

Hypoxic training is superior to protein supplementation during resistance exercise in team-sport athletes

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Abstract:

Background: Team sport athletes require optimal muscle strength and endurance, but traditional high-load resistance training may increase injury risk. Exercise performed under hypoxia or combined with protein supplementation may offer viable alternatives. **Methods:** Thirty male team-sport athletes completed low-load knee extension and flexion exercises at 50% of one-repetition maximum three times weekly for five weeks. Participants were randomly assigned to normoxic resistance training (RT), resistance training under hypoxia (RTH; FiO₂ = 13.6%), or resistance training with protein supplementation (RTP). Pre- and post-intervention assessments included muscle strength and endurance, muscle thickness, superoxide dismutase, growth hormone, blood lactate, and athletic performance. **Results:** RTH athletes exhibited the highest gain in knee extension maximal strength (33.11 ± 15.81 kg), which was significantly greater than that of the RT group (18.38 ± 7.26 kg, $p = 0.044$). For knee extension muscular endurance, the RTH group improved significantly more than the RT group (7.33 ± 2.45 vs. 4.22 ± 2.73 reps, $P = 0.038$). Both RTH and RTP significantly increased muscle thickness from baseline: rectus femoris (RTH: 0.35 ± 0.29 cm, $P = 0.015$; RTP: 0.32 ± 0.35 cm, $P = 0.027$) and biceps femoris (RTH: 0.54 ± 0.36 cm, $P = 0.001$; RTP: 0.47 ± 0.52 cm, $P = 0.027$). Only RTH elevated superoxide dismutase level by 1.10 U/mL ($p = 0.029$). In the RTH group, immediate post-training blood lactate increased significantly more from the first to final session (2.45 ± 1.14 mmol·L⁻¹) compared to both the RT (0.74 ± 1.17 mmol·L⁻¹) and RTP groups (0.78 ± 1.61 mmol·L⁻¹; $P < 0.05$). **Discussion:** The RTH group's superior adaptations likely stem from amplified metabolic stress evidenced by higher blood lactate where hypoxia and mechanical tension boost local anabolic signaling and antioxidant pathways via reactive oxygen species. In contrast, while protein supplementation supplied enough substrate for muscle hypertrophy, it lacked the systemic metabolic and neuromuscular stimuli needed to translate these structural gains into improved performance within five weeks. **Conclusions:** Low-load hypoxic resistance training comprehensively boosts muscle strength, endurance, hypertrophy, and antioxidant defenses. While protein supplementation supports hypertrophy, it adds no functional or antioxidant gains over training alone, making hypoxia a far more effective, multifaceted strategy for athletes.

Keywords: Hypoxia; Egg-white protein; Superoxide dismutase; Muscle strength; Muscle thickness

Introduction

The development of muscular strength is a fundamental component of athletic conditioning, serving as a cornerstone for optimizing performance across diverse sporting disciplines. Substantial evidence underscores the direct transfer of muscle strength gains to key performance indicators. For instance, research has demonstrated that improved lower body strength, achieved through modalities such as squat training, significantly enhances sprint acceleration in junior soccer players (Chelly et al., 2009). Furthermore, the crucial role of strength as the main determinant of explosive power has been fully confirmed; It forms the foundation of outstanding jumping performance, which is an important attribute of competitive performance for athletes in

team sports events (Suchomel et al., 2016). Additionally, strength training reduces injury risk by fortifying connective tissues and stabilizing joints, thereby supporting long-term athletic resilience (Lauersen et al., 2018). Further research highlights that strength development underpins sport-specific skills, such as agility and acceleration, in elite athletes (Nimphius et al., 2010). These findings collectively underscore the necessity of prioritizing strength adaptations to maximize athletic outcomes.

Resistance training (RT) is widely recognized as the most effective and evidence-based intervention for enhancing muscular strength, explosive power, and specific performance metrics such as sprinting and vertical jumping (Cormie et al., 2011; Suchomel et al., 2016). This central role of RT in strength and power development is robustly supported by foundational research in exercise physiology (Kraemer & Ratamess, 2004). A research review found that using high load ($\geq 60\%$ 1RM) resistance training can achieve greater strength advantage than low-load resistance training ($\leq 60\%$ 1RM), but muscle hypertrophy can be achieved in various load ranges, and compared to high loads, low-load resistance training programs are easier and safer to implement (Schoenfeld et al., 2017). However, conventional high-load RT protocols ($\geq 80\%$ 1RM) have some drawbacks, including elevated risks of musculoskeletal injury, particularly in tendons and ligaments (Lauersen et al., 2018). Such risks are exacerbated in athletes recovering from prior injuries or those with physical limitations, such as joint instability. Therefore, some studies have explored alternative strategies, such as combining low-load resistance training with hypoxia (Manimmanakorn et al., 2013; Thuwakum et al., 2017) or combining with protein supplementation (Whitehouse & Lawlis, 2017). The findings indicate that although the underlying physiological mechanisms require further investigation, these alternative methods may induce muscular hypertrophy and strength gains similar to those elicited by high-load resistance training, while concurrently reducing injury risk.

