as a viable alternative to conventional high-load (HL) resistance training regimens. Despite increasing evidence confirming comparable muscle adaptations between LL-BFR and HL resistance exercise, only very little is known about tendinous mechanical and morphological adaptations following LL-BFR. Therefore, the aim of the present study was to examine the effects of 14 weeks of LL-BFR and HL training on patellar tendon adaptations.

Methods: N = 29 recreationally active male participants were randomly allocated into the following two groups: LL-BFR resistance training (20-35% one repetition maximum/1RM) or HL resistance training (70-85% 1RM). Both groups trained three times per week for 14 weeks. One week before and after the intervention, patellar tendon mechanical and morphological properties were assessed via ultrasound and magnetic resonance imaging (MRI). Additionally, changes in muscle cross-sectional area (CSA) were quantified by MRI and muscle strength via dynamic 1RM measurements.

Results: The findings demonstrated that both LL-BFR and HL training resulted in comparable changes in patellar tendon stiffness (LL-BFR: + 25.2%, p = 0.003; HL: + 22.5%, p = 0.024) without significant differences between groups. Similar increases in tendon CSA were observed in HL and LL-BFR. Muscle mass and strength also significantly increased in both groups but were not statistically different between HL (+ 38%) and LL-BFR (+ 34%), except for knee extension 1RM where higher changes were seen in LL-BFR.

Conclusion: The present results support the notion that both HL and LL-BFR cause substantial changes in patellar tendon properties and the magnitude of changes are not significantly different between conditions. Further studies are needed which examine the physiological mechanisms underlying the altered tendon properties following LL-BFR training.

KEYWORDS: vascular occlusion, tendon stiffness, muscle hypertrophy, strength

INTRODUCTION

As a link between muscles and the skeletal system, tendons hold diverse functions and are essential for human locomotion and efficient movements (1-3). Due to their viscoelastic properties, tendons are vital for transmitting and storing energy and thus creating favorable conditions for muscle fibers by optimizing the force-length-velocity relationship (4). Previous findings have demonstrated that tendons display a highly mechanosensitive tissue with high sensitivity to mechanical as well as morphological adaptations when exposed to increased loading (5). While single bouts of mechanical loading induce elevations in net collagen synthesis (6), long-term exposures to repetitive loading facilitate increases in tendon stiffness and cross-sectional area (CSA) (5, 7). Evidence from a recent meta-analysis (8) suggests that predominantly training loads greater than 70% of maximal voluntary contraction (MVC) are needed to elicit mechanical and material tendon adaptations, whereas lower training loads only cause limited changes at the tendon level.

Interestingly, research during the past two decades has shown that the induction of a local hypoxic environment via blood flow restriction (BFR) during low-load (LL) exercise potentiates the adaptive responses seen during regular LL exercise without BFR (9, 10). In the majority of studies, this hypoxic milieu is created by pressurized cuffs which are placed at the most proximal portion of the respective limb leading to reduced venous return (11, 12). Previous findings from multiple trials revealed that the combination of LL resistance training (20-40% one-repetition maximum / 1RM) with BFR facilitated substantial increases in muscle growth (13-16) and muscle strength (17) which are typically seen following high-load (HL) training with 70-85% 1RM (10, 18). Interestingly, recent evidence suggests that LL-BFR training induces not only muscular but also tendinous adaptations. Data from our laboratory indicated that mechanical and morphological adaptations of the Achilles tendon after 14-weeks are comparable following HL and LL-BFR resistance training (19). However, these findings differ from an earlier study by Kubo and colleagues (20), which did not find significant effects of LL-BFR training on the patellar tendon. Whether this discrepancy is related to tendon specificity

(in metabolic activity and blood circulation (21)) or to methodological reasons (e.g., training parameters) is unclear. Indeed, both tendons (Achilles vs. patellar tendon) demonstrate distinct functions and display non-identical adaptive responses to training (5). Given the conflicting findings and overall scarce evidence regarding the effects of LL-BFR training on tendinous adaptations, highlights the need for further investigations on this topic.

The aim of the current study was to re-investigate the differences between LL-BFR and HL on patellar tendon adaptations following 14 weeks of mechanical loading. Within our study design, we complemented the methodological approach of Kubo et al. (20) and implemented a standardized load progression (LL-BFR: 20-35% 1RM; HL: 70-85% 1RM) throughout a 14 weeks intervention period. Additionally, we aimed to use a between-subject design which allows to eliminate potential bias from cross-educational effects frequently seen in within-subject trials (using each leg for a different training regimen) (20). Based on findings from Kubo and co-workers (20) and previous studies showing that high stress and strain levels are needed to elicit beneficial morphological and mechanical tendon adaptations (7, 8), we hypothesized that at the patellar tendon level, significantly greater adaptations can be observed following HL compared to LL-BFR. As secondary outcome parameters coordinated adaptations of the muscular system were investigated (muscle hypertrophy and muscle strength).

METHODS

Participants

An a-priori power analysis [G*Power 3.1.9.2] was conducted based on the effect sizes observed in a previous study examining the chronic effects of high-load resistance training on patellar tendon morphology in young men (22). The results revealed that a total of n = 36 participants were needed to identify the observed effect sizes (partial $\eta^2 = 0.055$ (derived from

(22)) as statistically significant (power = 0.8, α = 0.05). Sample size calculation referred to the calculation of a mixed ANOVA (time × group interaction).

A total of *n* = 40 male participants were included with an age between 18 and 40 years. Additionally, all participants were untrained in resistance exercise and with a maximal amount of 1-2 hours of physical activity per week. Participants with an acute or chronic injury of the patellar tendon, uncontrolled hypertension or any other chronic diseases were excluded from the study. Furthermore, smokers and participants with a history of deep vein thrombosis or a body mass index exceeding 30 kg/m^2 were excluded.

