with pBFR compared to an active control group without pBFR. Furthermore, a study by Yamanaka et al. (2012) has shown that 4 weeks of low-load resistance training combined with pBFR increased 1RM bench press performance, chest girth, and left upper arm girth compared to a control group without pBFR in NCAA Division IA football players.

Thereby, the BFR training-induced physiological adaptations and performance changes strongly depend on the application of an adequate BFR pressure (e.g., muscle hypertrophy (Lixandrão et al., 2015), vascular adaptations (Mouser et al., 2019)). In order to produce an adequate, standardized, and reliable restriction pressure, different pBFR application techniques have been used that are based on (i) the perceived application pressure (Wilson et al., 2013), (ii) the absolute or relative overlap of the cuff (Thiebaud et al., 2019), and (iii) the maximal tensile strength of the cuff (Behringer et al., 2017). However, each of these techniques has limitations regarding its application during training studies. For instance, the reproducibility of the perceived pressure technique is low between sessions (Bell et al., 2020) and pain modulation effects due to the repetitive application of the cuff during the training period might affect the perceived pressure and thus, the applied cuff pressure (Bielitzki et al., 2021). Furthermore, as limb circumference influences the AOP (Loenneke et al., 2015), the absolute overlap technique, during which the cuff is initially applied and then pulled to a fixed overlap value in order to reduce the initially applied cuff length around the limb, may cause insufficient pBFR pressures (Bielitzki et al., 2021). Moreover, the relative overlap technique, which standardizes the pBFR pressure by using an overlap in relation to subjects' limb circumference, requires cuffs with material properties that should be equal to already investigated cuffs (e.g., elastic powerlifting knee wraps with hook-and-loop closure by Grizzly Fitness (Luebbers et al., 2014; Luebbers et al., 2019), "Red-Line" elastic knee wrap by Harbinger (Loenneke et al., 2010)) and that are constant over time (Abe et al., 2019). Otherwise, the optimal overlap for an effective pBFR pressure has to be determined before actual use. The effects of the pBFR application technique based on the cuffs' maximal tensile strength was rarely studied (Behringer et al., 2017) and seems more complex compared to other techniques (Bielitzki et al., 2021). Therefore, in a recent review article on the currently available pBFR techniques, it was recommended to combine different techniques to ensure an effective and time-stable pBFR pressure (Bielitzki et al., 2021).

Previously, studies compared the effects of resistance exercise combined with BFR using pneumatic cuffs and pBFR using elastic wraps (Thiebaud et al., 2019), elastic bands (Miller et al., 2020), and rigid cuffs (Oliveira et al., 2020) on different physiological parameters. Due to the fact that the level of the BFR pressure is an important factor for training-induced adaptations and the associated changes in motor performance (Mouser et al., 2019), it is essential to adjust the pBFR pressure to the subjects' individual AOP.

Therefore, the purpose of the present study was to examine whether low-load resistance exercise (4 sets of isotonic knee extensions at 20% 1RM (Husmann et al., 2018)) with pBFR using an elastic knee wrap, which was applied based on the pressure perception to a BFR pressure corresponding to 60% AOP, is suitable to induce similar changes in motor performance fatigue (i.e., decrease in maximal voluntary torque [MVT]) as well as physiological (i.e., muscle activity, muscle oxygenation) and perceptual responses (i.e., effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort) compared to traditional BFR using a pneumatic nylon cuff in males and females. Due to sex differences in the physiological adjustments to fatiguing exercise (Hunter, 2018) as well as the perceptual responses to exercise (Cook et al., 1998), male and female participants were investigated. It was hypothesized that low-load resistance exercise with a perceptually primed pBFR pressure induces similar performance, physiological, and perceptual changes as traditional BFR. Furthermore, it was suspected that these changes in response to pBFR and BFR exercise are sex-dependent.

Methods

Experimental Procedure

All participants completed three laboratory visits (familiarization and two experimental trials). During the first visit, participants' (i) arterial occlusion pressure, (ii) overlap of the elastic wrap for pBFR pressure, (iii) systolic blood flow velocity at 60% AOP in the BFR condition (pneumatic cuff) as well as with the adjusted overlap in the pBFR condition (elastic wrap), and (iv) 1RM during a unilateral isotonic knee extension were determined. Additionally, participants were comprehensively familiarized with the maximal voluntary isometric contractions (MVIC) and exercise protocol including the explanation of the perceptual ratings (i.e., effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort).

In a randomized and counterbalanced cross-over design, participants completed two experimental trials consisting of low-load resistance exercise either with pBFR or BFR on two separate days. All testing sessions were separated by 7 days and were conducted at the same time of day to mitigate the influence of circadian variations. Upon arrival, participants' blood pressure was measured and checked for hypertension. Subsequently, surface electromyography (sEMG) electrodes were applied to the three superficial quadriceps muscles of the right leg to record maximal muscle activity during MVICs and muscle activity during exercise. Furthermore, a muscular near-infrared spectroscopy (mNIRS) monitor was applied to the vastus lateralis muscle of the right thigh to measure muscle oxygenation during exercise. After completing a standardized warm-up, participants performed three MVICs of the knee extensors. The exercise protocol consisted of 4 sets of unilateral isotonic knee extensions. At the end of each set, effort and exercise-induced leg muscle pain perception were ascertained. Immediately after exercise termination, the participants had to perform one MVIC of the knee extensors (Figure 1). Cuff pressure-induced discomfort of the elastic wrap during pBFR and the pneumatic cuff during BFR was queried before each experimental condition and immediately after finishing the last set right before wrap loosening and cuff deflation, respectively.

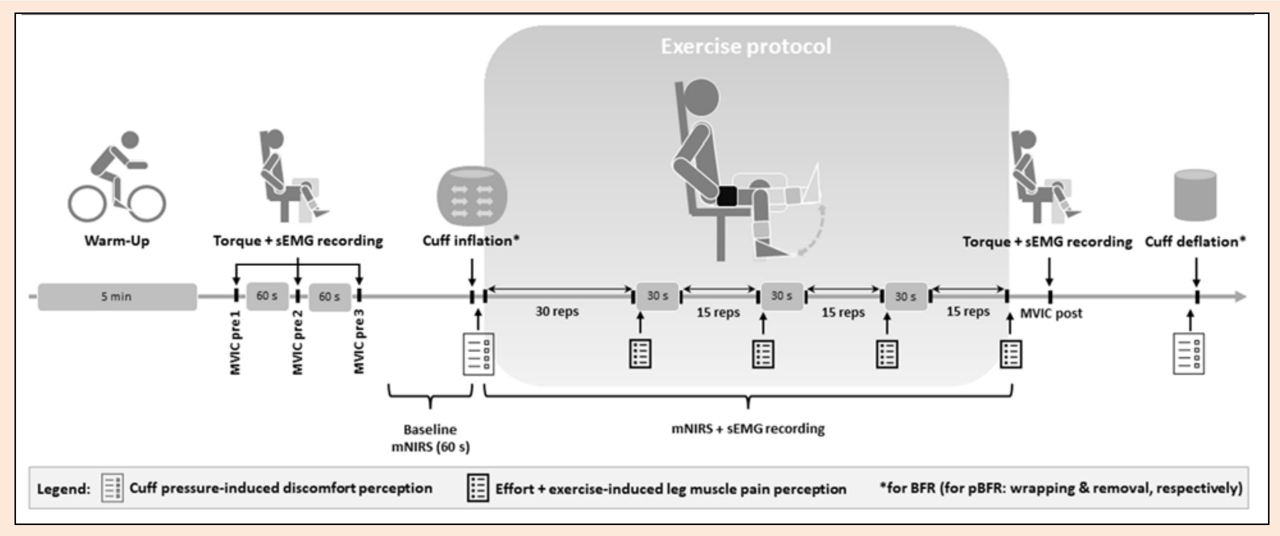

Figure 1. Schematic overview of the experimental procedure including warm-up, maximal voluntary isometric contractions (MVIC), exercise protocol, physiological (i.e., surface electromyography (sEMG), muscular near-infrared spectroscopy (mNIRS)), and perceptual recordings, as well as MVIC testing immediately after exercise termination.

Table 1. Participants' characteristics expressed as means ± standard deviations.

		N = 30 (15 males / 15 females)
Age (yrs)		23.0 ± 2.9
Weight (kg)		72.6 ± 13.3
Height (cm)		175.7 ± 9.7
Body mass index (kg·m^{-2})		23.3 ± 2.8
Right thigh circumference (cm)		59.2 ± 4.8
Skinfold thickness of vastus lateralis (cm)		1.9 ± 0.9
Physical activity (h·week^{-1})		8.2 ± 5.0
Resistance training (h·week^{-1})		3.0 ± 2.6
Systolic blood pressure (mmHg)		121.5 ± 8.5
Diastolic blood pressure (mmHg)		80.5 ± 6.2
One-repetition maximum knee extension (Nm)		165.3 ± 41.3
20% of one-repetition maximum knee extension (Nm)		33.1 ± 8.3
Blood flow restriction pressure	Arterial occlusion pressure (mmHg)	227.7 ± 36.7
	60% of arterial occlusion pressure (mmHg)	136.6 ± 22.0
Practical blood flow restriction pressure	Overlap (cm)	27.7 ± 4.1
	Overlap relative to thigh circumference (%)	46.8 ± 5.9

Baseline measurement of muscle oxygenation was performed at rest 60 s prior to the exercise (Figure 1). Muscle activity and muscle oxygenation were recorded continuously during each experimental condition. Participants were instructed to avoid consumption of alcohol, analgesics, and caffeine for 24 h before, and strenuous exercise 48 h before all 3 laboratory visits.