Emerging research evidence suggests that low-load RT (20-50% 1RM) under hypoxic conditions may elicit muscle strength gains and hypertrophy outcomes comparable to traditional high-load RT in normoxia (Namboonlue et al., 2020). Kon et al. (2012) demonstrated that low-intensity (50% 1RM) resistance training under 13% hypoxia induced elevated growth hormone (GH) levels, thereby favoring protein synthesis. Similarly, De Smet et al. (2017) observed superior knee extension strength gains in hypoxic trained participants (12.3% FiO_2 , 20-25% 1RM) versus normoxic controls after 5 weeks of training. Kurobe et al. (2015) also reported congruent findings, wherein low-intensity hypoxic resistance training promoted greater muscle hypertrophy. Previous research has also shown that hypoxic training protocols can improve team-sport performance (Brocherie et al., 2015) and boost skeletal muscle transcriptional responses (Brocherie et al., 2018). Specifically, the application of a hypoxic stimulus is believed to amplify the inherent metabolic stress of exercise, which is proposed as a key moderator for downstream anabolic adaptations (Scott et al., 2015). However, a recent meta-analysis by Ramos-Campo et al. (2018a) highlighted that while resistance training in hypoxia can improve muscle size and strength, the benefits over normoxic training are not always consistent across studies due to methodological differences. Furthermore, a recent investigation from our research group demonstrated that a 5-week hypoxic low-load RT protocol effectively enhanced muscle strength and lean mass without inducing hematological shifts, suggesting that muscular adaptations may occur independently of systemic oxygen-carrying capacity (Zheng et al., 2026). Although these findings suggest that low-load resistance training combined with hypoxia is a viable alternative, the underlying physiological mechanisms, such as hypoxia's role in modulating reactive oxygen species (ROS) production, satellite cell activation, and mechanistic target of rapamycin (mTOR) pathway regulation, remain incompletely characterized.

Resistance training induces skeletal muscle fiber microtrauma, thereby activating anabolic signaling pathways. Long-term resistance training combined with protein supplementation stimulates satellite cell activation, promoting their differentiation into myonuclei that incorporate into muscle fibers to support myofiber hypertrophy (Bird et al., 2024). A comprehensive meta-analysis by Morton et al. (2018) demonstrated that dietary protein supplementation significantly augments gains in fat-free mass and 1RM strength during prolonged RT, but also identified a plateau effect where protein intakes beyond ~ 1.6 g/kg/day do not confer additional benefits. Protein supplementation serves as a fundamental ergogenic strategy for potentiating resistance training adaptations, primarily through enhancing muscle protein synthesis (MPS) while suppressing exercise induced proteolysis (Snijders et al., 2015). Dietary protein provides essential amino acids particularly leucine which directly activates the mTOR-p70S6K (70 kDa ribosomal protein S6 kinase) signaling axis, facilitating translational initiation and myofibrillar protein synthesis (Cermak et al., 2012; Kerksick & Leutholtz, 2005; Willoughby et al., 2006). At the same time, protein supplements, especially when taken with carbohydrates, increase insulin levels, which subsequently inhibit the ubiquitin-proteasome system (e.g., downregulation of MuRF-1 expression) and reduce myofibril degradation (Figueiredo & Cameron-Smith, 2013). Furthermore, protein intake modulates key hormonal responses (e.g., increased IGF-1, decreased cortisol), creating a net anabolic environment (Griffen et al., 2022; Willoughby et al., 2006). Notably, Willoughby et al. (2006) demonstrated that whey protein supplementation significantly elevates serum IGF-1 levels, activating the PI3K/Akt pathway to potentiate muscular hypertrophy. Although whey protein dominates empirical research, novel supplements such as L-bumax® Gold, derived from egg whites of Thai native chickens and characterized

by high-quality protein with enriched branched-chain amino acid (BCAA) content, may elicit comparable anabolic effects. However, it remains unclear whether protein supplementation alone can sufficiently compensate for the reduced mechanical tension inherent in low-load RT protocols.

