Hypoxia and venous occlusion improve muscular performance but no effect on growth hormone in athletes

La hipoxia y la oclusión venosa mejoran el rendimiento muscular sin afectar la hormona del crecimiento en deportistas

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Abstract

Introduction: Resistance training enhances muscle strength and size; however, high-load exercise (>85% 1RM) may increase the risk of injury. Low-load resistance training with hypoxia or blood flow restriction (BFR) offers safer alternatives, although comparative data are limited.
Objective: To examine the effects of hypoxia and BFR on resting growth hormone (GH) levels after five weeks of low-load resistance training.
Methods: Thirty male athletes (19–24 years) were assigned to three groups: RT (50% 1RM), RT + HPX (50% 1RM under hypoxia, $FiO_2 = 0.137$), and RT + BFR (50% 1RM with BFR). Participants performed knee extension and flexion (3 sets × 15 reps, 1-min rest) three times weekly for five weeks. Muscle thickness, strength, resting GH, and blood lactate levels were measured before and after training.
Results: After training, RT + HPX and RT + BFR showed significant increases in rectus femoris and biceps femoris thickness. Strength improved in all groups, with knee extension strength higher in the RT+HPX (30.9 ± 16.3%, p = 0.047) than RT (16.1 ± 7.3%). The resting GH levels did not differ significantly between the groups (p > 0.05). Post-exercise lactate increased significantly only in the RT+BFR (68.7 ± 57.2%, p = 0.018).
Conclusion: Low-load training with hypoxia or BFR enhances muscle hypertrophy and strength, and hypoxia produces greater strength gain. Resting GH levels appear to be unrelated to these adaptations, suggesting that further studies are needed to clarify the underlying mechanisms.

Keywords

Hypoxic training; low-load resistance training; hypertrophy; blood lactate; venous occlusion.

Resumen

Introducción: El entrenamiento de resistencia mejora la fuerza y el tamaño muscular, pero los métodos de alta carga (>85% 1RM) pueden aumentar el riesgo de lesiones. El entrenamiento de baja carga con hipoxia o restricción del flujo sanguíneo (BFR) ofrece una alternativa más segura, aunque la evidencia comparativa es limitada.
Objetivo: Analizar los efectos de la hipoxia y la BFR sobre los niveles de hormona del crecimiento (GH) en reposo tras cinco semanas de entrenamiento de resistencia con baja carga.
Metodología: Treinta atletas masculinos (19–24 años) fueron asignados a tres grupos: RT (50% 1RM), RT+HPX (50% 1RM con hipoxia, FiO_2 0.137) y RT+BFR (50% 1RM con BFR). Realizaron extensiones y flexiones de rodilla (3 series de 15 repeticiones, 1 min de descanso) tres veces por semana durante cinco semanas. Se evaluaron el grosor y la fuerza muscular, la GH en reposo y el lactato sanguíneo antes y después del entrenamiento.
Resultados: RT+HPX y RT+BFR mostraron aumentos significativos en el grosor del recto y bíceps femoral. La fuerza mejoró en todos los grupos, siendo mayor la extensión de rodilla en RT+HPX (30.9 ± 16.3%, p=0.047) frente a RT (16.1 ± 7.3%). Los niveles de GH en reposo no difirieron entre grupos (p>0.05). El lactato aumentó significativamente solo en RT+BFR (68.7 ± 57.2%, p=0.018).
Conclusiones: El entrenamiento de baja carga con hipoxia o BFR mejora la fuerza y la hipertrofia muscular, siendo la hipoxia más efectiva para aumentar la fuerza. Se requiere más investigación para aclarar el papel de la GH en reposo en estas adaptaciones.

Palabras clave

Entrenamiento en hipoxia; entrenamiento de resistencia con cargas bajas; hipertrofia; lactato en sangre; oclusión venosa.

Introduction

Resistance training under hypoxic conditions has gained popularity in exercise and health sciences as an alternative method for improving muscle performance. Recent research on hypoxic resistance training improved the agonist/antagonist strength ratio and thigh muscle cross-sectional area in untrained males (Fashi & Ahmadizad, 2021), as well as in young and older individuals (Törpel et al., 2020). Traditional high-load resistance training at 80-100% of one repetition maximum (RM) is widely recognized as the most effective approach for improving muscle strength, 60-80% of 1RM for hypertrophy, and less than 60% of 1RM for muscular endurance improvement (Schoenfeld et al., 2021). Despite its effectiveness, high-load resistance training may cause considerable stress on muscles, tendons, and ligaments, which can increase the risk of injuries such as strains, tears, and overuse problems(Radovanović et al., 2022). Consequently, researchers have explored other training methods that aim to minimize the risk of injury without compromising the benefits of training.

Over the past decade, researchers have investigated alternative resistance training strategies aimed at reducing the risk of musculoskeletal injuries while preserving the training efficacy. Among these, low-load resistance training performed at 20–50% of the one-repetition maximum (1RM) in conjunction with systemic hypoxia or blood flow restriction (BFR) has garnered significant attention. Empirical evidence suggests that both hypoxic training at 50% 1RM(Thuwakum et al., 2017) and BFR training (Lixandrão et al., 2018) can elicit gains in thigh muscle strength comparable to those achieved through traditional high-load resistance training despite utilizing substantially lighter loads. Although both systemic hypoxia and blood flow restriction (BFR) have been shown to enhance muscle strength and hypertrophy, they also exhibit differing degrees of potential disadvantages when applied to athletic populations, particularly resistance or load use, which warrants further investigation.