Prior to inclusion, all participants were informed about the study procedures and were informed about any potential risks before giving their written informed consent. The study was approved by the local ethics committee and all experiments were conducted in accordance with the latest version of the Declaration of Helsinki. Additionally, the trial was prospectively registered at the German Clinical Trials Register (DRKS00022567).

Experimental design

A randomized-controlled, repeated measures design was implemented to investigate the effects of 14-weeks of HL and LL-BFR resistance training on patellar tendon morphology. As secondary outcomes, mechanical tendon properties and quadriceps muscle properties were assessed.

Before commencing the training program, participants were screened to fit the abovementioned inclusion criteria. After confirming eligibility, they were randomly and concealed allocated into either a 14-week HL resistance training (70-85% 1RM) or LL-BFR resistance training program (20-35% 1RM). A random number generator was used for allocation sequence generation. A total training duration of > 12 weeks has previously been demonstrated to efficiently induce tendon adaptive responses (8). All participants completed the same measurements before and after the training period which consisted of *i)* assessment of

patellar tendon mechanical properties using *b-mode* ultrasound, *ii)* examination of patellar tendon and quadriceps muscle CSA by magnetic resonance imaging and *iii)* 1RM assessment of the quadriceps muscle. All measurements and training sessions were supervised by trained personnel and completed at the Department of Sport and Sport Science of the University of Freiburg, Germany. All outcome assessors were blinded to group assignments.

Exercise protocol

Both groups performed three exercise sessions per week for 14 weeks with two consecutive sessions being separated by at least one day of rest to ensure optimal recovery. Each exercise session was preceded by a 10-min standardized warm-up on a stationary cycle ergometer at ~ 50 W.

High-load training (HL)

The HL protocol consisted of three sets of dynamic exercises for the lower extremities including bilateral leg press, knee extensions as well as standing and sitting calf-raises. During the 14 weeks, the training load was progressively increased every 4 weeks by 5% from 70% to 85% 1RM, which led to a respective adjustment of performed repetitions (70% 1RM = 12 repetitions, 75% 1RM = 10 repetitions, 80% 1RM = 8 repetitions, 85% 1RM = 6 repetitions). At these time points, dynamic 1RM testings were implemented to adjust the load for the current strength level of each individual. All exercises were performed throughout full range of motion, and each set was separated by a one-minute resting period. Three minutes rest was allowed between exercises. To increase compliance during training, two additional exercises for the trunk and upper body muscles (lat pull, bench press) were performed following the same loading regiment as the lower extremity exercises.

Low-load blood flow restriction training (LL-BFR)

Participants in the LL-BFR group performed the same exercises than the HL group. However, training load for the lower extremities started with 20% 1RM and was progressively increased by 5% every four weeks until 35% 1RM in the final two weeks. Similar to the HL group, dynamic 1RM testings were implemented adjust the load to the current strength level. For each lower extremity exercise, four sets with 30 repetitions in the first set and 15 repetitions in the remaining three sets were completed. This protocol was chosen as this has been frequently applied in BFR literature (23, 24). During each lower extremity exercise, a 12-cm-wide pneumatic nylon tourniquet [Tourniquet Touch TT20, VBM Medizintechnik GmbH, Germany] was applied with a snug fit at the most proximal portion of each thigh. Before each exercise session, arterial occlusion pressure (AOP) was determined in a sitting position for each participant. The cuff was incrementally increased until the arterial pulse at the posterior tibial artery was no longer detected by Doppler ultrasound [Handydop, Kranzbühler, Solingen, Germany]. This point was defined as 100% of arterial occlusion. During exercise, cuff pressure was set to 50% (23, 24) of each individual's AOP and kept inflated during the entire exercise including the 60 sec interset rest periods. Between the four exercises (standing calf raises, sitting calf raises, knee extension, leg press), the cuff was deflated for three minutes.

In order to increase compliance to the training program, all participants were afforded with the same trunk and upper body exercises (lat pull, bench press) as the HL group. All exercise sessions were supervised by trained sport scientists to ensure proper exercise technique and BFR application.

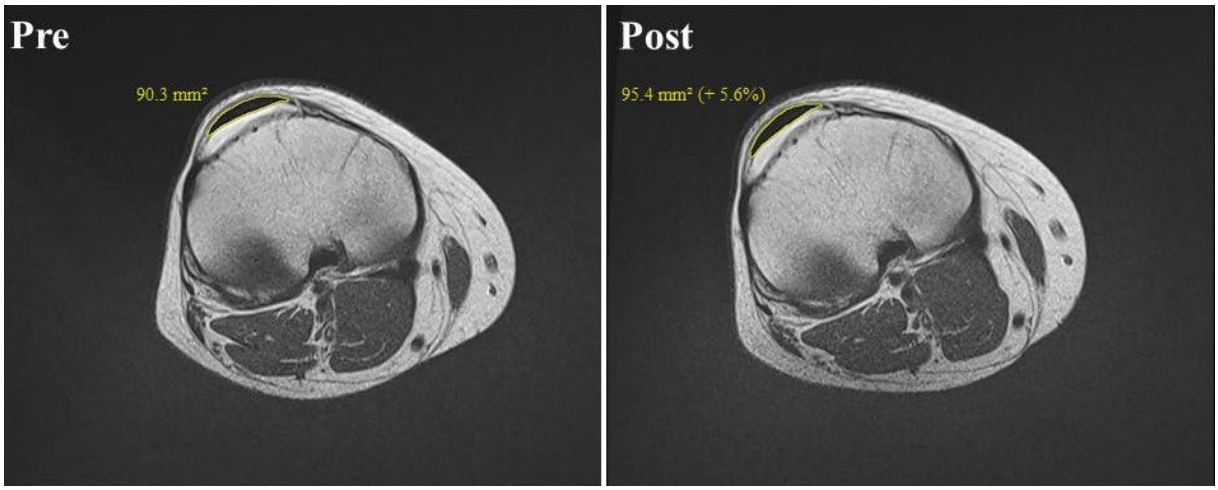
One-repetition maximum assessment

Dynamic 1RM measurements were conducted for all exercises at the beginning and every four weeks during the training program to adjust the exercise load to individual strength levels. Prior to the 1RM assessment, participants completed an exercise-specific warm-up of two sets with ten repetitions with a submaximal load (~50% estimated 1RM). Subsequently,