In addition, exercise combined with hypoxia or protein supplementation has been hypothesized to enhance antioxidant capacity via upregulation of enzymes like superoxide dismutase (SOD) and glutathione peroxidase (GPx). Hypoxia may stimulate mitochondrial biogenesis and ROS scavenging systems, improving redox balance (Mason et al., 2007), while certain amino acids (e.g., leucine) may activate Nrf2-mediated antioxidant pathways (Merry & Ristow, 2016). However, contradictory findings persist: Radak et al. (Radak et al., 2005) observed no significant changes in antioxidant markers after hypoxic RT, whereas Vollaard et al. (2005) reported protein supplementation blunts exercise-induced oxidative stress only in untrained individuals. Such inconsistencies may stem from differences in intervention duration, hypoxic dose (e.g., 12% vs. 16% FiO₂), and athlete training status. To date, a direct comparison of low-load RT combined with either systemic hypoxia or protein supplementation in team-sport athletes remains largely unexplored. It is practically important to determine which strategy yields superior functional and physiological adaptations, especially when high-load training is contraindicated. Therefore, this study aims to explore the effects of 5-week low-load resistance training combined with hypoxia or protein supplementation on antioxidant marker and muscular performance in team sport athletes.

Material & methods

Participants

According to the statistical calculations conducted in the previous study by Namboonlue et al. (2020), there were 30 participants in this study. The study involved 37 participants, and their results showed that after 5 weeks of low-load resistance training in a hypoxic environment with an oxygen concentration of 13.6%, the knee extension isometric MVC6 force of the participants increased from 45.3 ± 5.5 before the experiment to 60.5 ± 8.2 after the experiment. We set the effect size to 0.98, the alpha level to 0.05, and the power ($1 - \beta$) to 0.8. The minimum sample size calculated according to formula ($N = \frac{2(Z_{\alpha/2} + Z_{\beta})^2 \sigma^2}{\Delta^2}$) was 7. Considering the dropouts, we increased the sample size of each group to 10.

Therefore, this study publicly recruited 30 healthy male university team sport athlete volunteers aged 19-24. All participants met the following inclusion criteria: have at least 2 years of experience in systematic training in team sports events; in the past 3 months, no exposure to environments with an altitude greater than 1000 meters, no specialized resistance training program, no medication (such as synthetic metabolic steroids, creatine, sympathetic adrenal drugs), and no protein supplements taken. The exclusion criteria were as follows: have a history of severe acute altitude sickness; have contraindicative health conditions (such as cardiovascular diseases such as hypertension, lung diseases, muscle and joint diseases). All participants provided written informed consent and the study was approved by the local University Human Research Ethics Committee (Approval No. HE651425).

Experimental design

This study was a single-blind randomized controlled trial that compared the changes in muscle strength and endurance, muscle and fat layer thickness, athletic physical performance, blood lactate, resting serum growth hormone, superoxide dismutase among three groups of participants after a 5-week experimental intervention. The participants were randomly divided into three experimental groups: normoxic low-load (50% 1RM) resistance training group (RT, $n = 10$), hypoxic (FiO₂ = 13.6%) low-load (50% 1RM) resistance training group (RTH, $n = 10$), and normoxic low-load (50% 1RM) resistance training combined with protein supplementation group (RTP, $n = 10$).

Throughout the 5-week training intervention, the RTP group continuously ingested a commercially available egg-white protein supplement (L-bumax Gold, KKU Select, Khon Kaen University, Thailand) as an additional protein source. Each bottle contained 30 tablets with a total net weight of 36 g, corresponding to approximately 1.2 g per tablet. According to the manufacturer, one tablet is equivalent to the protein content of one local chicken egg white.

The supplement is derived from pasteurized egg whites of indigenous Thai chickens and is characterized by high quality protein and branched chain amino acids (BCAA), as well as the rich proline and glycine, which are associated with immune support, collagen type I synthesis, and tissue repair. In this study, participants in RTP group consumed the supplement twice daily following each main meal; specifically, two tablets were ingested after breakfast, lunch, and dinner, resulting in a total daily intake of six tablets. The RTH group inhaled normobaric hypoxic gas via a hypoxic generator (ATS-HP Hyperoxic; Altitude Technology Solutions Company, Ltd., Australia).

Each participant underwent an identical series of tests conducted by the same researcher before and after the experiment period.

The detailed timeline of training and testing is presented in Figure 1.