Subjects

To the best of our knowledge, there is no study that has compared the effect of pBFR and BFR on our main outcomes and therefore no effect size for a sample size calculation could be derived. Therefore, the sample size was chosen in accordance with Freitas et al. (2020) who compared the acute physiological responses to bilateral leg press and knee extension exercises (30 - 15 - 15 - 15 repetitions) at 30% 1RM combined with pBFR and traditional BFR. Accordingly, 30 young, recreationally active males (n = 15) and females (n = 15) voluntarily participated in the present study. Participants' characteristics are shown in Table 1. All subjects were normotensive (< 140/90 mmHg) and free from (i) musculoskeletal injuries, (ii) neurological, mental, and cardiovascular disorders or diseases, (iii) medication with central nervous or cardiovascular effects, (iv) pregnancy, and (v) open wounds or sensitive scar tissue at the limb. The participants provided their written consent about their study participation. The study received approval by the Ethics Committee of the Otto von Guericke University Magdeburg at the Medical Faculty and University Hospital Magdeburg (No. 122/20) conforming to the principles of the Declaration of Helsinki on human experimentation.

Stiffness of the elastic wrap

In order to characterize the material properties of the elastic wrap, a stress-strain relationship was established to determine the cuff stiffness. Using a similar approach to Abe et al. (2019), one end of the elastic wrap was fixed to a wall, while the other was equipped with a clamp. A distance of 10 cm was marked on the elastic wrap. Subsequently, a 0.5 kg weight was applied to the clamp and progressively increased by 0.5 kg. With each additionally applied weight, the change in length of the previous resting distance was determined. The force was continuously applied until the stress-strain relationship was not linear anymore. A linear function was modelled with the applied weight (kg) on the X-axis and the change in length (%) on the Y-axis. The cuff stiffness test was performed three times (initial testing, 1 h and 24 h after the initial testing) to test for reliability of the stress-strain relationship (Abe et al., 2019). There was a linear relationship in the stress-strain curve for all three trials (pre: y = 14.43x + 2.93, R = 0.988, R^2 = 0.975, p < 0.001; post (1 h): y = 14.80x + 4.33, R = 0.982, R^2 = 0.964; p < 0.001; post (24 h): y = 14.80x + 4.08, R = 0.981, R^2 = 0.963, p < 0.001). Already shown by the slope of the curves, the initial testing was different to 1 h and 24 h (p < 0.001) without a difference between the two latter indicating that the initial testing has led to a slight slackening of the material (Behringer et al., 2017) without any changes afterwards. However, the intraclass correlation coefficient revealed an excellent reliability between the three trials ($ICC_{3,1}$ = 0.999).

Determination of BFR and pBFR pressure

The BFR pressure was set based on participants' AOP for the lower body. The participants were seated in an upright position with their right foot on a box (hip, knee, and ankle joint angle = 90°). The seated position during the determination of AOP was chosen to ensure an equal orthostatic position as during the exercise protocol. After resting for 10 min, a 10 x 76 cm pneumatic cuff (UT 1330-L, Ulrich Medical, Ulm, Germany) was applied at the most proximal part of the right thigh and connected to an autoregulated medical tourniquet system (Heidi™, Ulrich Medical, Ulm, Germany) that adjusted the pressure automatically. The blood flow was measured by placing a handheld, bidirectional, and highly sensitive 8 MHz Doppler probe (Dopplex DMX, Huntleigh Healthcare Ltd, Cardiff, UK) over the posterior tibial artery. The cuff was progressively inflated until the pulse could not be detected anymore. The AOP was set to the nearest 10 mmHg as the lowest cuff pressure at which the pulse was not present. The inflation protocol was performed in accordance with Loenneke et al. (2012a).

In the pBFR condition, individual priming at a pressure of 60% AOP was performed using a pneumatic cuff and, subsequently, the elastic knee wrap was applied. The pneumatic cuff was inflated to 60% AOP for about 30 s, while the participants were instructed to focus on the perceived pressure and try to remember this target pressure. Immediately after deflating and removing the pneumatic cuff, a modified 7.5 x 90 cm elastic knee wrap (C.P. Sports, Munich, Germany) was applied to the same area (Figure 2A). The width of the elastic wrap was equal to the inflation tube of the pneumatic cuff (7.5 cm). The elastic wrap was marked with 1.0 cm intervals and a buckle was applied for easier tightening. Furthermore, a Velcro fastener was attached to fix the end of the wrap. The elastic wrap was increasingly tightened by a researcher (only during familiarization; supervised self-application during the experimental trials) until the participant gave the signal to perceive the same pressure as with the pneumatic cuff (Figure 2B). The remaining end of the elastic wrap was wound around the thigh by keeping the tension constant (Figure 2C). After fixing the wrap (Figure 2D), participants were asked again, if the perceived pressure is correct. If participants felt the pressure was too low or too high, the elastic wrap was adjusted until the perceived pressure was equal to that induced by the pneumatic cuff (Oliveira et al., 2020). The overlap was set in relation to the limb circumference (%overlap = overlap · limb circumference^{-1} · 100%), which was assessed using perimeter measuring tape (Seca 201, Seca GmbH & Co. KG, Hamburg, Germany) at the most proximal part of the thigh (Thiebaud et al., 2019; Abe et al., 2019). The absolute overlap of the elastic wrap at 60% AOP was 27.7 ± 4.1 cm, which resulted in a %overlap of 46.8 ± 5.9% (Figure 2E - F).

Systolic blood flow velocity

Systolic peak blood flow velocity was measured in both the pBFR and BFR condition. The participants were seated in an upright position with their right foot on a box (hip, knee, and ankle joint angle = 90°). After applying the elastic wrap or the pneumatic cuff to the limb with the target pressure, the handheld, bidirectional Doppler probe was placed over the posterior tibial artery with an insonation angle of ~ 45° opposite to the direction of flow according to the manufacturer's manual. Measurements were performed in 3 intervals of 12 s each, immediately followed by removing or deflating the elastic wrap or pneumatic cuff, respectively. After a rest period of 10 min, the second condition was applied following the same procedure. The order of application was randomized. The mean of all three intervals was used for further analysis.

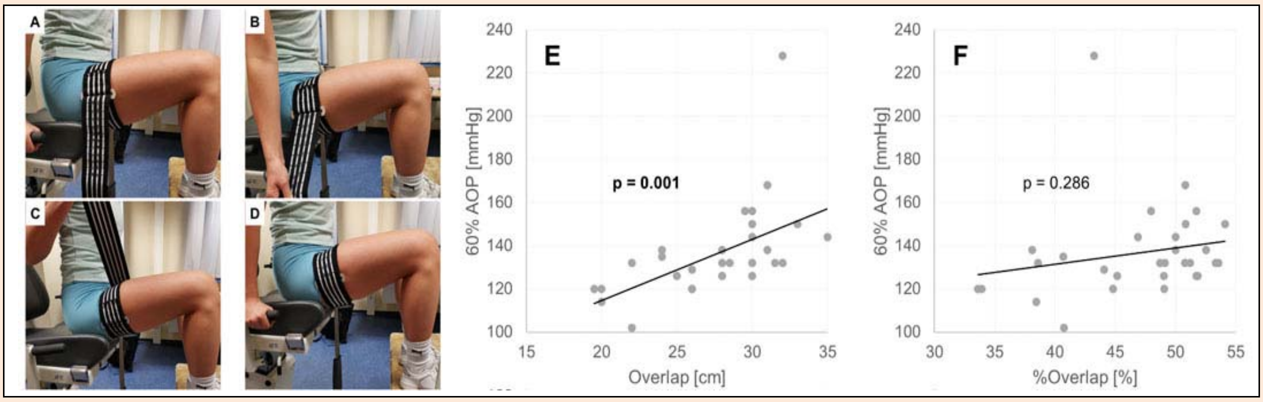

Figure 2. Application of the elastic wrap (A – D) as well as the correlation between 60% of arterial occlusion pressure (AOP) and the overlap (E) as well as the percentage overlap (F) in the pBFR condition.

Determination of one repetition maximum

During the familiarization session, the participants' unilateral isotonic knee extension 1RM was determined to define the percentage load for the exercise sessions (20% 1RM). The 1RM was determined using a Biodex dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY, USA) set in the isotonic mode. Prior to the testing procedure, participants performed a 5 min warm-up on a bicycle ergometer with 90 rpm at 100 W (males) or 80 W (females). This was followed by two submaximal knee extension sets with 8, 4, and 2 repetitions at about 50%, 70%, and 80% of the estimated 1RM, respectively. Subsequently, the load was progressively increased until the participants were incapable to lift the weight controlled through the defined range of motion (i.e., 90° knee angle to full extension (~ 0°)). The 1RM was determined within a maximum of five attempts with ~ 4 min rest between trials (Haff and Triplett, 2016). The participants were given standardized verbal encouragement to ensure maximal performance.

Maximal voluntary torque

A Biodex dynamometer was used to measure MVT (i.e., torque during MVIC). MVICs were performed for 5 s at 70° knee and hip angle (0° = full extension). Participants completed 3 trials prior to the first exercise set and 1 trial immediately after termination of the fourth set. Prior to the testing, participants initially performed a 5 min warm-up on a bicycle ergometer with 90 rpm at 100 W (males) or 80 W (females) followed by two submaximal isometric knee extensions (50% and 80% of estimated 1RM). In each trial, participants were instructed to cross their arms in front of their chest and to push as fast and hard as possible. Strong verbal encouragement was provided to achieve maximal torque output. Visual feedback of the torque-time curve as well as feedback about the produced torque value was provided. For the pretest, 3 maximal attempts with a rest period of 60 s between each trial were recorded. If the coefficient of variation of the 3 trials was above 5%, further maximal attempts were performed until this threshold was reached within 3 consecutive trials (Behrens et al., 2015) (pBFR = 2.31 ± 1.16%; BFR = 2.25 ± 1.58%). The mean of all 3 trials prior to the exercise was calculated and defined as pre-value. Motor performance fatigue was quantified via the percentage change in MVT from pre- to post-exercise (ΔMVT) (Behrens et al., 2020).