The selection of 50% 1RM in hypoxic training protocols is substantiated by findings indicating superior improvements in knee extension strength at this intensity compared with 30% 1RM in male athletes (Thuwakum et al., 2017). Conversely, previous studies involving female athletes have employed lower intensities such as 20% 1RM combined with hypoxia or BFR (Manimmanakorn et al., 2013), suggesting that this may be a more suitable approach for female populations. Other investigations have utilized varying load intensities and training modalities, resulting in diverse protocols and outcomes. This variability underscores the necessity for further research into the effects of 50% 1RM resistance training combined with hypoxia or BFR, particularly in male team athletes.

Research has shown that resistance training performed under hypoxia, including leg extensions (Van Doorslaer De Ten Ryen et al., 2021), back squats (Fashi & Ahmadizad, 2021), and group exercises (bench press, leg extension, front pull-down, deadlift) (Martínez-Guardado et al., 2019) over a 4-to-8-week period can promote increases in muscle strength and thickness, cross-sectional area, and lean mass. However, hypoxic training reduces the oxygen supply to body tissues, which can present difficulties for certain athletes. Some individuals, categorized as non-responders, may experience acute mountain sickness (AMS) in the early stages of systemic hypoxic training (Hamlin & Ainslie, 2010), potentially leading to performance decline. This highlights the importance of exploring alternative or complementary training strategies to optimize outcomes in diverse athletic populations.

The use of blood flow restriction (BFR) combined with low-load resistance training has been identified as an alternative approach for enhancing muscle strength and mass (Centner et al., 2022; Iversen et al., 2016). Low-load resistance training has demonstrated positive effects on muscle growth and various physiological adaptations, serving as a potential substitute for heavy-load strength rehabilitation in diverse clinical populations (Hughes et al., 2017), and has been used in clinical trials for populations with musculoskeletal injuries (Bahamondes-Avila et al., 2024). However, in athletic settings, where optimal muscle performance is necessary for competitive success, higher pressures are often used to restrict blood flow to the targeted muscles to maximize performance gains and adaptations. This increased intensity can lead to discomfort, including sensations of numbness (22.5%) and pain (28%), during BFR or cuff occlusion exercises (Colapietro et al., 2024).

In addition to mechanical loading, resistance exercise (RE) induces hormonal responses, particularly growth hormone (GH), which contribute to muscle remodeling and performance enhancement (Kraemer et al., 2017; Kraemer & Ratamess, 2004). GH secretion patterns are influenced by exercise intensity, type, and individual characteristics such as age and sex (Mennitti et al., 2024). Typically, GH levels rise within 15-30 minutes post-RE and return to baseline or resting levels within an hour (Kraemer et al., 2017). While most studies have investigated acute GH responses following hypoxic or BFR resistance exercise training (Friedmann et al., 2003; Grønfeldt et al., 2020; Kon et al., 2014; Lim et al., 2022; Ramos-Campo et al., 2021), few have explored resting GH levels post-intervention, which may provide insight into long-term anabolic adaptation (Chikani & Ho, 2014). GH may serve as a critical physiological mechanism contributing to enhancements in muscular performance and therefore warrants further scientific investigation. Resting GH concentration plays a crucial role in muscle growth and recovery, reflecting both hormonal storage and overall endocrine function (Haeffner et al., 1999).

One potential mechanism underlying increased GH secretion is lactate accumulation during exercise. Both hypoxic and BFR training promote metabolite build-up and acid-base imbalance, which may stimulate GH release via chemoreflexes and intramuscular metaboreceptors (Feriche et al., 2017). Additionally, the decrease in pH associated with metabolic acidosis could enhance GH release through chemoreflex stimulation mediated by intramuscular metaboreceptors (Loenneke et al., 2010; Pearson & Hussain, 2015). Moreover, during blood flow restriction, local hypoxia is generated in the occluded area, leading to a build-up of metabolites, including lactate, which increases plasma GH concentrations and stimulates satellite cell proliferation. This process contributes to muscle hypertrophy while placing less stress on injured joints, allowing for continued recovery (Loenneke et al., 2010). Some studies have suggested that BFR training leads to higher lactate accumulation due to restricted blood flow, forcing muscles into anaerobic metabolism (Nitzsche et al., 2018). In contrast, systemic hypoxic training primarily enhances oxygen efficiency and endurance adaptations with a less pronounced lactate response (Huang et al., 2023).

However, there is limited evidence regarding the effects of a 5-week low-load resistance training program combined with either hypoxia or blood flow restriction (BFR) on resting growth hormone (GH) levels, particularly following an exercise bout (e.g., 48 h post-exercise) in team sport athletes. In addition, few studies have directly compared blood lactate levels following blood flow restriction training and systemic hypoxic training. This gap in the literature highlights the need for further research to elucidate the differential metabolic responses elicited by these two modalities. Therefore, this study aimed to compare the additional effects of hypoxia and BFR on muscle strength, muscle thickness, resting serum GH, and blood lactate levels in athletes following a 5-week low-load resistance training program. It is hypothesized that both training modalities, low-load resistance training under hypoxia and with blood flow restriction (BFR), will enhance muscular performance. However, BFR may elicit greater lactate accumulation and a more pronounced elevation in resting growth hormone levels, potentially due to its higher localized metabolic stress.