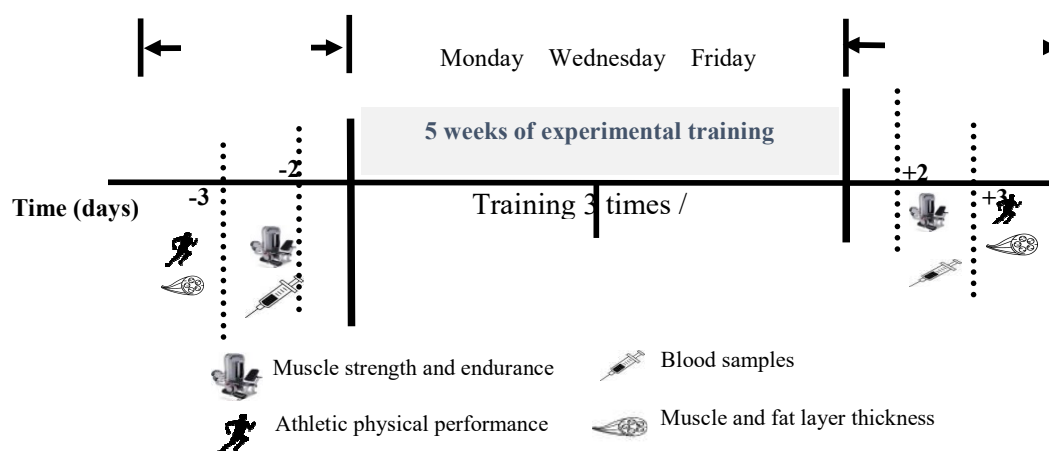


Figure 1. Outline of training and testing schedule.

Participants were instructed to maintain their normal dietary and physical activities throughout the study period. They were required to refrain from strenuous physical activities, as well as from staying up late, consuming alcohol, and caffeine, 72 hours prior to performance testing. During the study period, participants continued to engage in their respective sports team training but ceased any additional resistance training outside of the study protocol.

Training program

All participants utilized resistance training machines (knee extension: Nautilus One™ S6LE, USA; knee flexion: Nautilus EVOTM S9LCP, USA) to perform bilateral knee extension and flexion exercises in seated and prone positions (ranging from 0° to 90°, with 0° representing full extension). The resistance training regimen lasted for 5 weeks, with three sessions per week on Mondays, Wednesdays, and Fridays. Participants initially engaged in seated knee extension exercises, followed by prone knee flexion exercises. The training load was set at 50% 1RM for each exercise. Each exercise consisted of three sets, with 15 repetitions per set and a 60-second inter-set rest interval. Under the guidance of a metronome, participants performed eccentric and concentric movements rhythmically, with each movement lasting 2 seconds and the range of motion for the knee joint being 90 degrees. Participants in the RTH group breathed through a respiratory mask connected to a hypoxic generator (ATS-HP Hyperoxic; Altitude Technology Solutions Company, Ltd., Australia), with the inspired oxygen level set at Grade 9.0 (simulating an altitude of 3,420 meters, $FiO_2 = 13.6\%$). In contrast, participants in the RT and RTP groups breathed room air. Additionally, the RTP group also took egg-white protein supplement for additional protein supplementation during the training period. Prior to each training session, all participants performed a 10-minute standardized warm-up, which included 7 minutes of cycling on a power bike (Monark cycle 828E, at a cadence of 50–55 rpm) and 3 minutes of stretching the leg muscles. During the experiment, participants did not report any discomfort.

Measures

Muscle strength and endurance measurement

The tests were conducted under normoxic conditions, with knee extension and flexion assessments performed using a stationary weight machine (knee extension: Nautilus One™ S6LE, USA; knee flexion: Nautilus EVOTM S9LCP, USA). We used the 10RM protocol and the formula proposed by Brzycki (Brzycki, 1993) ($1RM = \text{weight lifted} / [1.0278 - (0.0278 \times \text{repetitions})]$) to estimate muscle strength (1RM). The initial weight for the test was determined by the participants themselves as the weight they believed they could lift for 10 repetitions. If a participant was able to complete 10 repetitions, the weight was increased after a sufficient rest period, until the participant could no longer complete 10 repetitions at a given weight. Prior to the test, participants completed a 10-minute standardized warm-up. The training load was based on the 1RM measured prior to the experiment. After the 1RM test, participants rested for 90 minutes and then performed knee extension and flexion at a load of 50% 1RM on the same machine until exhaustion. Muscle endurance was measured by recording the maximum number of repetitions each participant could complete.