Exercise protocol

The exercise protocol followed a commonly used procedure for research and practical applications in the field of BFR (Loenneke et al., 2012b). The protocol consisted of 4 sets (30 - 15 - 15 - 15 repetitions with 30 s rest between sets) of unilateral knee extensions at 20% 1RM. The movement velocity was paced using a metronome set at 40 bpm to ensure 1.5 s concentric and 1.5 s eccentric muscle actions (Husmann et al., 2018). During the pBFR and BFR condition, the elastic cuff and the pneumatic cuff were applied and inflated prior to the first exercise set and removed and deflated immediately after finishing the fourth set, respectively. The target pressure for the exercise was set at the %overlap in the pBFR condition, which was determined during the first visit, and at 60% AOP in the BFR condition.

Maximal muscle activity and muscle activity during exercise

Muscle activity was measured during MVIC and the exercise protocol. The sEMG recording procedure was performed as described in detail by Behrens et al. (2015). Myoelectrical signals (Noraxon Desktop DTS, Noraxon U.S.A., Inc., Scottsdale, AZ, USA) of the vastus medialis, rectus femoris, and vastus lateralis were recorded using 30 x 24 mm gel coated self-adhesive surface electrodes (Kendall ECG Electrodes, Covidien Ilc, Mansfield, MA, USA). The sEMG signals were sampled at a rate of 1000 Hz, band pass filtered (8 - 450 Hz) (Golas et al., 2018), and rectified. After cutting off the first and last second of each MVIC trial and each set during exercise, mean sEMG amplitude was calculated. Mean sEMG amplitude of vastus medialis, rectus femoris, and vastus lateralis during exercise was normalized to the sEMG amplitude recorded during MVIC and were expressed as percentage of MVIC. Finally, normalized sEMG data of all three muscles were averaged to provide an index of whole quadriceps muscle activity. The decline in maximal muscle activity was quantified via the percentage change from pre- to post-exercise.

Muscle oxygenation

During the experimental trials, muscle oxygenation was monitored using an mNIRS device (MOXY, Fortiori Design LLC, Hutchinson, MN, USA). The MOXY monitor (61 x 44 x 21 mm, 48 g) gathered changes in total tissue hemoglobin concentration (tHb) and oxygenated hemoglobin as a percentage of total hemoglobin (muscle oxygen saturation [S_mO_2]). Before fixing the mNIRS device, skinfold thickness of vastus lateralis (19.2 ± 9.2 mm) was measured at the halfway between the base of the patella and great trochanter using a caliper (Harpenden Ltd., British Indicators Ltd, West Sussex, Great Britain). Prior to the application, the corresponding area was shaved and cleaned with alcohol. The mNIRS device was placed on the muscle belly of the vastus lateralis of the right thigh half distance between patellar base and trochanter major. To avoid the irradiation of external light sources, a light protection rubber cap (diameter = 125 mm) was attached around the mNIRS device and fixed to the thigh with elastic adhesive tape. The location of the mNIRS device was marked to reproduce its application in the subsequent test session. S_mO_2 and tHb were recorded at rest in a seated position 60 s before the cuff or wrap application (baseline) and throughout the exercise protocol.

The mNIRS data were recorded at a sampling rate of 2 Hz and filtered with a 4^{th} order low-pass zero-phase Butterworth filter with a cutoff frequency of 0.2 Hz (Husmann et al., 2019). Data were averaged across 30 s for baseline recording and across each set and each rest interval. Percentage changes of S_mO_2 and tHb were used for statistical analyses (ΔS_mO_2 and ΔtHb).

Effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort perception

For the assessment of effort and exercise-induced leg muscle pain perception, standardized instructions were used (Behrens et al., 2020) and both were measured using 15-point Borg Scales (Borg, 1982). Cuff pressure-induced discomfort perception was assessed using a category-ratio 10 (CR-10) scale in order to document the discomfort produced by the application of the elastic wrap at the corresponding %overlap in the pBFR condition and the pneumatic cuff at 60% AOP in the BFR condition. Participants were asked to rate the intensity of discomfort at the location of the cuff. Briefly, instructions were given including the definition of discomfort, specific descriptions ('How uncomfortable do you feel about the cuff?'), and anchoring ('maximal discomfort corresponds to the sensation of a very high pressure with clearly noticeable pain'). Participants were also advised to accurately distinguish between exercise-induced leg muscle pain perception and the mechanical pressure induced by the wrap or cuff.

Statistical analysis

Data analyses were conducted using JASP Statistics (Version 0.16.2, University of Amsterdam, Amsterdam, Netherlands). All data were screened for normality of distribution and homogeneity of variance using the Shapiro-Wilk and Levene´s tests, respectively. Since studies revealed that analysis of variance (ANOVA) is robust against moderate and even severe violation of normality and homogeneity, nonparametric tests were not used to check for differences (Blanca et al., 2017). Therefore, a two-way ANOVA (condition × sex) with repeated measures was performed for systolic blood velocity. Three-way ANOVAs (time × condition × sex) with repeated measures were conducted for MVT, maximal muscle activity, quadriceps muscle activity during exercise, ΔS_mO_2, ΔtHb, effort perception, exercise-induced leg muscle pain perception, and cuff pressure-induced discomfort perception. The effect size was determined by calculating the partial eta squared (η_p^2) interpreted according to Cohen (2013) (0.01 - 0.05 = small, 0.06 - 0.13 = medium, and ≥ 0.14 = large). If sphericity was violated, Greenhouse-Geisser and Huynh-Feldt correction was applied for Greenhouse-Geisser-Epsilon < 0.75 and > 0.75, respectively (Atkinson, 2001). In case of significant condition- and sex-related interactions as well as main effects of condition and sex, post-hoc tests with Bonferroni correction were performed. Furthermore, the effect size Cohens´ *d* was calculated and interpreted according to Cohen (2013) (0.20 - 0.49 = small, 0.50 - 0.79 = medium, 0.80 - 1.29 = large, ≥ 1.30 = very large). Pearson's *r* for normally distributed data and Spearman's *ρ* for not normally distributed data was calculated to check for correlations between the changes in parameters (i.e., MVT, maximal muscle activity, cuff pressure-induced discomfort perception) as well as at specific time points during exercise (i.e., muscle activity, ΔS_mO_2, ΔtHb, effort perception and exercise-induced leg muscle pain perception) in response to the pBFR and BFR exercise protocol (0.10 - 0.39 = weak, 0.40 - 0.69 = moderate, 0.70 - 0.89 = strong, 0.90 – 1.00 = very strong (Schober et al., 2018)). All data were expressed as means ± standard deviations (SD) and the level of significance was set at $p < 0.05$. In addition, mean differences (MD) as well as lower and upper limits of the 95% confidence intervals (95% CI) were provided.

Results

All 30 participants successfully completed the exercise protocol in both conditions. Due to data loss, there were missing values for systolic blood flow velocity (2 males and 1 female) and maximal muscle activity (1 female) as well as muscle activity of quadriceps femoris during exercise (1 female) due to sensor and measurement errors. As most statistical analyses resulted in no differences, only the significant correlations between the conditions as well as interactions and main effects are presented within the result section. All statistical results of the ANOVA and sex-specific data are shown in supplemental material Table S1 and Table S2, respectively. MD (95% CI) of all parameters at each time point are displayed in Table 2.

Systolic blood velocity

There was a strong correlation between systolic blood velocity recorded in the pBFR and BFR condition (r = 0.85, p < 0.001) without differences between conditions (Table 2).

Maximal voluntary torque

A moderate correlation (r = 0.56, p = 0.001) between conditions for ΔMVT was found. There was a time × sex ($F_{1,28}$ = 15.384, p < 0.001, η_p^2 = 0.355) and condition × sex interaction ($F_{1,28}$ = 5.277, p = 0.029, η_p^2 = 0.159) as well as a main effect of time ($F_{1,28}$ = 84.158, p < 0.001, η_p^2 = 0.750) and sex ($F_{1,28}$ = 21.913, p < 0.001, η_p^2 = 0.439). Post-hoc analysis revealed that, irrespective of time, MVT was higher in males during both the pBFR (MD = 92.58 Nm (95% CI: 41.69 to 143.46 Nm), p < 0.001, d = 1.65) and BFR condition (MD = 71.03 Nm (95% CI: 20.15 to 121.92 Nm), p = 0.003, d = 1.27) compared to females with no differences between conditions. Moreover, irrespective of the condition, MVT was higher in males before (MD = 116.38 Nm (95% CI: 62.14 to 170.61 Nm), p < 0.001, d = 2.07) but not after exercise (p = 0.122) compared to females, indicating a higher decline in MVT in males compared to females. Means ± SD of ΔMVT in pBFR and BFR are shown in Figure 3A.

Maximal muscle activity during MVIC

A moderate correlation (r = 0.46, p = 0.013) was found for the decline in muscle activity of the quadriceps femoris muscle during MVIC between conditions. There was a main effect of time ($F_{1,27}$ = 16.713, p < 0.001, η_p^2 = 0.382) and sex ($F_{1,27}$ = 12.347, p = 0.002, η_p^2 = 0.314). Post-hoc analysis revealed that maximal muscle activity of quadriceps femoris during MVIC was higher in males compared to females (MD = 122.34 µV (50.90 to 193.78 µV), p = 0.002, d = 1.12). Means ± SD of decline in muscle activity of the quadriceps femoris muscle during MVIC are shown in Figure 3B.

Muscle activity during exercise

Strong correlations between conditions were found for muscle activity during exercise for all sets (set 1: r = 0.79, p < 0.001, set 2: r = 0.74, p < 0.001, set 3: r = 0.80, p < 0.001, set 4: r = 0.73, p < 0.001). There was a time × condition × sex interaction ($F_{1.7,46.6}$ = 6.679, p = 0.004, η_p^2 =

Table 2. Mean differences (MD) and lower as well as upper limits of the 95% confidence intervals (95% CI) between the pBFR and BFR condition for performance, physiological, and perceptual measures.