two additional warm-up sets with three to five repetitions were completed (25). For the actual 1RM test, care was taken that the weight was lifted through full range of motion with the correct technique. After each successful lift the load was progressively increased by 5 – 10% until participants were unable to lift the weight through the full range of motion with a proper technique (25, 26). After each trial a four-minutes resting period was allowed to assure optimal recovery. All final 1RMs were achieved within five attempts. The average coefficient of variation (CV) was 2.2%.

Muscle Cross-Sectional Area

Rectus femoris muscle CSA was assessed by magnetic resonance imaging (Magnetom, Aera 1.5T, Siemens, Berlin, Germany). Participants were positioned in a supine position with knees extended and legs straight. A T1-weighted, turbo spin-echo, axial plane sequence was performed with a repetition time of 544ms and an echo time of 9.9ms (27). Contiguous axial MRI scans with a slice thickness of 1.0cm were completed in perpendicular direction to the thigh, from the knee joint to the iliac crest. The CSA of the rectus femoris muscle was manually outlined (ImageJ 1.51, NIH, Maryland, USA) and the mean of three calculations was used for further analysis of this location. To assess region-specific muscle adaptations, this procedure was completed throughout the full muscle length and CSA was interpolated at each 10% interval of each participant's total muscle length (0% - 100%). The average CV across all muscle lengths was 1.3%.



[***Please insert figure 1 about here***]

Patellar tendon cross-sectional area

Patellar tendon CSA was determined by axial MRI scans [Magnetom, Aera 1.5T, Siemens, Berlin, Germany] with the following parameters: repetition time = 540ms, echo time = 12ms, slice thickness = 4mm, FOV = 200 × 200, Matrix = 448 × 358, interslice gab = 0 mm. Contiguous axial scans were acquired in perpendicular direction to the patellar tendon alignment from the apex of the patellar to the tibial tuberosity. All images were transferred to a personal computer and analyzed using image analysis software [1.51, NIH, Maryland, USA]. Each image (from patellar insertion to tibia insertion) was manually analyzed three times and the average value was used for statistical analyses (Figure 1). All tendon CSAs were interpolated at each 10% interval of the total tendon length (28). The latter was acquired via sagittal MRI images. The CV across all tendon length ranged between 0.3 and 1.5%.

Patellar tendon mechanical properties

To assess tendon mechanical properties, B-mode ultrasound (US) scans [ArtUs EXT-1H, Telemed, Vilnius, Lithuania] of the patellar tendon were performed using a linear 60 mm probe (10 MHz) at a sampling frequency of 100 Hz. For US recordings, a hypoechoic marker was placed on the skin and kept in line with a marker at the US probe in order to correct for

potential probe movements. To enhance US image quality, a gel pad [Parker Laboratories Inc., Fairfield, NJ, USA] was positioned between the skin and the probe.