Method

Participants

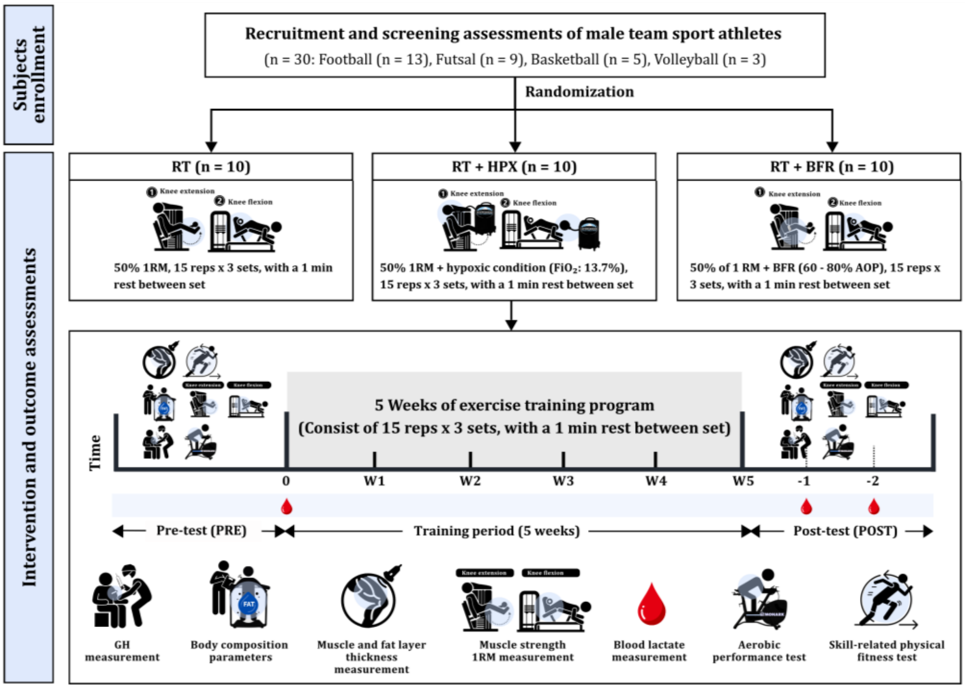
A total of 33 participants were initially enrolled in the study. However, three individuals withdrew because of scheduling conflicts. The final sample included 30 male team sport athletes (mean ± SD: age 22.1 ± 0.6 years, height 174.2 ± 2.6 cm, body mass 69.7 ± 4.2 kg), all of whom successfully completed both the training program and subsequent analysis. The athletes were soccer, futsal, and basketball players with at least 2 years *of* training experience. The exclusion criteria were as follows: participants who reported no exposure to an altitude of > 1,000 m within the last three months, no contraindicative health conditions, and no injuries in the last six months (e.g., bone, joint, or muscle). Participants provided written informed consent to participate in the study, which was approved by the Khon Kaen University Human Ethics Committee (HE651425). All participants were in their competitive training phase and refrained from consuming caffeine or alcohol or performing fatiguing exercises for 24 h prior to testing.

The required sample size was calculated using G*Power (v3.1) based on an estimated effect size (f = 0.66), α = 0.05, and power = 0.80, resulting in a minimum of 10 participants per group. This effect size has been reported in previous studies investigating changes in muscle hypertrophy and performance following hypoxic and BFR resistance training (Laurentino et al., 2022). Although this estimate was guided by the relevant literature, we acknowledge that it may be somewhat optimistic; therefore, the findings should be interpreted with appropriate caution.

Procedure

Thirty-three participants were recruited for this study, and three participants did not complete the training program. Thus, 30 participants were randomly divided into three experimental groups using a random number generator in Excel: (i) resistance training (RT) group, low-load resistance training (50% 1RM, n = 10); (ii) resistance training + hypoxia (RT+HPX) group, low-load resistance training (50% 1RM) combined with hypoxic training (FiO2 = 0.137) (n = 10); and (iii) resistance training + blood flow restriction (RT+BRF) group, low-load resistance training (50% 1RM) combined with blood flow restriction at a pressure equal to 80% of the arterial occlusion pressure (AOP) (n = 10). We used an ultrasound flow meter (LOGIQ e, GE Model Co., Ltd., USA) to evaluate blood flow conditions during vascular assessments, including the measurement of arterial occlusion pressure (%AOP). During the experimental period, all participants were instructed to complete their normal routine sports training without other resistance training. Hypoxic conditions were generated using a hypoxicator machine (ATS-HP-Hyperoxic; Altitude Technology Solutions Company, Ltd., Australia), where the participants breathed hypoxic air for the complete training period. Blood flow restriction was generated using a rigid pneumatic cuff applied to the upper portion of both lower limbs, which remained inflated for the complete training period (B-Strong, California, USA). The participants performed the same series of performance and mechanistic tests two days prior to and two days after five weeks of training.