Muscle and fat layer thickness measurement

The thickness of the rectus femoris and the subcutaneous fat on the anterior aspect of the thigh were measured at the midpoint between the anterior superior iliac spine and the medial condyle of the femur, with the participants maintaining a supine position with their legs fully extended. The thickness of the biceps femoris and the subcutaneous fat on the posterior aspect of the thigh were measured at the midpoint between the ischial tuberosity and the lateral condyle of the femur, with the participants maintaining a prone position with their legs fully extended. All measurements were performed by the same physician using an ultrasound scanner (LOGIQ e,

GE Model Co., Ltd., USA) equipped with a 5-13 Hz linear probe transducer, who was blinded to the participants' group assignments. Each measurement site was assessed twice, and the mean value was recorded. To avoid the influence of muscle swelling on the measurement results, the thickness of the muscle and fat layers was measured 3 days before the first training session and 3 days after the last training session.

Blood Sampling and analyses

In accordance with standard phlebotomy procedures, venous blood samples (10 mL) were collected from the antecubital vein of each participant by qualified medical technicians. Collections occurred two days prior to the initial training session and two days following the final training session. All samples were subsequently analyzed using a fully automated hematology analyzer (Cobas e411; Roche Diagnostics Co., Ltd., Tokyo, Japan). Participants' blood lactate concentration was measured by analyzing fingertip blood samples collected before training, immediately post-training, and 15 minutes post-training during both the first and last training sessions, using an automated blood analyzer (Accutrend Plus system; Roche Diagnostics Co., Ltd., USA).

Athletic physical performance measurement

All participants completed a series of physical fitness tests 1 to 3 days before and after the 5-week training intervention period, with each test performed twice and the best score recorded for subsequent analysis. All tests were conducted at the same time of day and under similar temperature conditions. Countermovement jump height (CMJH) was assessed to evaluate lower limb muscular power using a kinematic measurement system (Fitness Technology Pty Ltd, Australia; 0.001 s resolution), with jump height derived from flight time ($\text{height} = g \times \text{time}^2/8$, where $g = 9.81 \text{ m/s}^2$). Agility was evaluated using the arrowhead agility test, requiring participants to sprint maximally through a series of markers following a prescribed path. Sprint speed was measured over 20 m from a stationary start. Maximal aerobic capacity ($\dot{V}\text{O}_{2\text{max}}$) was estimated using a standard Åstrand-Rhyming protocol.

Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics (Version 28.0; IBM Corp., Armonk, NY, USA). All data were presented as mean $\pm$ standard deviation (SD). Firstly, the normality of the data was evaluated using the Shapiro-Wilk test, while the homogeneity of the data was assessed using Levene's test. If the data are normally distributed, a paired-sample t-test was used to evaluate the intra-group differences in the measured data before and after the experiment. And one-way ANOVA was used to evaluate the inter group differences in the changes in various indicators (post-test minus pre-test). If there was a significant overall group effect, post hoc testing (Bonferroni for homogeneous variance and Tamhane's T2 test for heterogeneous variance) were used for inter group comparison. If the data were not normally distributed, the Wilcoxon Signed-Rank Test from non-parametric tests was employed to evaluate within-group differences in measured data before and after the experiment, while the Kruskal-Wallis H Test was utilized to assess between-group differences in delta values (post-test minus pre-test) for each indicator. P values less than 0.05 were considered to be statistically significant.

Results

The general characteristics and baseline measurement results of three groups (RT, RTH, RTP) were shown in Table 1. It can be seen that before the experiment, there were no significant differences in the variables among each group.

Table 1. Athletes' characteristics in the 3 training groups.

Characteristics	RT (n = 10)	RTH (n = 10)	RTP (n = 10)	P-Value (Overall difference)
Age (year)	21.60 $\pm$ 0.90	21.80 $\pm$ 1.20	22.10 $\pm$ 1.40	0.896
Height (cm)	176.30 $\pm$ 5.70	175.00 $\pm$ 6.13	172.40 $\pm$ 2.88	0.239
Weight (kg)	72.60 $\pm$ 18.08	71.63 $\pm$ 15.94	62.94 $\pm$ 7.41	0.280
BMI (kg/m ²)	23.18 $\pm$ 4.63	23.27 $\pm$ 4.27	21.18 $\pm$ 2.57	0.418
Resting heart rate (bpm)	72.40 $\pm$ 12.37	71.20 $\pm$ 13.40	63.70 $\pm$ 6.41	0.187
SBP (mm Hg)	119.00 $\pm$ 12.09	114.50 $\pm$ 9.36	123.80 $\pm$ 10.23	0.187
DBP (mm Hg)	71.10 $\pm$ 6.76	71.80 $\pm$ 7.38	76.40 $\pm$ 6.87	0.204

Values are presented as means $\pm$ SD. BMI = body mass index; SBP = systolic blood pressure; DBP = diastolic blood pressure; cm = centimeter; kg = kilograms; kg/m² = kilograms per square meter; bpm = beat per minute; mm Hg = millimeters of mercury; ml/kg/min = milliliters per kilogram of body weight per minute; n = number of participants; RT = resistance training group; RTH = resistance training combined with hypoxia; RTP = resistance training combined with protein supplementation. No significant differences were found between the three groups for any variable.