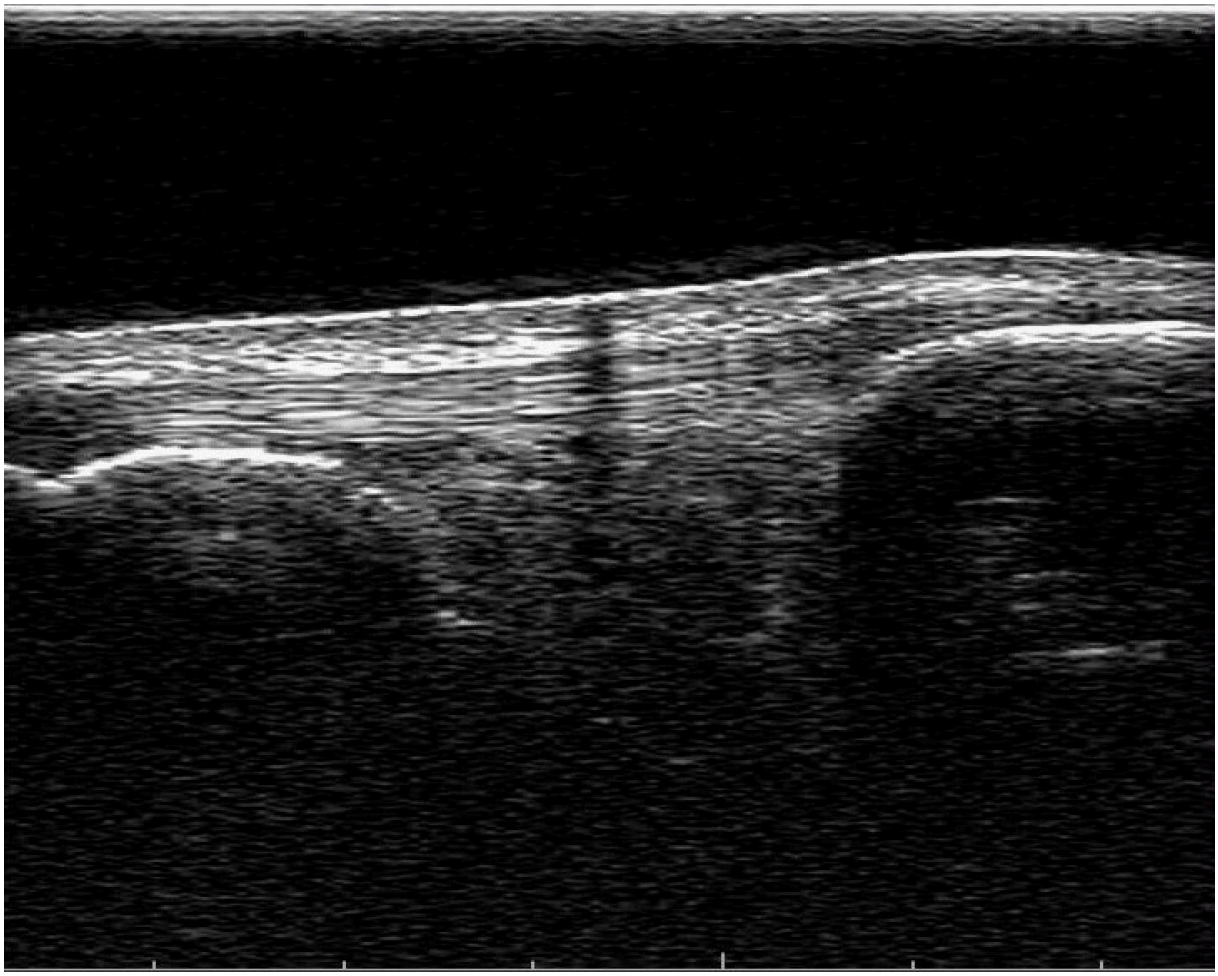
Prior to performing ramped maximal isometric contractions on an isokinetic dynamometer [ISOMED 2000, Ferstl, Germany] with the right leg at 90° knee angle and hip at 60°, participants were familiarized with the procedure and performed five submaximal isometric contractions at 80% of MVC to ensure proper preconditioning (29). Subsequently, five maximal ramped isometric contractions with a standardized loading rate of 50 Nm/s were completed (19). This loading rate was used since it resulted in a ramped isometric knee extension contraction lasting between 3 and 5 s for all subjects (19, 30). During the course of this procedure, visual feedback of the torque signal was provided. Torque data were sampled with a frequency of 2 kHz and synchronized with the US recordings.

Although traditionally implemented in the mechanical assessment of patellar tendon stiffness (22, 28), the correction of antagonist co-activation via electromyography (EMG) was not applied in the current study since recent data suggest that EMG activity of the hamstrings and their tension are not necessarily related to antagonist torque production (31, 32).

Patellar tendon force was estimated by dividing knee extension torque by the tendon moment arm. Patellar tendon moment arm was calculated within the acquired MRI scans as the perpendicular distance from the tendon to the midpoint of the distance between tibio-femoral contact points in the lateral and medial femoral condyles (28).

All collected position and displacement data were filtered using a second order low-pass Butterworth filter with a cut-off frequency of 15 Hz. Subsequently, longitudinal tendon deformation was analyzed offline using semi-automatic tracker software (Tracker, V 4.95) by tracking tendon insertion sites at the tibia as well as the inferior tip of the patella (33). Tendon stiffness was then calculated as the slope of the force-elongation curve between 50-80% MVC and individual maximal torque from baseline was used to set the range over which stiffness was

quantified. This procedure has previously been used in scientific literature (34) and the CV was 7.5%.



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Statistics

All statistical analyses were conducted with SPSS version 24.0 [IBM, Armonk, USA]. After confirming normal distribution and homogeneity of variances for all variables, mixed ANOVA with the within-group factor ‘time’ and between-group factor ‘group’ was performed to test for interaction effects. In case of significant interactions effects, Benjamini-Hochberg corrected post-hoc paired t-test were calculated. Outliers in main outcome criteria were

identified with Grubb's test (35) and truncated according to (36). Missing values were imputed using a multiple imputation approach. All data is presented as mean ± standard deviation, if not indicated otherwise. The level of significance was set to $p < 0.05$. Effect sizes are calculated using partial eta-squared (η^2).

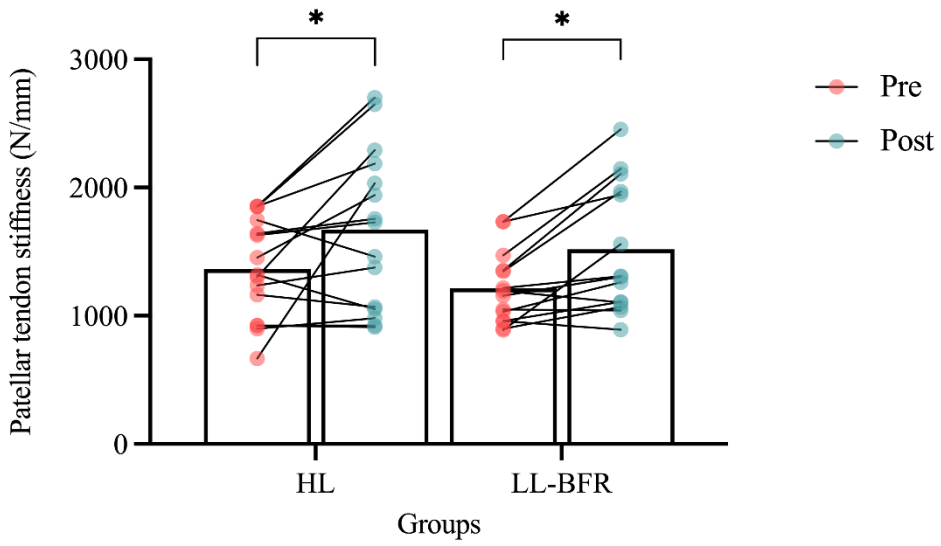
RESULTS

In total, $n = 29$ participants successfully completed the 14-week intervention with $n = 5$ and $n = 6$ dropouts in the HL and LL-BFR group, respectively. None of the dropouts was related to side effects of the training. Baseline characteristics of the participants are presented in table 1. No significant baseline differences at any anthropometric or main outcome variable were detected between groups ($p > 0.05$).