Figure 1. Outline of training and testing schedule



Training program

All participants performed a 5-week, 3 days per week resistance training program of knee extensions (Nautilus OneTM S6LE, USA) and knee flexions (Nautilus EVOTM S9LCP, USA). Participants completed three sets of 15 repetitions at 50% 1RM with a 1-minute recovery between sets and a movement speed of 2 s for contraction and 2 s for relaxation. The RT group was exposed to normal room air, whereas the RT + HPX group underwent training under hypoxic breathing using a respiratory mask connected to the hypoxicator device. The cuff pressure was gradually increased in the RT+BFR group to mitigate discomfort, numbness, and bruising. It started at 60% AOP for the initial two weeks and then increased to 80% AOP for the subsequent three weeks. The cuff was secured as much as possible to the upper thigh. All participants performed resistance training for 11 minutes a day with 5 minutes of warm-up and 5 minutes of cool-down by active stretching. Resistance training was performed for 63 minutes per week.

Data collection

Body composition

Body composition was measured using a bioelectrical impedance analysis device (Seca mBCA, Hamburg, Germany) to determine the weight, skeletal muscle mass, fat-free mass, and percentage of body fat before and after the training period. The participants did not perform any strenuous exercise 48 h before measuring body composition, emptied their bladders, and removed all bulky clothes and shoes prior to measurement.

Muscular strength

Maximum extension and flexion were measured in normal room air using a stationary machine (Nautilus OneTM S6LE, USA). Prior to measurement, a 5-min warm-up on a bicycle ergometer (Monark cycle 828E at 50-55 rpm) and stretching of the major muscle groups were performed. We estimated 1RM strength using the 10RM protocol (Brzycki, 1993). Each participant was asked to complete the 10RM protocol in extension first and then flexion with a 60 minutes' rest between the two tests. The estimated 1RM was calculated using the following formula: weight lifted /1.0278 − (0.0278 × reps) (Brzycki, 1993). After 90 min of recovery, muscular endurance was determined at the same testing positions (extension and flexion) using the same machine. Each participant performed knee extensions with a load of 50% of 1RM until exhaustion. After 60 min of rest, the same test was performed for knee flexion. The number of repetitions was recorded for each position for all the participants.

Muscle thickness

The thickness of the rectus femoris muscle was measured on the anterior mid-thigh at the midpoint between the anterior superior iliac spine and medial femoral condyle (measured in the supine position with straight knees) exactly at the midpoint of the girth of the muscle. The thickness of the biceps femoris muscle was also measured at the midpoint between the ischial tuberosity and the lateral femoral condyle in the prone position with straight knees again at the midpoint of the girth of the muscle. All ultrasonographic measurements were performed twice on the left leg using a linear probe (5–13 MHz) with a portable ultrasound device (LOGIQ e, GE Model Co., Ltd., USA). All measurements were completed twice on the athlete's left leg by a rehabilitation physician who was blinded to participants' group allocation and the study's hypotheses to minimize potential measurement bias during ultrasonographic assessments. The average of the two measurements was used for the analysis. In addition to muscle thickness, subcutaneous fat thickness was also measured at the same anatomical site. The fat layer was identified as the layer between the epidermal surface and superficial aponeurosis. Muscle and fat layer thicknesses were measured 3 days before training and again 3 days after the last training session to avoid any effects of swelling on measurements.

Blood samples

Blood samples were obtained from participants' antecubital veins while resting on a chair to measure resting serum growth hormone. Venous blood samples (10 mL collected in EDTA tubes taken after 10 min of seated rest) were collected 2 days prior to training to baseline and 2 days post-training and analyzed using an automatic hematology analyzer (Cobas e411; Roche Diagnostics Co., Ltd., Japan). Athletes' blood lactate concentrations were measured from fingertip samples using an automated blood analyzer (Accutrend Plus system; Roche Diagnostics Co., Ltd., USA) before, immediately after, and 15 minutes after training on the first and last day of training.

Physical performance

One to three days before and after the 5-week resistance training period, all participants completed a series of physical performance tests. The participants were accustomed to these tests, which are a regular part of their normal testing routines. Muscle power was assessed using a countermovement jump (CMJ) performed with maximal effort and measured using a kinematic measurement system (Fitness Tech., Australia). Explosive speed was evaluated using a 20-meter sprint test, with the best time recorded from two trials (Thuwakum et al., 2017). We used a standard arrowhead to test agility, with the best time from the two trials recorded (Namboonlue et al., 2020). We used a standard astrand-rhyming protocol to estimate $\dot{V}O2$. All tests were performed at the same time of the day under similar temperature conditions on a nonslip surface in a covered stadium.

Data analysis

All statistical analyses were performed using SPSS version 21 software (IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was used to verify data normality. For all variables, the pre- and post-test values were compared using a paired t-test. One-way ANOVA with a post-hoc Bonferroni adjustment was used to evaluate any differences in baseline measures and percentage changes between groups, with P values < 0.05. For blood lactate measurements, repeated-measures ANOVA was used to examine within-group changes across three time points (pre-training, immediately post-training, and 15 min post-training), with Bonferroni correction applied for multiple comparisons. Statistical significance was set at $p < 0.05$.

Results

Table 1 presents the baseline characteristics of participants in the three training groups: resistance training (RT), resistance training with hypoxia (RT + HPX), and resistance training with blood flow restriction (RT + BFR), with 10 participants in each group. No statistically significant differences were observed among the groups for any measured parameters, including age, height, weight, BMI, resting heart rate, %SpO_2, and systolic and diastolic blood pressure ($p > 0.05$).

Table 1. Participant characteristics in all three training groups.