As shown in Table 2, following the 5-week training intervention, neither the rectus femoris nor biceps femoris thickness showed significant changes in the RT group ($P > 0.05$). In contrast, the RTH group demonstrated significant increases in both rectus femoris thickness (0.35 ± 0.29 cm, $P = 0.015$) and biceps femoris thickness (0.54 ± 0.36 cm, $P = 0.001$). Similarly, the RTP group exhibited significant increases in rectus femoris thickness (0.32 ± 0.35 cm, $P = 0.027$) and biceps femoris thickness (0.47 ± 0.52 cm, $P = 0.027$), though these increases were less pronounced than those observed in the RTH group.

Post hoc analysis revealed no statistically significant intergroup differences among the three conditions. Additionally, no significant alterations in leg fat layer thickness were observed in any group after experiment ($P > 0.05$).

Table 2. Mean changes in muscle and fat layer thickness in all 3 training groups after 5-week training.

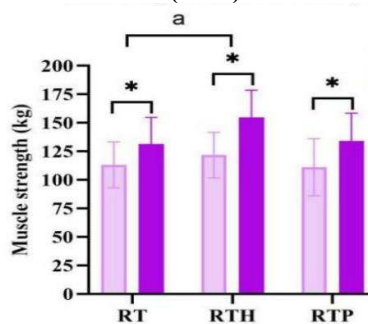
Parameters	RT (n = 10)			RTH (n = 10)			RTP (n = 10)			P-Value (overall difference of changes)
	Pre	Post	Changes	Pre	Post	Changes	Pre	Post	Changes	
Muscle thickness (cm)										
Rectus Femoris	2.27 ± 0.33	2.37 ± 0.29	0.11 ± 0.43	2.26 ± 0.28	2.61 ± 0.40 *	0.35 ± 0.29	2.18 ± 0.19	2.50 ± 0.38 *	0.32 ± 0.35	0.337
Biceps Femoris	2.49 ± 0.55	2.79 ± 0.70	0.31 ± 0.61	2.90 ± 0.74	3.43 ± 0.59 *	0.54 ± 0.36	2.41 ± 0.39	2.88 ± 0.40 *	0.47 ± 0.52	
Fat layer thickness (cm)										
Rectus Femoris	0.68 ± 0.34	0.67 ± 0.38	-0.01 ± 0.07	0.67 ± 0.24	0.66 ± 0.25	-0.02 ± 0.05	0.62 ± 0.20	0.64 ± 0.18	0.02± 0.07	0.501
Biceps Femoris	0.77± 0.32	0.79 ± 0.33	0.02 ± 0.09	0.68 ± 0.22	0.66 ± 0.18	-0.02 ± 0.07	0.66 ± 0.20	0.67 ± 0.20	0.01 ± 0.09	

* $p < 0.05$ vs. pre-test within group

After the 5-week intervention, all groups showed significant improvements in muscle strength and endurance compared to baseline (within-group comparisons, $p < 0.05$), with the RTH group demonstrating the greatest increases across all four tested parameters. One-way ANOVA revealed significant overall group differences in the change of knee extension strength (1RM) ($p = 0.039$) and knee extension muscular endurance (repetitions at 50% 1RM) ($p = 0.041$).

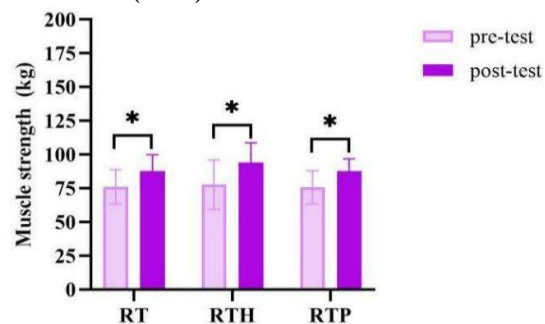
Consistent with the trends observed in muscle thickness, RTH athletes exhibited the highest gain in knee extension maximal strength (33.11 ± 15.81 kg), which was significantly greater than that of the RT group (18.38 ± 7.26 kg, post-hoc $p = 0.044$). Similarly, the RTH group showed a significantly larger improvement in knee extension muscular endurance (7.33 ± 2.45 reps) compared to the RT group (4.22 ± 2.73 reps, post-hoc $p = 0.038$). The RTP group also demonstrated greater increases in both maximal strength and muscular endurance than the RT group, although these differences did not reach statistical significance ($p > 0.05$) (Figure 2).