[***Please insert table 1 about here***]

Patellar tendon stiffness

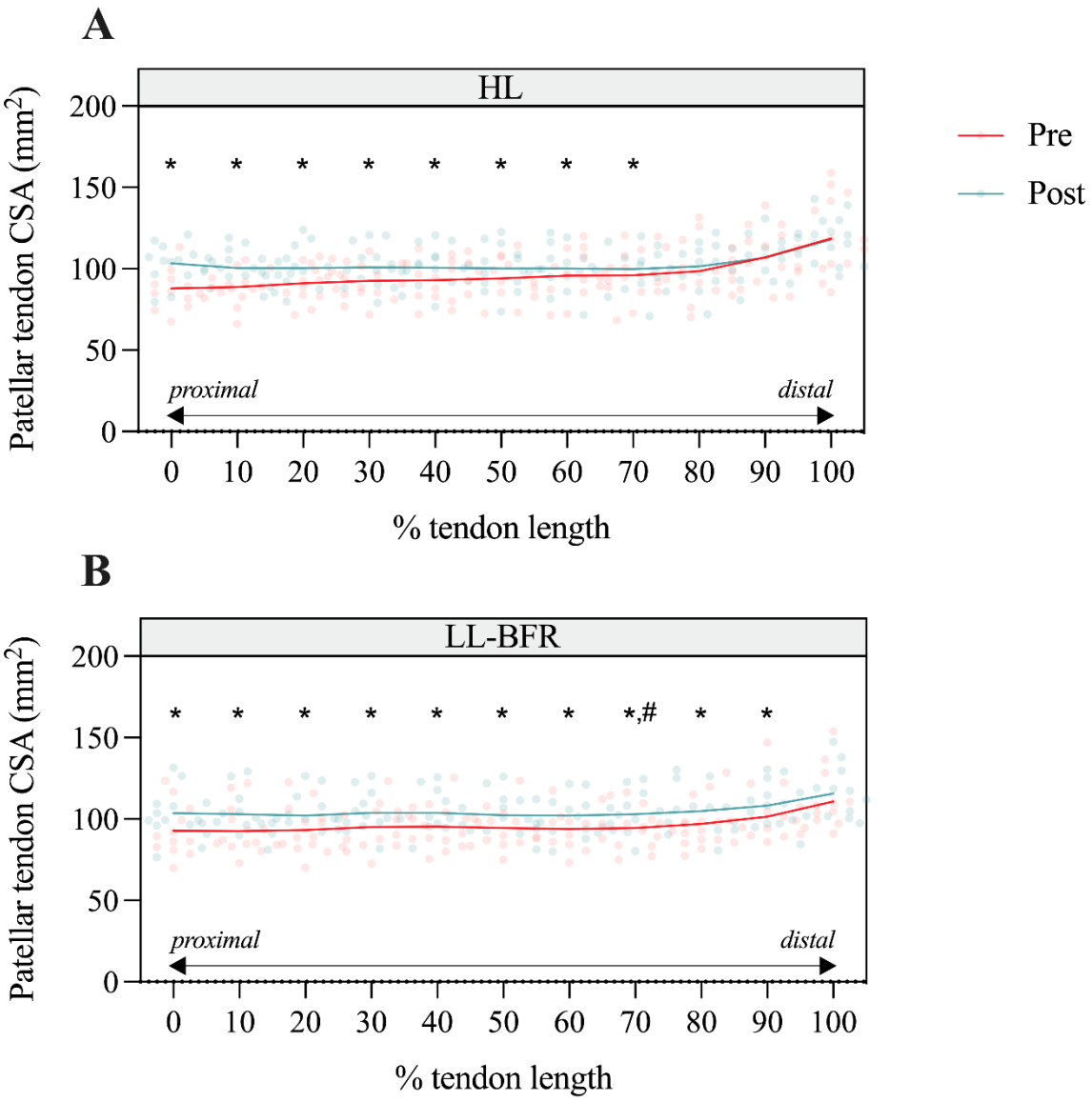
Patellar tendon stiffness increased from 1364.2 ± 394.0 N/mm to 1671.0 ± 619.2 N/mm and from 1213.6 ± 283.6 N/mm to 1519.0 ± 505.0 N/mm in the HL and LL-BFR group, respectively. Statistical analysis revealed a significant time effect ($F_{(1, 27)} = 15.89$, $p < 0.001$, $\eta_p^2 = 0.370$) but no time × group interaction($F_{(1, 27)} = 0.00$, $p = 0.99$, $\eta_p^2 = 0.001$) as both groups demonstrated comparable within-group differences (HL: + 22.5%, $p = 0.024$; LL-BFR: + 25.2%, $p = 0.003$, Figure 2)



[***Please insert figure 3 about here***]

Patellar tendon CSA

Analyses of patellar tendon CSA at each location (0-100%) showed significant time effects ($p < 0.01$) for all locations except 90% ($p = 0.105$) and 100% ($p = 0.395$). Interaction effects were not statistically significant for all locations except at 70% tendon length, where a significant time × group interaction ($F_{(1, 26)} = 6.42$, $p = 0.018$, $\eta_p^2 = 0.198$) revealed differences in favor of a greater change with LL-BFR. At this location, patellar tendon CSA changed from 95.9 ± 15.1 mm^2 to 99.8 ± 13.2 mm^2 in HL and from 94.6 ± 12.8 mm^2 to 103.1 ± 12.8 mm^2 in the LL-BFR group, respectively (Figure 3).