Characteristics	RT (n = 10)	RT+HPX (n = 10)	RT+BFR (n = 10)
Age (years)	21.6 ± 0.9	21.8 ± 1.2	22.8 ± 2.4
Height (cm)	174.3 ± 4.9	173.8 ± 6.2	170.8 ± 7.9
Weight (kg)	69.5 ± 16.2	71.9 ± 17.8	65.1 ± 5.4
BMI (kg/m^2)	22.7 ± 4.4	23.6 ± 4.7	22.4 ± 2.8
Resting heart rate (bpm)	72.4 ± 12.4	71.2 ± 13.4	73.9 ± 11.1
SpO_2 (%)	98.2 ± 0.6	98.1 ± 0.3	98.0 ± 0.7
SBP (mm Hg)	119.2 ± 12.6	114.5 ± 11.1	116.8 ± 11.5
DBP (mm Hg)	71.2 ± 7.5	71.8 ± 6.4	68.4 ± 9.3

Table Note: Values are presented as mean ± SD. BMI = body mass index; bpm = beat per minute; cm = centimeter; DBP = diastolic blood pressure; kg = kilograms; kg/m^2 = kilograms per square meter; mm Hg = millimeters of mercury; n = number of participants; RT+BFR = resistance training combined with blood flow restriction; RT+HPX = resistance training combined with hypoxia; RT = resistance training group; SBP = systolic blood pressure; SpO_2 = resting arterial oxygen saturation. No significant differences were found between the three groups for any variable.

As shown in Table 2, after five weeks of resistance training at 50% of one-repetition maximum (1RM), the RT group exhibited no statistically significant changes in muscle thickness or subcutaneous fat thickness of the rectus femoris and biceps femoris muscles ($p > 0.05$). In contrast, participants in the experimental groups—RT combined with hypoxia (RT+HPX) and RT combined with blood flow restriction (RT+BFR)—demonstrated significant increases in muscle thickness for both the rectus femoris (RT+HPX: 11.50 ± 14.86%, $p = 0.047$; RT+BFR: 11.77 ± 9.17%, $p = 0.009$) and biceps femoris (RT+HPX: 23.32 ± 15.53%, $p = 0.001$; RT+BFR: 24.63 ± 25.69%, $p = 0.036$) relative to baseline values. Moreover, the RT + BFR group showed a significant reduction in fat layer thickness (−9.68 ± 7.47%, $p = 0.039$) following the intervention period.

Table 2. Mean changes in muscle thickness and fat layer thickness in all 3 training groups.

Parameters	RT (n = 10)	RT+HPX (n = 10)	RT+BFR (n = 10)
Muscle thickness (cm)			
Rectus Femoris			
Pre-test	2.28 ± 0.33	2.35 ± 0.25	2.11 ± 0.23
Post-test	2.44 ± 0.38	2.60 ± 0.27	2.36 ± 0.32
%Change	6.97 ± 7.96	11.50± 14.86*	11.77± 9.17*
Biceps Femoris			

Pre-test	2.25 ± 0.08	2.85 ± 0.77	2.37 ± 0.36
Post-test	2.46 ± 0.24	3.44 ± 0.62	2.91 ± 0.45
%Change	9.36 ± 10.20	23.32± 15.53*	24.63 ± 25.69*
Fat layer thickness (cm)			
Rectus femoris			
Pre-test	0.72 ± 0.38	0.68 ± 0.26	0.82 ± 0.19
Post-test	0.72 ± 0.41	0.65 ± 0.27	0.74 ± 0.12
%Change	-0.63 ± 1.84	-5.57 ± 7.47	-9.68 ± 7.47 *
Biceps femoris			
Pre-test	0.81 ± 0.31	0.71 ± 0.23	0.77 ± 0.25
Post-test	0.82 ± 0.33	0.67 ± 0.20	0.71 ± 0.19
%Change	0.84 ± 10.07	-5.41 ± 5.52	-4.01 ± 16.22

Table Note: Values are presented as mean ± SD. cm; n, number of participants; RT+BFR, resistance training combined with blood flow restriction; RT+HPX, resistance training combined with hypoxia; RT, resistance training group. *p < 0.05 (pre-vs. post-test).

As shown in Table 3, all groups exhibited statistically significant improvements in knee extension (RT, p = 0.001; RT + HPX, p = 0.001; RT + BFR, p = 0.001) and flexion (RT, p = 0.007; RT + HPX, p = 0.005; RT + BFR, p = 0.003) relative to baseline values. Notably, the RT+HPX group demonstrated significantly greater gains in knee extension (30.9 ± 16.3%, mean ± 95% CI, p = 0.047) than the RT group (16.1 ± 7.3%). Furthermore, both experimental groups, RT+HPX and RT+BFR, showed substantial improvements in muscle endurance for knee extension and flexion (RT+HPX: p = 0.002 and p = 0.001; RT+BFR: p = 0.007 and p = 0.003, respectively).

Table 3. Mean changes in muscular strength and endurance in all 3 training groups.