Knee extension (1RM)



Knee extension (No. of reps at 50% 1RM)

Knee flexion (1RM)



Knee flexion (No. of reps at 50% 1RM)

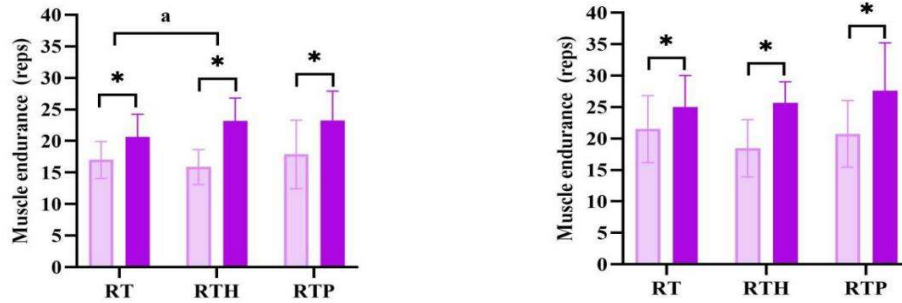


Figure 2. Changes in muscle strength (kg) and muscle endurance (reps) in knee extension and flexion. Data are mean $\pm$ SD. * $p < 0.05$ vs. pre-test within group; ^a $p < 0.05$ vs. RT group (post-hoc).

As shown in Table 3, after 5 weeks of training, there were no significant changes in the test indicators related to athletic physical performance in both the RT group and RTP group. CMJH and $\dot{V}O_{2\max}$ test of the RTH group were significantly improved compared to the baseline (1.49 ± 1.35 cm, $p = 0.017$; 2.59 ± 1.05 ml/kg/min, $P < 0.001$). One-way ANOVA revealed a significant overall group difference in the change of $\dot{V}O_{2\max}$ ($p = 0.020$), with post-hoc analysis indicating that the improvement in the RTH group was significantly greater than that in the RT group ($p = 0.046$). No significant between-group differences were observed for CMJH, agility, or 20-m sprint speed ($p > 0.05$ for all).

Table 3. Mean changes in athletic physical performance in all 3 training groups after 5-week training.

Parameters	RT (n = 10)			RTH (n = 10)			RTP (n = 10)			P-Value (overall difference of changes)
	Pre	Post	Changes	Pre	Post	Changes	Pre	Post	Changes	
CMJH (cm)	36.03 $\pm$ 2.15	36.50 $\pm$ 2.11	0.47 $\pm$ 2.11	39.75 $\pm$ 3.75	41.24 $\pm$ 4.56*	1.49 $\pm$ 1.35	37.59 $\pm$ 2.67	38.69 $\pm$ 1.57	1.10 $\pm$ 2.73	0.632
Arrow head	9.16 $\pm$ 0.37	9.15 $\pm$ 0.39	-0.01 $\pm$ 0.29	9.17 $\pm$ 0.41	8.98 $\pm$ 0.26	-0.19 $\pm$ 0.30	9.29 $\pm$ 0.71	9.21 $\pm$ 0.68	-0.08 $\pm$ 0.27	0.375
Agility (s)	3.18 $\pm$ 0.18	3.25 $\pm$ 0.15	0.07 $\pm$ 0.11	3.21 $\pm$ 0.17	3.29 $\pm$ 0.11	0.07 $\pm$ 0.12	3.15 $\pm$ 0.18	3.25 $\pm$ 0.15	0.10 $\pm$ 0.26	0.943
Speed 20 m (s)	38.61 $\pm$ 6.63	39.33 $\pm$ 6.85	0.72 $\pm$ 1.63	40.18 $\pm$ 6.65	42.78 $\pm$ 7.02*	2.59 $\pm$ 1.05 ^a	42.40 $\pm$ 8.05	43.42 $\pm$ 7.28	1.02 $\pm$ 1.78	0.020
$\dot{V}O_{2\max}$ ml/kg/min										

* $p < 0.05$ vs. pre-test within group. $\dot{V}O_{2\max}$ = Maximal oxygen uptake; ^a $p < 0.05$ vs. RT group (post-hoc).