		MD (95% CI) [pBFR – BFR]
Systolic blood flow velocity [cm·s^{-1}]		-0.8 (-3.2 to 1.6)[###]
Maximal voluntary torque	Pre [Nm]	-3.3 (-9.5 to 3.0)[####]
	Post [Nm]	3.2 (-14.4 to 20.7)[##]
	Percentage decline [%]	-0.9 (-8.2 to 6.4)[###]
Maximal muscle activity during MVIC	Pre [µV]	-5.0 (-49.0 to 39.1)[###]
	Post [µV]	-12.6 (-56.7 to 31.4)[##]
	Percentage decline [%]	1.1 (-7.2 to 9.3)[##]
Muscle activity during exercise [% of sEMG-MVIC]	Set 1	0.6 (-3.4 to 4.6)[###]
	Set 2	-0.4 (-4.4 to 3.5)[###]
	Set 3	-0.6 (-4.6 to 3.4)[###]
	Set 4	-1.1 (-5.0 to 2.9)[###]
S_mO_2 during sets [%] (%-change from baseline)	Set 1	-1.1 (-9.5 to 7.3)[###]
	Set 2	1.1 (-7.3 to 9.5)[###]
	Set 3	2.3 (-6.1 to 10.7)[####]
	Set 4	-1.7 (-6.6 to 10.1)[###]
S_mO_2 during rest intervals [%] (%-change from baseline)	Rest 1	3.1 (-4.4 to 10.)[###]
	Rest 2	6.3 (-1.1 to 13.8)[###]
	Rest 3	6.6 (-0.9 to 14.0)[###]
tHb during sets [a. u.] (%-change from baseline)	Set 1	-1.0 (-1.9 to 0.5)[##]
	Set 2	-0.7 (-1.8 to 0.4)[###]
	Set 3	-0.9 (-1.9 to 0.2)[###]
	Set 4	-1.2 (-2.2 to -0.1)[###]
tHb during rest intervals [a. u.] (%-change from baseline)	Rest 1	-0.8 (-1.9 to 0.2)[###]
	Rest 2	-1.0 (-2.1 to 0.0)[###]
	Rest 3	-1.2 (-2.3 to -0.1)[###]
Effort perception [a. u.]	Set 1	0.3 (-1.1 to 1.7)
	Set 2	0.3 (-1.1 to 1.7)
	Set 3	0.3 (-1.1 to 1.7)
	Set 4	0.3 (-1.1 to 1.7)[##]
Exercise-induced leg muscle pain perception [a. u.]	Set 1	-0.0 (-1.4 to 1.3)[##]
	Set 2	-0.1 (-1.4 to 1.3)[##]
	Set 3	-0.1 (-1.5 to 1.2)[##]
	Set 4	-0.2 (-1.6 to 1.2)[###]
Cuff pressure-induced discomfort perception [a. u.]	Pre	-0.6 (-1.3 to 0.1)[##]
	Post	-1.1 (-1.8 to -0.4)[###]

MVIC: maximum voluntary isometric contraction, sEMG: surface electromyography, S_mO_2: muscle oxygenation, tHb: total hemoglobin concentration. Significant correlation between conditions (Pearson's r / Spearman's ρ) are presented as follows: [#]weak = 0.1 - 0.39, [##]moderate = 0.4 - 0.69, [###]strong = 0.7 - 0.89, [####]very strong = 0.9 - 1.0.

0.198) and a main effect of time ($F_{1.3,34.7}$ = 44.950, p < 0.001, η_p^2 = 0.625). Post-hoc tests showed that muscle activity in both conditions was significantly higher in set 3 (pBFR: MD = 5.17% (95% CI: 0.66 to 9.69%), p = 0.007, d = 0.58; BFR: MD = 8.02% (95% CI: 3.51 to 12.53%), p < 0.001, d = 0.90) and set 4 (pBFR: MD = 7.33% (95% CI: 2.81 to 11.84%), p < 0.001, d = 0.83; BFR: MD = 12.06% (95% CI: 7.55 to 16.58%), p < 0.001, d = 1.36) compared to set 1 in males, while muscle activity in females was significantly higher only in set 4 (pBFR: MD = 8.45% (95% CI: 3.78 to 13.13%), p < 0.001, d = 0.95; BFR: MD = 6.79% (95% CI: 2.12 to 11.46%), p < 0.001, d = 0.77), but not in set 3 (p ≥ 0.133) compared to set 1. However, there were no differences between conditions and sexes in each set. Means ± SD of muscle activity during exercise are presented in Figure 3C.

Muscle oxygenation

ΔS_mO_2: Strong to very strong correlations for ΔS_mO_2 between conditions were found for all sets (set 1: r = 0.88, p < 0.001; set 2: r = 0.87, p < 0.001; set 3: ρ = 0.92, p < 0.001; set 4: r = 0.89, p < 0.001) and rest intervals (rest 1: r = 0.87, p < 0.001; rest 2: r = 0.83, p < 0.001; rest 3: r = 0.81, p < 0.001).

There was a time × sex interaction ($F_{1.8,49,7}$ = 3.966, p = 0.030, η_p^2 = 0.124) as well as a main effect of time ($F_{1.8,49,7}$ = 15.302, p < 0.001, η_p^2 = 0.353) and sex ($F_{1,28}$ = 42.517, p < 0.001, η_p^2 = 0.603) for ΔS_mO_2 during sets. Post-hoc tests revealed that the decline in S_mO_2 was higher in set 3 (MD = -6.17% (95% CI: -11.20 to -1.14%), p = 0.004, d = 0.36) and set 4 (MD = -9.36% (95% CI: -14.38 to -4.33%), p < 0.001, d = 0.54) compared to set 1 in females but not in males. Furthermore, the decline in S_mO_2 was higher in males compared to females during each set (set 1: MD = -38.49% (95% CI: -58.74 to -18.25%), p < 0.001, d = 2.21; set 2: MD = -41.11% (95% CI: -61.36 to -20.86%), p < 0.001, d = 2.37; set 3: MD = -37.26% (95% CI: -57.51 to -17.02%), p < 0.001, d = 2.14; set 4: MD = -33.65% (95% CI: -53.89 to -13.40%), p < 0.001, d = 1.94). Moreover, a time × condition ($F_{1.5,42.7}$ = 7.708, p = 0.003, η_p^2 = 0.216) and time × sex interaction ($F_{1.3,35.1}$ = 8.984, p = 0.003, η_p^2 = 0.243) as well as a main effect of time ($F_{1.3,35.1}$ = 6.870, p = 0.009, η_p^2 = 0.197), condition ($F_{1,28}$ = 5.452, p = 0.027, η_p^2 = 0.163), and sex ($F_{1,28}$ = 35.636, p < 0.001, η_p^2 = 0.560) was found for ΔS_mO_2 during rest intervals.

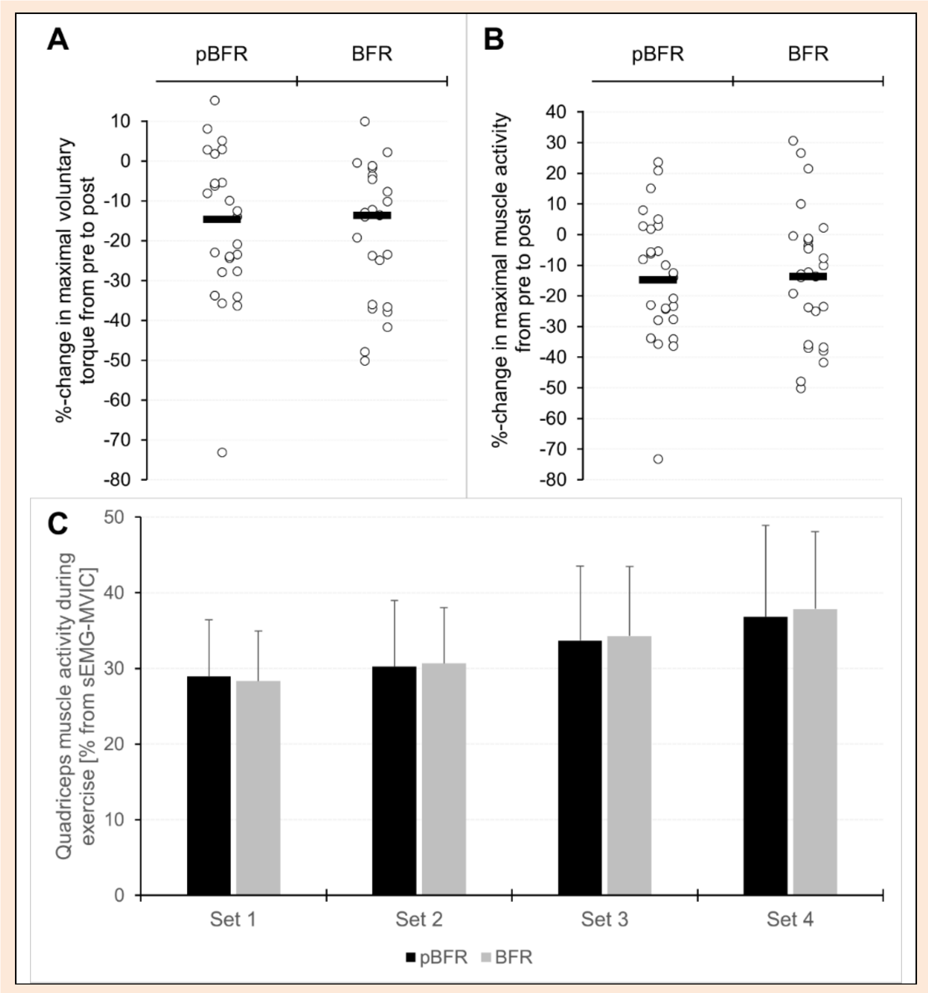

Figure 3. Percentage change in maximal voluntary torque (A) and maximal muscle activity (B) before and after exercise as well as quadriceps muscle activity during sets (C) in the pBFR and BFR condition.