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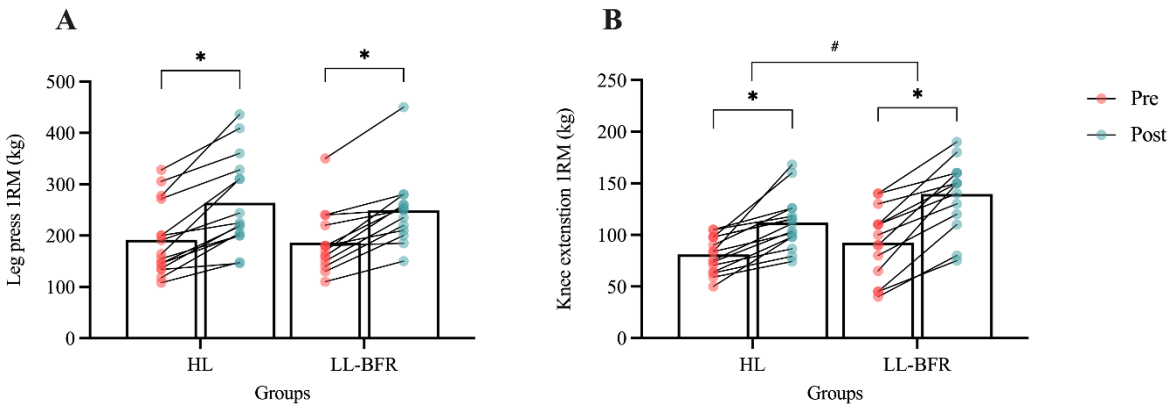
Muscular strength

Leg press 1RM increased in the HL group from 192.0 ± 71.0 kg to 263.9 ± 89.9 kg and in the LL-BFR group from 186.4 ± 60.7 kg to 248.9 ± 68.8 kg. Mixed ANOVA results revealed a significant time effect ($F_{(1, 27)} = 87.45$, $p < 0.001$, $\eta_p^2 = 0.764$) but no interaction effect ($F_{(1, 27)} = 0.428$, $p = 0.518$, $\eta_p^2 = 0.016$). Significant within-group differences were observed in both groups ($p < 0.001$; Figure 4A). Additionally, knee extension 1RM increased from 81.2 ± 17.6 kg to 112.0 ± 26.2 and from 92.5 ± 32.1 kg to 139.6 ± 33.8 kg in the HL and LL-BFR group,

respectively (Figure 4B). After statistical analyses, a significantly higher increase in the LL-BFR group was observed (time × group: $F_{(1, 27)} = 4.464$, $p = 0.044$, $\eta_p^2 = 0.142$).