Parameters	RT (n = 10)	RT+HPX (n = 10)	RT+BFR (n = 10)
Muscle strength (1RM)			
Knee extension (kg)			
Pre-test	115.4 ± 18.9	123.5 ± 20.7	116.9 ± 32.9
Post-test	134.1 ± 23.6	159.3 ± 21.4	142.1 ± 36.4
%Change	16.1 ± 7.3*	30.9 ± 16.3*, [a]	22.2 ± 7.6*
Knee flexion (kg)			
Pre-test	76.4 ± 9.7	76.9 ± 16.3	76.7 ± 20.1
Post-test	93.9 ± 11.0	95.9 ± 14.8	95.6 ± 17.9
%Change	23.4 ± 8.5*	26.6 ± 13.5*	27.9 ± 19.0*
Muscle endurance (Number of Reps at 50 %1RM)			
Knee extension (reps)			
Pre-test	17.5 ± 4.9	16.5 ± 3.2	18.8 ± 4.5
Post-test	20.5 ± 3.2	20.7 ± 2.9	22.6 ± 3.9
%Change	22.8 ± 28.5	30.3 ± 31.4*	24.1 ± 25.4*
Knee flexion (reps)			
Pre-test	23.4 ± 6.4	19.1 ± 4.8	23.7 ± 5.0
Post-test	26.5 ± 4.2	25.3 ± 3.4	30.9 ± 6.0
%Change	23.5 ± 46.1	39.4 ± 35.4*	35.0 ± 35.1*

Table Note: Values are presented as mean ± SD. kg = kilograms; n = number of participants; reps = repetitions; 1RM = one repetition maximum; RT+BFR = resistance training combined with blood flow restriction; RT+HPX = resistance training combined with hypoxia; RT = resistance training group. *p < 0.05 (pre-vs. post-test). [a]p < 0.05, between groups RT and RT + HPX.

As shown in Table 4, all groups exhibited significant reductions in resting serum growth hormone (GH) levels following the intervention compared to baseline values (RT, p = 0.012; RT+HPX, p = 0.024; RT+BFR, p = 0.017). However, despite these within-group decreases, no statistically significant differences were observed in the percentage changes in GH levels between the groups post-intervention (mean ± 95% CI, p > 0.05).

Table 4. Mean changes in resting growth hormone levels in all three training groups.

Parameters	RT (n = 10)	RT+HPX (n = 10)	RT+BFR (n = 10)
GH (ng/mL)			
Pre-test	0.26 ± 0.31	0.21 ± 0.32	0.12 ± 0.12
Post-test	0.04 ± 0.03	0.08 ± 0.07	0.05 ± 0.04
%Change	-63.33 ± 29.74*	-41.14 ± 55.36*	-45.00 ± 36.73 *

Table Note: Values are presented as mean ± SD. ng/mL; n, number of participants; RT + BFR, resistance training combined with blood flow restriction; RT+HPX, resistance training combined with hypoxia; RT, resistance training group. *p < 0.05 (pre-vs. post-test).

Figure 2 presents the changes in blood lactate concentration (mmol/L) measured at three time points across all groups. Immediately following exercise, the RT+BFR group demonstrated a significantly greater percentage increase in blood lactate levels (68.7 ± 57.2 %, mean ± 95 % CI, p = 0.018) compared to both the RT group (9.1 ± 15.3 %) and the RT+HPX group (11.2 ± 18.7 %, p = 0.023). These findings suggest a heightened metabolic response in the RT + BFR condition relative to other training modalities.

Figure 2. Blood lactate levels at the first)A(and last)B(training sessions in all resistance training groups. Data are presented as the mean ± standard deviation)SD(. *p < 0.05, significant difference between RT and RT+BFR; #p < 0.05, significant difference between RT+HPX and RT+BFR at the same time point.

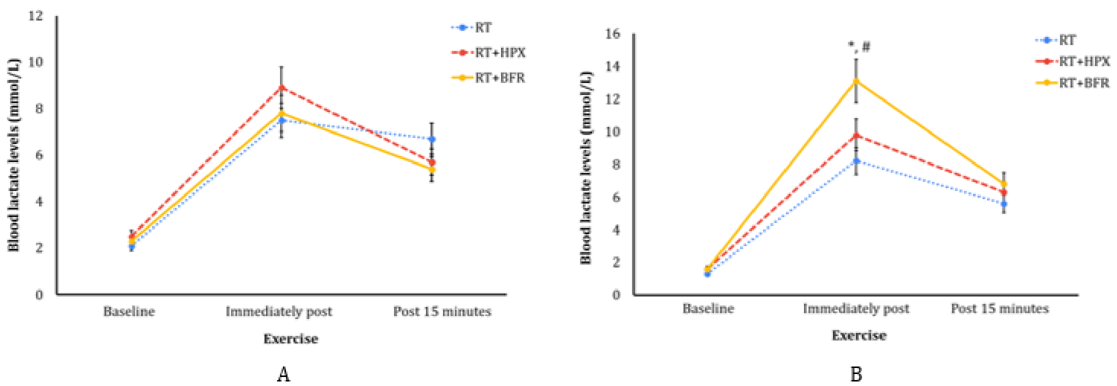


Table 5 indicates that both the RT + HPX and RT + BFR groups experienced significant improvements in physical performance following the intervention, as reflected by increased countermovement jump height (RT + HPX: p = 0.001; RT + BFR: p = 0.033) relative to baseline values. Additionally, agility performance showed a statistically significant enhancement exclusively in the RT + HPX group (p = 0.015) when compared to pre-training levels.

Table 5. Mean changes in physical performance.