Post-hoc analyses showed that the decline in S_mO_2 was higher in rest interval 2 (MD = -3.01% (95% CI: -5.77 to 0.25%), p = 0.022, d = 0.20) and rest interval 3 (MD = -4.59% (95% CI: -7.35 to -1.83%, p < 0.001, d = 0.30) compared to rest interval 1 in BFR but not in pBFR with no differences between conditions during each rest interval. However, the main condition effect revealed a higher decline in S_mO_2 during BFR compared to pBFR (MD = -4.91% (95% CI: -9.22 to -0.60%), p = 0.027, d = 0.33) over all rest intervals. Regarding sex differences, the decline in S_mO_2 was higher in rest interval 3 compared to rest interval 1 (MD = -6.17% (95% CI: -9.55 to -2.80%), p < 0.001, d = 0.41) in females but not in males. In addition, ΔS_mO_2 was higher in males compared to females during each rest interval (rest 1: MD = -33.14% (95% CI: -49.31 to -16.98%), p < 0.001, d = 2.19; rest 2: MD = -29.61% (95% CI: -45.78 to -13.45), p < 0.001, d = 1.96; rest 3: MD = -26.56% (95% CI: -42.72 to -10.39%), p < 0.001, d = 1.76).

ΔtHb: A moderate correlation for ΔtHb between conditions was found for set 1 (r = 0.42, p = 0.022) as well as and a strong correlation for set 2 (r = 0.72, p < 0.001), set 3 (r = 0.72, p < 0.001), and set 4 (ρ = 0.79, p < 0.001). Furthermore, there were strong correlations for ΔtHb between conditions for each rest interval (rest interval 1: ρ = 0.81, p < 0.001; rest interval 2: ρ = 0.87, p < 0.001; rest interval 3: ρ = 0.86, p < 0.001).

There was a time × sex interaction ($F_{1.7,47.1}$ = 9.408, p < 0.001, η_p^2 = 0.251) as well as a main effect of time ($F_{1.7,47.1}$ = 40.685, p < 0.001, η_p^2 = 0.592), condition ($F_{1,28}$ = 6.875, p = 0.014, η_p^2 = 0.197), and sex ($F_{1,28}$ = 31.631, p < 0.001, η_p^2 = 0.530) for ΔtHb during sets. Post-hoc tests showed a higher ΔtHb in BFR compared to pBFR (MD = 0.86% (95% CI: 0.19 to 1.53%), p = 0.014, d = 0.52) over all sets. With regard to sex differences, tHb was higher in set 2 compared to set 1 (MD = 1.38% (95% CI: 0.65 to 2.11%), p < 0.001, d = 0.83) in females but not in males. Furthermore, the increase in tHb was higher in females compared to males during each set (set 1: MD = 1.62% (95% CI: 0.01 to 3.24%), p = 0.049, d = 0.98; set 2: MD = 2.31% (95% CI: 0.69 to 3.93%), p < 0.001, d = 1.39; set 3: MD = 2.74% (95% CI: 1.12 to 4.36%), p < 0.001, d = 1.65; set 4: MD = 3.26% (95% CI: 1.64 to 4.88%), p < 0.001, d = 1.96).

Moreover, a time × condition ($F_{1.4,39.7}$ = 6.973, p = 0.006, η_p^2 = 0.199) and time × sex interaction ($F_{1.2,34.6}$ = 18.765, p < 0.001, η_p^2 = 0.401) as well as a main effect of time ($F_{1.2,34.6}$ = 81.659, p < 0.001, η_p^2 = 0.745), condition ($F_{1,28}$ = 6.206, p = 0.019, η_p^2 = 0.181), and sex ($F_{1,28}$ = 28.319, p < 0.001, η_p^2 = 0.503) was found for ΔtHb during rest intervals. Post-hoc analyses showed no differences between conditions during each rest interval. However, the main condition effect revealed a higher ΔtHb during BFR compared to pBFR (MD = 0.95% (95% CI: 0.18 to 1.72%), $p = 0.017$, $d = 0.51$) over all rest intervals. Regarding sex differences, there were no time-related differences between males and females. However, the increase in tHb was higher in females compared to males during each rest interval (rest 1: MD = 2.53% (95% CI: 0.75 to 4.30%), $p = 0.001$, $d = 1.36$; rest 2: MD = 2.94% (95% CI: 2.94% (95% CI: 1.17 to 4.72%), $p < 0.001$, $d = 1.59$; rest 3: MD = 3.32% (95% CI: 1.54 to 5.09%), $p < 0.001$, $d = 1.79$).

Means ± SDs of ΔS_mO_2 and ΔtHb as well as ΔS_mO_2 and ΔtHb split by sex are presented in Figure 4 and Figure 5, respectively.

Effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort perception

A moderate correlation for effort perception between conditions was only found for set 4 ($\rho = 0.67$, $p < 0.001$). There was a time × sex interaction ($F_{1.6,44.7} = 4.575$, $p = 0.022$, $\eta_p^2 = 0.140$) and a main effect of time ($F_{1.6,44.7} = 55.906$, $p < 0.001$, $\eta_p^2 = 0.666$) for effort perception. Post-hoc analysis revealed that effort perception was higher in set 2 compared to set 1 (MD = 1.63 a.u. (95% CI: 0.37 to 2.90 a.u.), $p = 0.002$, $d = 0.85$) in males but not in females.

A moderate correlation for exercise-induced leg muscle pain perception between conditions was observed for set 1 ($\rho = 0.42$, $p = 0.022$), set 2 ($\rho = 0.50$, $p = 0.005$), and set 3 ($r = 0.54$, $p = 0.002$) as well as and a strong correlation for set 4 ($\rho = 0.71$, $p < 0.001$). There was a main effect of time ($F_{1.4,40.0} = 74.211$, $p < 0.001$, $\eta_p^2 = 0.726$) for exercise-induced leg muscle pain.

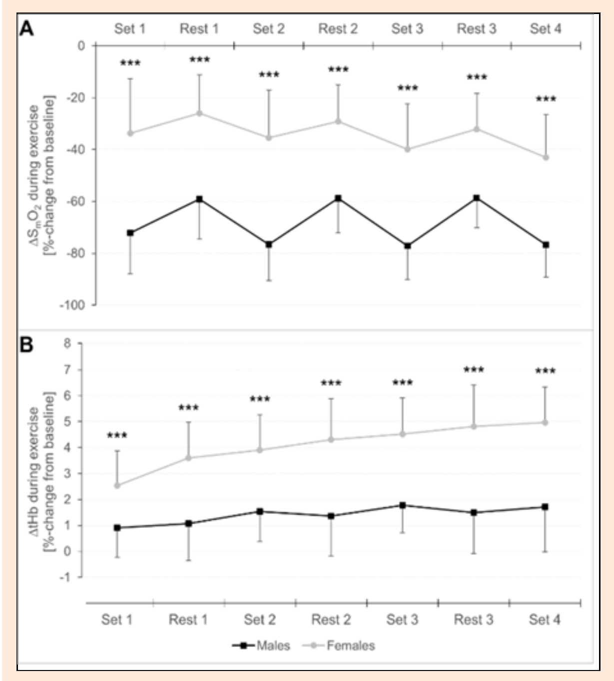

Figure 5. Percentage changes in muscle oxygen saturation (ΔS_mO_2, A) and total hemoglobin concentration (ΔtHb, B) during sets and rest intervals in males and females. Significant differences between sexes are marked as follows: $^{***}p < 0.001$.

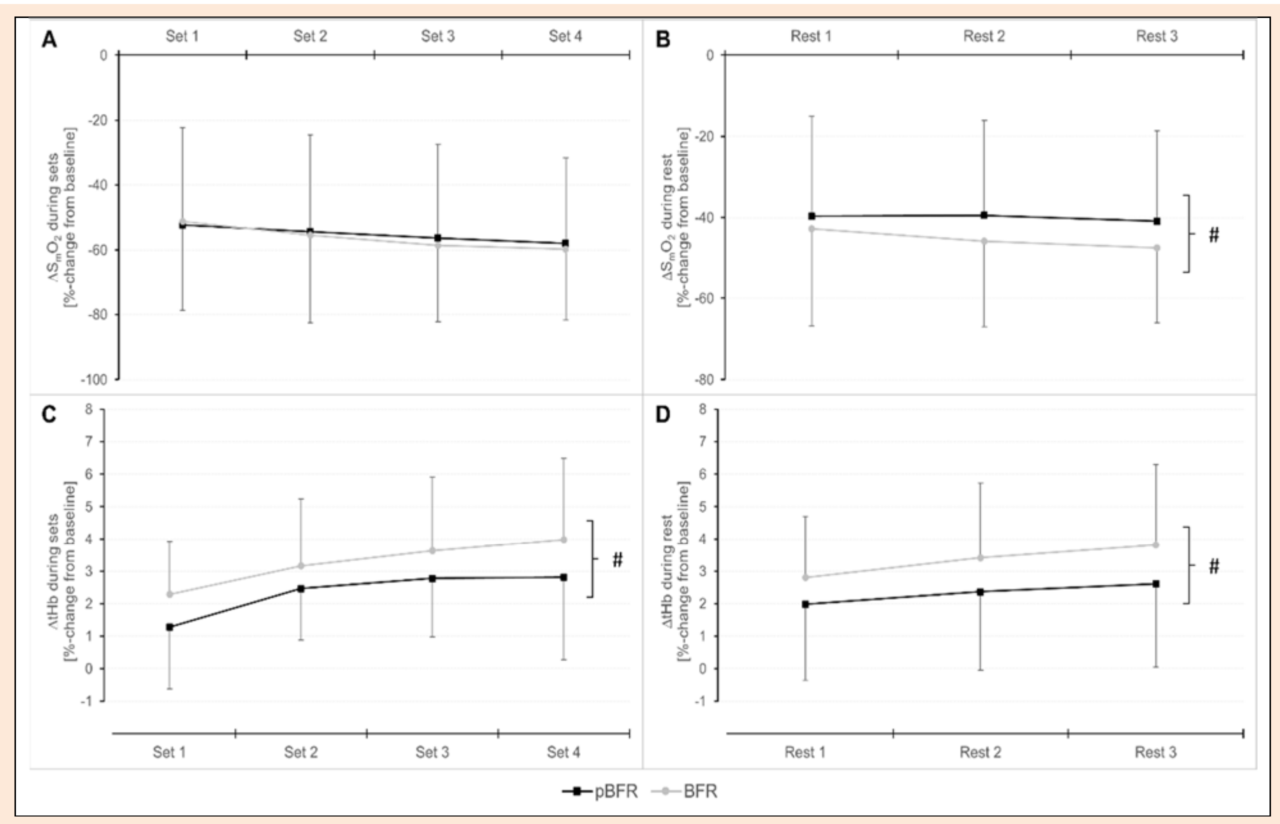

Figure 4. Percentage changes in muscle oxygen saturation (ΔS_mO_2) during sets (A) and rest (B) as well as in total hemoglobin concentration (ΔtHb) during sets (C) and rest (D) in the pBFR and BFR condition. Significant main effect of condition is marked as follows: $^{\#}p < 0.05$.