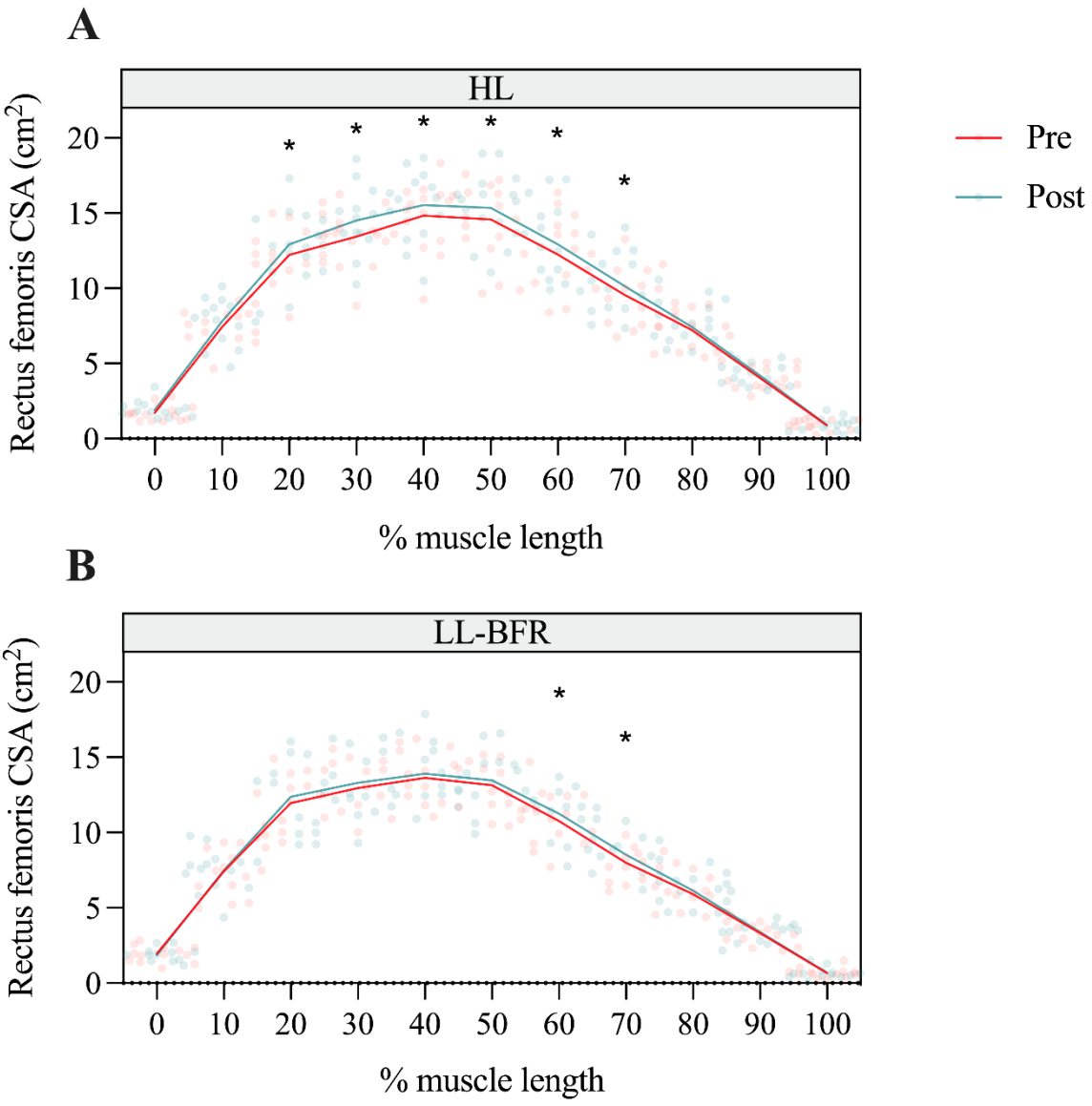


[***Please insert figure 5 about here***]

Muscle CSA

Statistical analysis of RF muscle CSA resulted in significant time effects for all locations within the mid portion of the muscle from 20 – 80% ($p < 0.05$). At the most proximal (0%: $p = 0.546$, 10%: $p = 0.200$) and distal (90%: $p = 0.159$, 100%: $p = 0.626$) portions, no significant time effects were observed. Averaged over all locations, RF CSA increased by 6% in the HL group

and 3% in the LL-BFR group with no significant time × group interactions at any location ($p > 0.05$; Figure 5).



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DISCUSSION

The present results demonstrated for the first time that low-load training with blood flow restriction is an effective strategy for increasing patellar morphological as well as mechanical properties. Magnitudes of both tendinous and muscular adaptations (muscle CSA and strength)

were comparable to that of the high-load training group which implied a ~3x higher training load and thus also higher mechanical exposure on the musculoskeletal system.

Tendinous adaptations

Although high level evidence indicates that LL-BFR training is a potent stimulator of myofibrillar muscle protein synthesis (37, 38) and elicits both structural and functional muscle adaptations (9, 10), literature is still scarce on the effects on the human tendinous system. First experiments by Kubo and colleagues in 2006 compared LL-BFR and HL training on mechanical and morphological adaptations of the patellar tendon (20). Following 12 weeks of resistance training, their findings pointed towards beneficial effects following HL but unchanged tendon properties following LL-BFR. However, LL-BFR training effects may have been missed in that publication because of suboptimal load matching between training groups (i.e. unstandardized load progression). In addition, the mean tendon CSA reported by Kubo and colleagues may have lacked the required level of sensitivity to detect regional differences (22). Using a standardized load progression and a randomized-controlled design, we demonstrated in a previous work on the Achilles tendon, that indeed favorable adaptive responses on the tendon can be seen also with LL-BFR training in young man (19). After 14-weeks of mechanical loading (either HL or LL-BFR) we found that Achilles tendon stiffness significantly increased. These changes in mechanical properties were paralleled by morphological adaptations as indicated via ultrasonic tendon CSA assessment (19).

In the present trial, we aimed to replicate these findings on the patellar tendon by using magnetic resonance imaging for quantifying morphological adaptations. Therefore, we complemented the approach from Kubo et al. (20) by implementing a highly standardized load progression between both groups by gradually increasing load by 5% every four weeks until a maximum load of 35% in the LL-BFR and 85% in the HL group was reached. With this approach, we assured that not only the HL but also the LL-BFR group received a constant progression in

training load. Moreover, the training duration was increased from 12 weeks (Kubo et al. (20)) to 14 weeks according to previous suggestions for optimal tendon adaptations (8). Interestingly, the present results corroborate our initial observations on the Achilles tendon and demonstrate that both patellar tendon stiffness (LL-BFR: 25.2%; HL: 22.5%) as well as CSA increased following 14 weeks of resistance training. At one tendon site (70% tendon length) LL-BFR even showed significantly higher CSA adaptations compared to HL. The functional relevance of this finding, however, remains unclear. Across all tendon measures, generally small (stiffness: $\eta_p^2 = 0.000$) to small-medium (mean patellar CSA: $\eta_p^2 = 0.062$) effect sizes were found, indicating a less meaningful effect. Although the study was originally powered to n = 38 participants, a post-hoc power analysis revealed a sufficiently high power of $\beta = 0.76$ after eliminating dropouts. Interestingly, effect sizes in patellar CSA mostly tend to be in favor of LL-BFR training (see fig. 3).

From a mechanistic point of view, we assume that tendinous adaptations are not merely mechanical stress and strain dependent (as evidenced by previous work (8)) but also strongly rely on the metabolic environment. By restricting venous outflow from the muscle, BFR facilitates a local hypoxic milieu and leads to an accumulation of numerous anabolic growth factors (39) and metabolites (40, 41). Among the potential candidates, that might mediate tendon adaptations, is growth hormone (GH). GH is as frequently discussed, multifunctional hormone with diverse functions on muscle protein synthesis (42), bone (43) and glucose metabolism (44). On the tendon site, previous research revealed that GH may also play a significant role in mediating tendon mechanical and morphological properties (45, 46). For instance, Boesen et al. (45) demonstrated that a daily dosage of GH facilitated greater increases in tendon stiffness following immobilization and subsequent 6 weeks of resistance training. Similar findings were reported by Doessing and co-workers (46) who found that an increased GH availability during 4 weeks of exercise and concomitant GH administration stimulated matrix collagen synthesis in both skeletal muscle and the tendon.