Parameters	RT (n = 10)	RT+HPX (n = 10)	RT+BFR (n = 10)
CMJ jump (cm)			
Pre-test	36.3 ± 0.1	41.1 ± 0.1	35.6 ± 0.1
Post-test	35.6 ± 0.4	42.9 ± 0.1	37.3 ± 0.1
%Change	-1.60 ± 8.6	4.50 ± 2.3*	4.90 ± 4.6*
Agility (s)			
Pre-test	9.19 ± 0.3	9.23 ± 0.4	9.20 ± 0.4
Post-test	9.19 ± 0.4	8.95 ± 0.2	9.17 ± 0.4
%Change	0.10 ± 3.3	-3.00 ± 2.6#	-0.20 ± 3.7
Speed 20 m (s)			
Pre-test	3.18 ± 0.2	3.27 ± 0.1	3.20 ± 0.1
Post-test	3.23 ± 0.2	3.29 ± 0.1	3.21 ± 0.1
%Change	1.80 ± 2.8	0.60 ± 2.8	0.60 ± 2.4

Table Note: Values are presented as mean ± SD. CMJ, counter movement jump; m, meters; ng/mL, nanograms per milliliter; n, number of participants; RT+BFR, resistance training combined with blood flow restriction; RT+HPX, resistance training combined with hypoxia; RT, resistance training group; s, seconds. *p < 0.05, #p < 0.01 (Pre-test vs. post-test).

Discussion

This study aimed to determine the effects of low-load resistance training combined with hypoxic training or blood flow restriction on thigh muscle strength and thickness in athletes. This study supports the partial additive effects of both hypoxia and blood flow restriction (BFR) programs. The major finding of this study was that both interventions led to increased muscle thickness of the rectus femoris and biceps femoris (Table 2). However, only the hypoxic training group demonstrated an additive effect on maximal strength (1RM) (Table 3). Improvements in muscular endurance and countermovement jump performance were observed in both groups when compared with baseline, suggesting functional benefits beyond hypertrophy. These findings indicate that low-load resistance training under hypoxic or BFR conditions may be a viable strategy for enhancing specific muscular adaptations in athletes. Furthermore, the mechanisms underlying these effects remain unclear. Although elevated blood lactate levels are often associated with metabolic stress during training, resting serum growth hormone (GH) levels do not show a clear correlation with these elevations. This suggests that other physiological factors, such as localized hypoxia, cellular swelling, and neural adaptations, may contribute to the observed improvements in muscle thickness and performance. Further research is needed to elucidate the specific pathways involved in training-induced adaptations.

In this study, muscle hypertrophy resulting from low-load resistance (50 % of 1RM) was observed in both experimental groups (RT + HPX and RT + BFR) but not in the control RT group. This indicated the additive effects of systemic and local hypoxia on muscle growth. Manimmanakorn et al. (2013) reported the comparison between two methods and found that either intermittent normobaric hypoxia or blood flow restriction by using occlusion pressure (240 mm Hg or approximately 80 %AOP) with low-load (20 % 1RM) resistance training enhanced in the same extent in the muscle cross-sectional area (CSA) of the knee extensor and flexor muscles than those occurred in control resistance exercise group in female netball athletes (Manimmanakorn et al., 2013). The current study indicated that low-load resistance training at 50 % of the one-repetition maximum (1RM), when combined with either hypoxia (13.6 % inspired O_2) or blood flow restriction (BFR at 60–80 % arterial occlusion pressure, AOP), provided sufficient stimulus to induce increases in muscle thickness. Additionally, the observed increase in muscle thickness or mass may be associated with other mechanisms, such as vascular endothelial growth factor (VEGF), a key regulator of angiogenesis (Ramadhan et al., 2025), which warrants further investigation.

The muscle strength was significantly increased in all 3 resistance training groups after 5 weeks when compared to their baseline. However, only the RT+HPX group showed a statistically significant increase compared to the RT group, while the RT+BFR group did not differ significantly from the RT group. These results suggest a potentially greater benefit of systemic hypoxia over BFR resistance training in enhancing muscle strength, although the clinical relevance of this difference remains uncertain. Several studies have revealed that 5 weeks of resistance training in hypoxia (FiO2 = 12.6 % and 16 %) (Yan et al., 2016) and (FiO2 = 13.7 % and 15.8 %) (Namboonlue et al., 2020) improved muscle strength related to muscle hypertrophy or muscle mass clement. In the current study, although muscle thickness increased in both the systemic hypoxia and BFR groups, an increase in muscle mass was not related to an improvement in muscle strength. These results contrast with those reported by Manimmanakorn et al. (2013), who found comparable benefits from systemic hypoxia and BFR training in female netball athletes following a 5-week program of 20 % 1RM (Manimmanakorn et al., 2013). In the present study, the use of 50 % 1RM for BFR training may have caused greater discomfort in the occluded limbs compared with lower-load protocols, potentially impairing force output and limiting strength gains. Additionally, differences in training load and participant sex may account for the discrepancy between these findings. Breathing hypoxic gas at 13.6 % FiO2 did not cause any adverse effects in athletes. However, the mechanism underlying this change requires further investigation.