A moderate correlation between conditions was found for cuff pressure-induced discomfort perception before ($\rho = 0.57$, $p < 0.001$) and a strong correlation after exercise ($\rho = 0.71$, $p < 0.001$). There was a main effect of time ($F_{1,28} = 7.426$, $p = 0.011$, $\eta_p^2 = 0.210$) and condition ($F_{1,28} = 16.244$, $p < 0.001$, $\eta_p^2 = 0.367$) for cuff pressure-induced discomfort perception. The post-hoc test showed that cuff pressure-induced discomfort perception was generally lower in the pBFR compared to the BFR condition (MD = -0.87 a. u. (95% CI: -1.83 to -0.42 a. u.), $p < 0.001$, d = 0.74). Means ± SD of perceptual responses are shown in Figure 6.

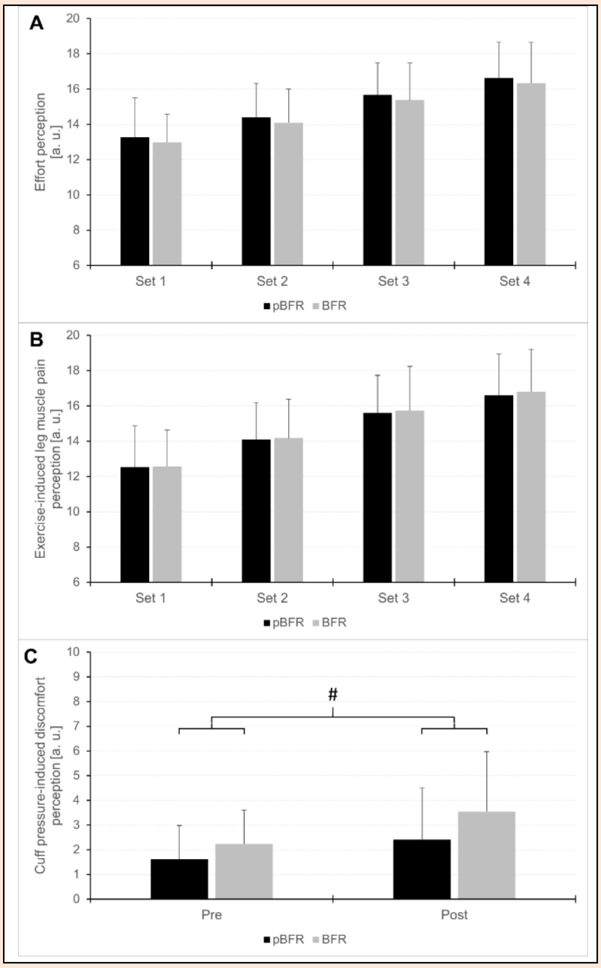

Figure 6. Ratings of effort (A) and exercise-induced leg muscle pain perception (B) during sets as well as cuff-pressure induced discomfort perception before and after exercise (C) in the pBFR and BFR condition. Significant main effect of condition is marked as follows: #p < 0.05.

Discussion

The present study investigated whether low-load resistance exercise combined with perceptually primed pBFR using an elastic knee wrap is suitable to induce similar changes in motor performance fatigue (i.e., decrease in MVT) as well as physiological (i.e., muscle activity, muscle oxygenation) and perceptual responses (i.e., effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort perception) compared to traditional BFR using a pneumatic nylon cuff in males and females. The main findings are: (i) the decrease in MVT and maximal muscle activity were moderately correlated and did not differ between conditions, (ii) during exercise, there were strong correlations for muscle activity as well as no to moderate correlations and moderate to strong correlations for effort and exercise-induced leg muscle pain perception, respectively, with no differences between conditions, (iii) there were moderate to very strong correlations with a lower decline and greater increase in ΔS_mO_2 and ΔtHb, respectively, in pBFR compared to BFR during rest intervals, (iv) ΔS_mO_2 was higher while ΔtHb was lower in males compared to females during exercise, and (v) perception of cuff pressure-induced discomfort was lower in the pBFR condition.

In the present study, we applied a pBFR pressure using perceptual priming based on the individuals' %AOP. It was shown that the individuals' 60% AOP positively correlated with the applied absolute overlap of the elastic wrap, meaning that subjects with a higher AOP need a greater overlap, when a %AOP is applied for exercise or training. Therefore, a fixed overlap value (Yamanaka et al., 2012) could lead to different amounts of %AOP between and within individuals (Bielitzki et al., 2021). However, no correlation was found between 60% AOP and %overlap indicating that absolute inter-individual differences in %AOP might be negligible when applying the individual overlap in relation to the participants' thigh circumference. Nevertheless, Thiebaud et al. (2019) used an overlap of 15% of thigh circumference to produce a high pBFR pressure with an elastic knee wrap with the same width as used in the present study (7.5 cm). The overlap which was determined in the present study and generated a comparable perceived pressure to 60% AOP was about three times higher than the 15% used by Thiebaud et al. (2019). This might be a result of different material properties of the cuffs used beyond just length and width. In this regard, Abe et al. (2019) determined the stress-strain relationship of a 5 cm-wide custom-made elastic cuff. They revealed a linear relationship between the applied force and change in length up to a stretch of 25% with a curve slope of 2.7% indicating that the elastic cuff would be stretched by 2.7% when 1 kg force is applied. It was shown that a stretch of 10% and 20% corresponded to 40% and 80% AOP, respectively (Abe et al., 2019). The stress-strain relationship in the present study revealed a curve slope of 14.7% (i.e., cuff would be stretched by 14.7% when 1 kg is applied) indicating that the elastic wrap was much more elastic compared to the elastic cuff used by Abe et al. (2019) and perhaps by Thiebaud et al (2019). This is in line with the finding that a much greater elongation (~ 47%) was required to induce approximately 60% AOP. Therefore, it might be necessary to determine and report the elastic properties (i.e., cuff stiffness) of an elastic cuff or wrap when using pBFR techniques to ensure comparison between studies (Bielitzki et al., 2021). In this regard, the repetitive stress-strain relationship testing of the cuff used in the present study indicated that there was slight slackening of the elastic material after the first testing, which remained constant afterwards. This was also reported by Behringer et al. (2017) using a 13-cm wide elastic knee wrap and might be a result of certain structural units breaking up when stretching the cuff to the non-elastic range for the first time. Therefore, it can be recommended to maximally stretch a new elastic cuff before the initial usage to minimize or avoid material slackening during future application.

The results of the present study have shown that 4 sets of low-load knee extension exercise combined with either perceptually primed pBFR or traditional BFR have led to a similar significant decline in maximal motor performance (i.e., decrease in MVT) and maximal muscle activity indicating a comparable effect of pBFR and BFR on neuromuscular function. This notion is supported by the correlations found between changes in MVT and maximal muscle activity recorded in the pBFR and BFR condition, respectively. Our results are in accordance to those of Thiebaud et al. (2019), who found no differences in the decrease in MVIC force between the pBFR and BFR conditions after 4 sets of unilateral knee extension to muscle failure with 30 s rest between sets at 30% 1RM using the absolute and relative overlap technique.

Furthermore, ΔS_mO_2 and muscle activity during exercise sets showed strong correlations and did not differ between the pBFR and the BFR condition. For the latter, similar results were observed by Freitas et al. (2020) during 4 sets (30-15-15-15 repetitions with 30 s rest between sets) of bilateral leg press and knee extension exercise at 30% 1RM as well as Thiebaud et al. (2019), when comparing the equivalent conditions (low-pressure pBFR vs. low-pressure BFR and high-pressure pBFR vs. high-pressure BFR). However, changes in muscle oxygenation during rest intervals differed between conditions with S_mO_2 being lower and tHb higher in BFR compared to pBFR. This result might be due to different material properties of the elastic knee wrap and the rigid pneumatic nylon cuff. The elasticity of the wrap and the eventual light slackening could have led to less compressive stress on the vessels in the pBFR condition, which caused less blood pooling and therefore a lower accumulation of deoxygenated hemoglobin and decrease in S_mO_2. However, the generally higher tHb in the BFR condition did not lead to differences in S_mO_2 during sets.

The perceptual responses during exercise increased in both the pBFR and BFR condition with a moderate correlation only in the last set for effort perception and moderate (set 1-3) to strong correlations (set 4) for exercise-induced leg muscle pain perception with no differences between conditions. These findings are in contrast to those of Miller et al. (2020) who found greater ratings of effort perception during the last 3 sets of a low-load knee extension exercise (4 sets [30-15-15-15] with 30 s rest between sets) at 30% 1RM in the BFR compared to the pBFR condition. These conflicting results might be due to methodological differences given that the BFR pressure was set at 50% AOP and the pBFR pressure at a 7 on a 0 to 10 perceived pressure scale in the study by Miller et al. (2020). This might have led to a lower pressure in the pBFR compared to the BFR condition resulting in stronger metabolic disturbances in the BFR condition, which could have contributed to stronger effort perception (Husmann et al., 2018; Marcora, 2009). However, similar changes in ΔS_mO_2 between pBFR and BFR during sets might have comparably modulated effort perception. Furthermore, changes in muscle activity during exercise were similar between conditions, which might also explain the resemblance in effort perception as muscle activity scales with effort perception according to the corollary discharge model (Pageaux, 2016).