Interestingly, earlier studies have reported that besides GH additional metabolic factors such as lactate are involved in collagen production and tendon cell proliferation (47). Since various independent trials have confirmed the increase in lactate levels and other metabolic stress factors following LL-BFR exercise (39, 48) it might be speculated that the present tendon adaptations might partly be influenced by such metabolic products. However, the physiological mechanisms behind the effects of LL-BFR on tendon stiffness remain speculative and cannot be ascertained in the current study since this was beyond the scope.

Therefore, future studies should investigate the possible role of growth factors and other metabolites (e.g. lactate) in tendon adaptations following LL-BFR training.

Muscular adaptations

The findings from the present study confirmed the frequently reported effects of LL-BFR training on muscular hypertrophy (9, 10). In addition to muscle mass assessments at one single muscle region, we further add important aspects regarding region specific adaptations of muscle mass. Interestingly, by systematically examining RF muscle CSA along the whole muscle length we found a tendency towards suppressed increases in muscle CSA at the region where the BFR cuff was applied. Although no significant interaction effect was observed between HL and LL-BFR, this might confirm the observations from Kazin and colleagues (49) or Ellefsen et al. (50) who stated that less hypertrophy was induced by LL-BFR in the proximal region compared to HL training. As a potential explanation, the authors argue that the pressure of the BFR tourniquet might result in excessive stress and/or altered mechanics during exercise (50).

The hypertrophic responses in the present study were also paralleled by positive changes in muscle strength. Although similar muscle strength improvements were detected for leg press, knee extension strength even showed favorable increases following LL-BFR compared to HL. This superior effect of LL-BFR in improving knee extension strength stands in contrast to

previous meta-analyses indicating that both regimens elicit similar (51) or even more augmented responses in muscle strength following HL training (10). A potential reason for this discrepancy might lay within the fact that the present study focused on the comparison of two common exercise regimens (HL and LL-BFR) using frequently applied protocols (52, 53) and therefore both groups were not volume-matched. Consequently, further studies are needed which compare both regimens using volume-matched protocols. Given that the LL-BFR training program involved ~ 1/3 of the load used in the HL group, these functional adaptation in muscle strength are of great interest for populations which are contraindicated to high mechanical stress such as during rehabilitation (54) or at the course of aging (10).

Limitations

Although the current study generated high-level evidence of beneficial effects of LL-BFR training on patellar tendon properties, no conclusions can be made regarding potential underlying mechanisms. Thus, further studies are needed which quantify collagen synthesis rates following this training regimen. Moreover, the primary aim of this study was to investigate the effects of LL-BFR training on patellar tendon adaptations and examine potential differences compared to conventional HL resistance training. Nevertheless, future studies are needed which also include a LL resistance training group without BFR in order to quantify the net-benefit of superimposition of BFR. Generally, although the sample size was compromised due to $n = 11$ dropouts, only small to small/medium effect sizes were identified, indicating that the overall magnitude/meaningfulness of the difference between HL and LL-BFR might be small. During training, additional upper-body exercises were implemented as a countermeasure for increased drop-out rates during long intervention periods. Although this is a commonly applied method in exercise science (55), it might hamper easy comparisons between the magnitude of myotendinous adaptations from the present study with studies performing lower-extremity exercises only.

Lastly, it needs to be mentioned that our findings from healthy and recreationally active males (18-40 yrs) may not be representative of findings in clinical populations or individuals from different aging groups.

CONCLUSION

These novel data demonstrated substantial improvements in morphological and mechanical patellar tendon properties with both LL-BFR training (20-35% 1RM) and HL resistance training (70-85% 1RM). Further research is warranted which investigate the potential efficacy of this training regimen in clinical rehabilitation with patients suffering from chronic tendinopathy or recover from a tendon rupture.

CONFLICT OF INTEREST

The authors declare no conflicts of interest or external funding or sponsorship related to this study. The results of the present investigation do not constitute an endorsement by the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

AUTHOR CONTRIBUTIONS

C.C., S.J., B.L., O.S., A.G., and D.K. conceived and designed research; C.C., S.J., T.F. and D.L. performed experiments; C.C., B.L., S.J., T.F. and D.L. analyzed data; C.C., S.J., B.L., O.S., A.G., and D.K. interpreted results of experiments; C.C. prepared figures; C.C. and B.L. drafted manuscript; C.C., S.J., B.L., O.S., T.F., D.L., A.G., and D.K. edited and revised manuscript; All authors approved the final version of the manuscript.

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FIGURE CAPTIONS

Figure 1 Representative magnetic resonance (MR) scan at pre and post 14 weeks of training with the patellar tendon outlined in yellow

Figure 2 Representative ultrasound image scan of the patellar tendon with a knee angle of 90°

Figure 3 Patellar tendon stiffness from pre (red) to post (green) exercise in the high-load (HL) and low-load blood flow restriction (LL-BFR) group. Dots represent individual data points and bars show the mean. * indicates significant within-group differences between pre and post

Figure 4 Patellar tendon cross-sectional area (CSA) from pre (red) to post (green) training in the high-load (HL, panel A) and low-load blood flow restriction (LL-BFR, panel B) group. Dots represent individual data points. * indicates significant within-group differences between pre and post, # indicates significant differences compared to HL

Figure 5 Panel "A" presents leg press and panel "B" knee extension one-repetition maximum (1RM) from pre (red) to post (green) exercise in the high-load (HL) and low-load blood flow restriction (LL-BFR) group. Dots represent individual data points and bars show the mean. * indicates significant within-group differences between pre and post, # indicates significant differences compared to HL.

Figure 6 Rectus femoris (RF) muscle cross-sectional area (CSA) from pre (red) to post (green) exercise in the high-load (HL, panel A) and low-load blood flow restriction (LL-BFR, panel B) group. * indicates significant within-group differences between pre and post