Muscular endurance or the number of repetitions increased in the RT+HPX and RT+BFR groups but not in the RT group. These results suggest that both hypoxia and BFR have an additive effect on muscle strength and endurance in team athletes. Machek et al. (2022) reported that low-load resistance (20 % of 1RM) combined with BFR at 80 % arterial occlusion pressure significantly increased the number of repetitions compared to high-load resistance (80% of 1RM) leg press exercise (Machek et al., 2022). The current research suggests that low-load resistance with BFR may produce comparable muscular endurance with conventional high-load training, especially regarding repetitions to the point of failure and endurance-related metrics (Davis et al., 2024). A recent study reported that athletes who trained with BFR techniques or under hypoxia combined with resistance training showed significantly greater improvements in muscle strength and endurance than those trained with resistance alone (Chang et al., 2023; Gamonales et al., 2023). The main mechanism responsible for these effects appears to be related to increased metabolite accumulation due to both systemic and local hypoxic environments. This suggests that changes in muscle strength may be related to muscle hypertrophy rather than neural adaptations; however, further research is needed to clarify these relationships. During resistance training with blood flow restriction, type I fibers become fatigued very quickly because of insufficient blood flow and oxygen shortage, leading to the recruitment of type II fibers to preserve strength (Aghaei et al., 2023; Friedmann et al., 2003).

The current study showed that the resting GH hormone levels decreased after five weeks of training compared to their baseline levels in all resistance training groups (Table 4). This suggests that low-load resistance training, whether combined with hypoxia or BFR, may influence growth hormone (GH) release in a similar way. GH levels are known to fluctuate in response to exercise, often increasing transiently during activity, and subsequently declining at rest. In the present study, resting GH levels decreased in all training groups after five weeks. Although the exact cause of this reduction remains unclear, several physiological mechanisms have been proposed in the literature, including negative feedback regulation, changes in metabolic demand, hormonal interactions, and adaptive responses over time (Godfrey et al., 2003; Wideman et al., 2002). However, these mechanisms were not directly measured in our study and should be interpreted with caution. It is also possible that other unmeasured factors contributed to the observed changes in the GH levels. Therefore, further research is needed to clarify its physiological basis.

Previous studies have reported that both the intensity of resistance exercise (RE) (Wideman et al., 2002) and the degree of hypoxic training play key roles in adaptation to the magnitude of GH secretion. For example, Jiang et al. (2024) found that hypoxia (FiO2 ~0.136) leads to higher resting plasma GH levels than moderate hypoxia or normoxia (Jiang et al., 2024). In the current study, despite employing a comparable hypoxic condition (FiO_2 ~0.137) alongside low-load resistance training, we did not observe statistically significant differences among the three groups (Table 4). Moreover, the mechanisms responsible for the reduction of resting GH levels after resistance training remain unclear. Future studies are needed to directly assess these physiological pathways and to clarify the roles of hypoxia and training intensity in GH regulation.

For blood lactate levels (% changes), after a 5-week training program, the results revealed a significant increase immediately post-training in the RT+BFR group compared to the RT and RT+HPX groups (Figure 2). These results indicate that the metabolic accumulation caused by BFR is more potent than hypoxic conditions created by breath hypoxic gas. Previous studies have reported that blood lactate levels tend to increase significantly during low-load resistance training with blood flow restriction (BFR) (Jagim et al., 2024; Kraemer & Ratamess, 2004) because of restricted oxygen supply and enhanced metabolic stress (Aghaei et al., 2023). Studies have shown that lactate accumulation is higher under BFR conditions than under traditional resistance training, leading to greater muscle fatigue and neuromuscular adaptations (Lauber et al., 2021). One study found that lactate concentration was significantly elevated in BFR training compared with non-BFR resistance training at similar loads. This suggests that the BFR can mimic the metabolic effects of high-intensity training while using lower loads, making it a valuable tool for rehabilitation and muscle hypertrophy (Nitzsche et al., 2018). However, these studies did not compare the two protocols in the same training program setting. Thus, this study suggests that alternative ways of using low-load resistance plus systemic hypoxia are more effective in improving muscle thickness and strength without blood lactate surge when compared to BFR.

This study showed that physical performance, including muscle power (counter movement jump) in the RT+HPX and RT+BFR groups, and agility in RT+HPX improved after a 5-week training program. A previous study reported resistance training with different types of hypoxias, focusing on strategies designed to improve muscle hypertrophy as well as power for explosive movements such as sprinting, jumping, or throwing performance (Feriche et al., 2017). These improvements in counter movement jump and agility may result from muscle strength improvement observed in the current study.

This study had several limitations. The sample included only trained male athletes from soccer, futsal, and basketball, limiting the generalizability to other populations, such as female athletes or those in different disciplines. The small sample size and lack of a non-exercising control group may have reduced statistical power and limited our ability to isolate the effects of hypoxia or blood flow restriction (BFR) from resistance training alone. However, the inclusion of a resistance training-only group allowed for a comparison of the additive effects of hypoxia and BFR. Although improvements in muscle performance were observed, the study design did not support causal conclusions regarding the role of resting growth hormone levels. Future research should include larger and more diverse samples, longer intervention periods, and rigorous control conditions to clarify these relationships.

Conclusions

Low-load resistance training under hypoxic conditions or with blood flow restriction (BFR) has been shown to enhance muscle thickness. Additionally, hypoxia-based training provided additive gains in knee extension strength among trained male soccer, futsal, and basketball athletes. These methods may offer viable alternatives to traditional high-load training, particularly when reducing joint strain is a priority. However, further investigation is necessary to clarify how prolonged training periods affect physiological mechanisms, such as resting growth hormone concentrations and blood lactate levels, which play a role in improving muscular performance.

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Conflict of interest

The authors declare that they have no conflict of interest.

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