This is also in line with the similar increase in exercise-induced leg muscle pain perception during exercise in both conditions. It could be suggested that the limited blood flow has led to comparable local hypoxic environment during exercise sets resulting in an increased nociceptive group III/IV muscle afferent input in both conditions similarly (Mauger, 2013). This could also explain the similar decline in maximal muscle activity as inhibitory group III/IV muscle afferents are thought to induce changes at spinal and/or supraspinal levels leading to a decrease in muscle activation after 4 sets of low-load resistance exercise with BFR (Husmann et al., 2018).

However, there was a lower cuff discomfort during pBFR, which was also found by Miller et al. (2020) using the perceived pressure technique. This might be also a result of the eventual light slackening of the elastic cuff leading to less compressive stress in the pBFR condition, which is known to stimulate mechano-nociceptors (Ge and Khalsa, 2003). Nevertheless, this argument is based on an animal study (Ge and Khalsa, 2003) and further research is required to provide valid statements.

Regarding sex differences, it was shown that MVT was lower in females compared to males. According to the findings by Miller et al. (1993), the greater strength of males compared to females might be primarily related to larger fibers and sex- differences in fiber-type composition. In general, females have a greater proportion of type I and a less type II muscle fibers in the vastus lateralis muscle compared to males (Roepstorff et al., 2006; Miller et al., 1993). However, the greater proportion of type I muscle fibers can explain the lower decline in MVT in females as a greater vasodilatory response of the femoral artery (Parker et al., 2007) and a higher capillary density per skeletal muscle unit in the vastus lateralis (Roepstorff et al., 2006) might have led to less motor performance fatigue development during dynamic knee extensions (Hunter, 2014; Behrens et al., 2023). Furthermore, the decline in S_mO_2 was higher in males compared to females during the whole exercise. This is in accordance with a previous study from our group revealing a greater decline in S_mO_2 of the vastus lateralis muscle during 3 sets of static balance BFR exercise at 80% AOP in males compared to females (Bielitzki et al., 2023). The lower decline in S_mO_2 in females might be explained by a greater vasodilatory response (Parker et al., 2007) and the previously mentioned higher proportion of type I muscle fibers, both leading to a higher perfusion (Hunter, 2014). This assumption is supported by a higher increase in ΔtHb throughout the exercise. However, this result should be interpreted with caution as mNIRS signals (i) do not directly assess blood flow, (ii) are limited to the application area, and (iii) can be influenced by the blood flow of the skin (Barstow, 2019). Furthermore, the differences in muscle oxygenation might be a result of higher skinfold thickness in females given that a thicker skinfold is associated with lower muscle tissue penetration, which might have influenced the measured values (McManus et al., 2018). However, the latter might be a methodological issue, which needs to be investigated in future studies. Interestingly, like in a previous investigation (Bielitzki et al., 2024), there were no differences in muscle activity and perceptual responses during exercise between males and females. However, the underlying mechanisms for these results require further investigations.

Nevertheless, the present study was not without limitations. The participants' AOP and 1RM were determined only during the familiarization session, which might have led to different %AOP and %1RM during the test trials, respectively. However, Husmann et al. (2018) found a moderate intersession reliability (ICC = 0.80) with a coefficient of variation of 5.5% for AOP of the right thigh between two trials separated by 7 ± 1 days indicating a high agreement of the AOP between measurement days. Furthermore, a recent systematic review (Grgic et al., 2020) revealed that test-retest reliability for 1RM in single-joint exercises, such as the knee extension, was excellent in 93% of the included studies (ICC ≥ 0.90) with a coefficient of variation ranging from 0.5% to 9.0% and can, therefore, be used as a reliable tool for testing muscle strength.

Conclusion

The present study has shown that low-load resistance exercise combined with a pBFR pressure individually primed to the pressure perception to the individuals' %AOP induces similar changes in motor performance fatigue as well as muscle activity, muscle oxygenation, and perceptual responses during exercise sets compared with traditional BFR. However, changes in muscle oxygenation were slightly lower in the pBFR compared to BFR condition during rest intervals, which could have contributed to a lower perception of cuff pressure-induced discomfort in the pBFR condition. These results indicate that low-load resistance exercise combined with perceptually primed pBFR is a convenient and less discomfort inducing alternative to traditional BFR. This is especially relevant for BFR training in group settings regarding cost minimizing, given that this kind of pBFR technique requires only one pneumatic cuff device for the validation of the pBFR pressure. Moreover, using elastic wraps for pBFR exercise might be more favorable for individuals who have a low cuff pressure-induced discomfort tolerance. Furthermore, applying an elastic wrap in relation to the limb circumference might be more precise compared to a fixed overlap value, when a specific %AOP is required for BFR exercise or training. Of note, elastic wraps should be stretched to the maximum extent before the first application to ensure constant material properties afterwards, because our data indicate that an initial slight slackening might occur when using new cuffs.

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Key points

- Perceptually primed pBFR induces similar changes in motor performance as well as muscle activity, muscle oxygenation, and perceptual responses during sets of low-load resistance exercise compared to traditional BFR
- Perceptually primed pBFR using elastic wraps induces less discomfort compared to traditional BFR using pneumatic nylon cuffs and therefore, might be more favorable for individuals who have a low cuff-induced discomfort tolerance
- The application of an elastic wrap relative to the limb circumference might be more accurate compared to a fixed overlap value, when a specific percentage arterial occlusion pressure is required for BFR exercise or training
- Elastic wraps should be stretched to the maximum before first use to ensure constant material properties thereafter, because initial slackening might be possible when using new elastic wraps

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Supplementary Tables

Table S1. Statistical results for all interactions and main effects in systolic blood flow velocity, maximal voluntary torque, muscle activity of quadriceps femoris (maximal muscle activity during maximal voluntary isometric contraction [MVIC], muscle activity during exercise), changes in muscle oxygenation during sets and rest (muscle oxygen saturation [ΔS_mO_2], total tissue hemoglobin concentration [ΔtHb]), and perceptual responses (ratings of effort, exercise-induced leg muscle pain, and cuff pressure-induced discomfort perception).

	Interactions				Main effects		
	time × condition × sex	**time × condition**	**time × sex**	**condition × sex**	**time**	**condition**	**sex**
Systolic blood flow velocity	-	-	-	$F_{1,25} = 2.001$, $p = 0.170$, $\eta_p^2 = 0.074$	-	$F_{1,25} = 0.275$, $p = 0.605$, $\eta_p^2 = 0.011$	$F_{1,25} = 0.981$, $p = 0.331$, $\eta_p^2 = 0.038$
Maximal voluntary torque	$F_{1,28} = 2.249$, $p = 0.145$, $\eta_p^2 = 0.074$	$F_{1,28} = 0.662$, $p = 0.423$, $\eta_p^2 = 0.023$	$F_{1,28} = 15.384$, $p < 0.001$, $\eta_p^2 = 0.355$	$F_{1,28} = 5.277$, $p = 0.029$, $\eta_p^2 = 0.159$	$F_{1,28} = 84.158$, $p < 0.001$, $\eta_p^2 = 0.750$	$F_{1,28} < 0.001$, $p = 0.992$, $\eta_p^2 < 0.001$	$F_{1,28} = 21.913$, $p < 0.001$, $\eta_p^2 = 0.439$
Maximal muscle activity during MVIC	$F_{1,27} = 0.004$, $p = 0.952$, $\eta_p^2 < 0.001$	$F_{1,27} = 0.234$, $p = 0.633$, $\eta_p^2 = 0.009$	$F_{1,27} = 2.934$, $p = 0.098$, $\eta_p^2 = 0.098$	$F_{1,27} = 0.137$, $p = 0.714$, $\eta_p^2 = 0.005$	$F_{1,27} = 16.713$, $p < 0.001$, $\eta_p^2 = 0.382$	$F_{1,27} = 0.403$, $p = 0.531$, $\eta_p^2 = 0.015$	$F_{1,27} = 12.347$, $p = 0.002$, $\eta_p^2 = 0.314$
Muscle activity during exercise	$F_{1.7,46.6} = 6.679$, $p = 0.004$, $\eta_p^2 = 0.198$	$F_{1.7,46.6} = 1.509$, $p = 0.232$, $\eta_p^2 = 0.053$	$F_{1.3,34.7} = 1.055$, $p = 0.330$, $\eta_p^2 = 0.038$	$F_{1,27} = 2.423$, $p = 0.131$, $\eta_p^2 = 0.082$	$F_{1.3,34.7} = 44.950$, $p < 0.001$, $\eta_p^2 = 0.625$	$F_{1,27} = 0.096$, $p = 0.759$, $\eta_p^2 = 0.004$	$F_{1,27} = 2.582$, $p = 0.120$, $\eta_p^2 = 0.087$
ΔS_mO_2 During sets	$F_{1.6,44.5} = 0.750$, $p = 0.450$, $\eta_p^2 = 0.026$	$F_{1.6,44.5} = 2.034$, $p = 0.151$, $\eta_p^2 = 0.068$	$F_{1.8,49.7} = 3.966$, $p = 0.030$, $\eta_p^2 = 0.124$	$F_{1,28} = 0.737$, $p = 0.398$, $\eta_p^2 = 0.026$	$F_{1.8,49.7} = 15.302$, $p < 0.001$, $\eta_p^2 = 0.353$	$F_{1,28} = 0.055$, $p = 0.816$, $\eta_p^2 = 0.002$	$F_{1,28} = 42.517$, $p < 0.001$, $\eta_p^2 = 0.603$
ΔS_mO_2 During rest intervals	$F_{1.5,42.7} = 1.655$, $p = 0.207$, $\eta_p^2 = 0.056$	$F_{1.5,42.7} = 7.708$, $p = 0.003$, $\eta_p^2 = 0.216$	$F_{1.3,35.1} = 8.984$, $p = 0.003$, $\eta_p^2 = 0.243$	$F_{1,28} = 0.061$, $p = 0.807$, $\eta_p^2 = 0.002$	$F_{1.3,35.1} = 6.870$, $p = 0.009$, $\eta_p^2 = 0.197$	$F_{1,28} = 5.452$, $p = 0.027$, $\eta_p^2 = 0.163$	$F_{1,28} = 35.636$, $p < 0.001$, $\eta_p^2 = 0.560$
ΔtHb During sets	$F_{2.0,55.5} = 0.055$, $p = 0.946$, $\eta_p^2 = 0.002$	$F_{2.0,55.5} = 1.054$, $p = 0.355$, $\eta_p^2 = 0.036$	$F_{1.7,47.1} = 9.408$, $p < 0.001$, $\eta_p^2 = 0.251$	$F_{1,28} = 1.053$, $p = 0.314$, $\eta_p^2 = 0.036$	$F_{1.7,47.1} = 40.685$, $p < 0.001$, $\eta_p^2 = 0.592$	$F_{1,28} = 6.875$, $p = 0.014$, $\eta_p^2 = 0.197$	$F_{1,28} = 31.631$, $p < 0.001$, $\eta_p^2 = 0.530$
ΔtHb During rest intervals	$F_{1.4,39.7} = 0.328$, $p = 0.064$, $\eta_p^2 = 0.105$	$F_{1.4,39.7} = 6.973$, $p = 0.006$, $\eta_p^2 = 0.199$	$F_{1.2,34.6} = 18.765$, $p < 0.001$, $\eta_p^2 = 0.401$	$F_{1,28} = 009$, $p = 0.926$, $\eta_p^2 < 0.001$	$F_{1.2,34.6} = 81.659$, $p < 0.001$, $\eta_p^2 = 0.745$	$F_{1,28} = 6.206$, $p = 0.019$, $\eta_p^2 = 0.181$	$F_{1,28} = 28.319$, $p < 0.001$, $\eta_p^2 = 0.503$
Effort perception	$F_{3,84} = 1.180$, $p = 0.320$, $\eta_p^2 = 0.040$	$F_{3,84} < 0.001$, $p = 1.000$, $\eta_p^2 < 0.001$	$F_{1.6,44.7} = 4.575$, $p = 0.022$, $\eta_p^2 = 0.140$	$F_{1,28} = 3.384$, $p = 0.076$, $\eta_p^2 = 0.108$	$F_{1.6,44.7} = 55.906$, $p < 0.001$, $\eta_p^2 = 0.666$	$F_{1,28} = 0.721$, $p = 0.403$, $\eta_p^2 = 0.025$	$F_{1,28} = 3.024$, $p = 0.093$, $\eta_p^2 = 0.097$
Exercise-induced leg muscle pain perception	$F_{1.7,48.2} = 0.092$, $p = 0.886$, $\eta_p^2 = 0.003$	$F_{1.7,48.2} = 0.092$, $p = 0.886$, $\eta_p^2 = 0.003$	$F_{1.4,40.0} = 2.334$, $p = 0.124$, $\eta_p^2 = 0.077$	$F_{1,28} = 0.759$, $p = 0.391$, $\eta_p^2 = 0.026$	$F_{1.4,40.0} = 74.211$, $p < 0.001$, $\eta_p^2 = 0.726$	$F_{1,28} = 0.094$, $p = 0.762$, $\eta_p^2 = 0.003$	$F_{1,28} = 1.411$, $p = 0.245$, $\eta_p^2 = 0.048$
Cuff pressure-induced Discomfort perception	$F_{1,28} = 0.001$, $p = 0.973$, $\eta_p^2 < 0.001$	$F_{1,28} = 3.096$, $p = 0.089$, $\eta_p^2 = 0.100$	$F_{1,28} = 1.536$, $p = 0.225$, $\eta_p^2 = 0.052$	$F_{1,28} = 0.390$, $p = 0.538$, $\eta_p^2 = 0.014$	$F_{1,28} = 7.426$, $p = 0.011$, $\eta_p^2 = 0.210$	$F_{1,28} = 16.244$, $p < 0.001$, $\eta_p^2 = 0.367$	$F_{1,28} = 0.086$, $p = 0.772$, $\eta_p^2 = 0.030$

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Table S2. **Performance, physiological, and perceptual measures of males and females for both conditions (pBFR, BFR). Data are expressed in means ± standard deviations.**

		pBFR		BFR	
		Males	Females	Males	Females
Systolic blood flow velocity [cm·s^{-1}]		32.2 ± 9.0	25.0 ± 9.6	31.5 ± 9.5	27.2 ± 7.6
Maximal voluntary torque	Pre [Nm]	315.3 ± 52.4	194.1 ± 35.1	313.7 ± 51.8	202.2 ± 34.3
	Post [Nm]	189.1 ± 77.5	158.6 ± 41.7	209.0 ± 85.1	145.1 ± 49.2
	Percentage decline [%]	34.6 ± 23.4	25.9 ± 20.5	40.3 ± 23.5	21.9 ± 13.4
Maximal muscle activity	Pre [µV]	433.1 ± 124.6	282.1 ± 61.0	433.6 ± 132.0	293.0 ± 97.4
	Post [µV]	349.8 ± 111.1	246.1 ± 81.7	357.8 ± 143.4	263.7 ± 96.3
	Percentage decline [%]	15.8 ± 23.8	13.5 ± 17.7	18.7 ± 18.8	8.2 ± 22.2
Muscle activity during exercise [% of sEMG-MVIC at pre-test]	Set 1	25.7 ± 5.5	32.4 ± 8.0	25.3 ± 4.8	31.6 ± 7.0
	Set 2	27.8 ± 7.2	32.9 ± 9.7	29.2 ± 7.2	32.3 ± 7.5
	Set 3	30.9 ± 8.1	36.7 ± 10.9	33.4 ± 9.3	35.3 ± 9.4
	Set 4	33.0 ± 10.4	40.8 ± 12.9	37.4 ± 11.1	38.4 ± 9.6
SmO_2 during sets [%-change from baseline]	Set 1	-72.6 ± 15.7	-32.0 ± 27.0	-70.8 ± 17.3	-33.1 ± 20.9
	Set 2	-76.8 ± 15.0	-31.9 ± 22.9	-75.4 ± 15.3	-35.4 ± 20.8
	Set 3	-77.0 ± 14.2	-35.5 ± 24.7	-76.4 ± 17.2	-40.7 ± 17.0
	Set 4	-76.7 ± 13.5	-39.3 ± 22.3	-75.9 ± 13.7	-43.6 ± 16.0
SmO2 during rest intervals [%-change from baseline]	Rest 1	-56.4 ± 18.4	-23.0 ± 17.7	-60.4 ± 15.8	-25.1 ± 16.5
	Rest 2	-55.0 ± 16.2	-24.0 ± 19.0	-61.2 ± 14.2	-30.5 ± 14.8
	Rest 3	-55.2 ± 15.3	-26.6 ± 18.8	-60.8 ± 11.7	-34.0 ± 13.9
tHb during sets [%-change from baseline]	Set 1	0.6 ± 1.6	1.9 ± 1.9	1.2 ± 1.1	3.4 ± 1.3
	Set 2	1.5 ± 1.0	3.4 ± 1.5	1.7 ± 1.4	3.9 ± 1.8
	Set 3	1.6 ± 1.1	4.0 ± 1.6	1.9 ± 1.3	4.4 ± 1.7
	Set 4	1.3 ± 2.5	4.3 ± 1.6	2.1 ± 1.5	5.9 ± 1.7
tHb during rest intervals [%-change from baseline]	Rest 1	0.7 ± 2.2	3.3 ± 1.6	1.5 ± 1.1	4.1 ± 1.6
	Rest 2	0.9 ± 2.2	3.8 ± 1.7	1.8 ± 1.3	5.1 ± 1.9
	Rest 3	1.0 ± 2.9	4.2 ± 1.7	2.0 ± 1.3	5.7 ± 1.9
Effort perception [a. u.]	Set 1	12.7 ± 2.4	13.9 ± 2.0	13.3 ± 1.8	12.7 ± 1.4
	Set 2	14.3 ± 1.6	14.7 ± 2.3	14.9 ± 2.0	13.3 ± 1.4
	Set 3	16.0 ± 1.2	15.3 ± 2.3	16.1 ± 2.3	14.6 ± 1.7
	Set 4	17.3 ± 1.9	16.0 ± 2.0	17.4 ± 2.1	15.3 ± 2.1
Exercise-induced leg muscle pain perception [a. u.]	Set 1	12.3 ± 2.3	12.7 ± 2.5	12.6 ± 2.3	12.5 ± 1.9
	Set 2	14.3 ± 2.1	13.9 ± 2.1	14.7 ± 2.6	13.6 ± 1.6
	Set 3	15.9 ± 2.1	15.3 ± 2.2	16.4 ± 2.7	15.1 ± 2.2
	Set 4	17.1 ± 2.6	16.1 ± 2.0	17.6 ± 2.5	16.0 ± 2.1
Cuff pressure-induced discomfort perception [a. u.]	Pre	1.5 ± 1.3	1.7 ± 1.5	2.0 ± 1.0	2.5 ± 1.7
	Post	2.8 ± 2.7	2.0 ± 1.2	3.8 ± 3.0	3.3 ± 1.7

a.u., arbitrary unit; sEMG, surface electromyography; MVIC, maximal isometric voluntary contraction; SmO2, muscle oxygen saturation; tHb, total hemoglobin