After the experiment, only the RTH group showed a significant increase in SOD levels relative to baseline values (1.10 ± 1.13 U/mL, $P = 0.029$), while no significant differences were observed in the other two groups. Despite the observed increase in the RTH group, the training-induced SOD changes showed no significant intergroup differences (Figure 3). Furthermore, after five weeks of training intervention, all three groups demonstrated significant decreases in resting serum GH levels compared to baseline values ($P < 0.05$). However, no significant differences were observed in the magnitude of changes among the groups ($P = 0.379$).

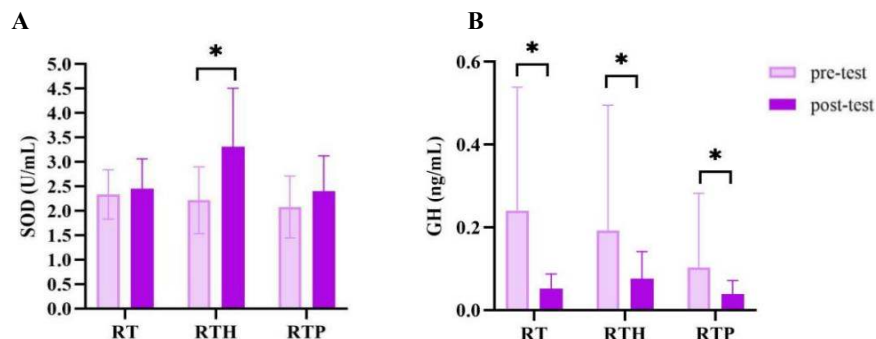


Figure 3. Change in SOD (A) and resting serum GH (B) before and after 5-week training. Values are present as mean $\pm$ SD. * significant $p < 0.05$ (pre-test vs. post-test).

After the first training session, blood lactate concentrations increased approximately 3-4 times compared to baseline values, but no significant differences were observed among groups at all three measurement time points (Figure 4). After 5 weeks of training, only the RTH group showed a significant increase in blood lactate concentrations ($10.78 \pm 2.08 \text{ mmol} \cdot \text{L}^{-1}$; $7.14 \pm 1.95 \text{ mmol} \cdot \text{L}^{-1}$) at both the immediate post-training and 15-minute post-training time points compared to baseline values ($8.33 \pm 1.86 \text{ mmol} \cdot \text{L}^{-1}$; $5.64 \pm 1.87 \text{ mmol} \cdot \text{L}^{-1}$). Additionally, the blood lactate concentrations measured immediately after the final training session in the RTH group was $2.45 \pm 1.14 \text{ mmol} \cdot \text{L}^{-1}$ higher than that measured immediately after the first training session, which was significantly greater than the increases observed in the RT group and RTP group ($0.74 \pm 1.17 \text{ mmol} \cdot \text{L}^{-1}$; $0.78 \pm 1.61 \text{ mmol} \cdot \text{L}^{-1}$).

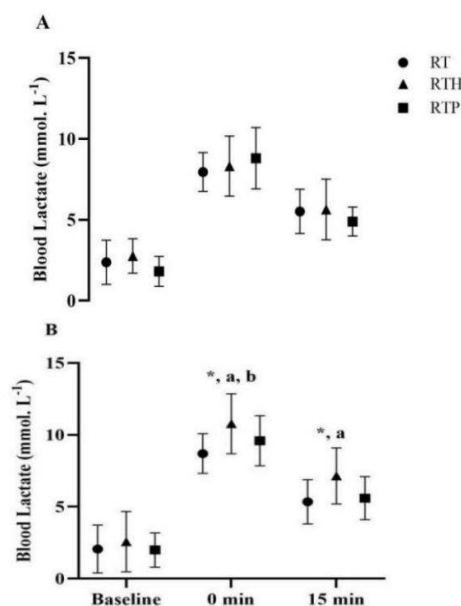


Figure 4. Change in blood lactate concentration before, immediately post, 15 min after the first training session (A) and last training session (B). * Significant $p < 0.05$ (First training session vs. Last training session), ^a significant $p < 0.05$ (RTH vs. RT), ^b significant $p < 0.05$ (RTH vs. RTP)

Discussion

This 5-week study examined how combining low-load resistance training (RT) with systemic hypoxia (RTH) or protein supplementation (RTP) affects team-sport athletes. The principal finding was that RTH elicited broad spectrum adaptations, significantly enhancing muscular strength, endurance, athletic performance, and the body's antioxidant defense system. In contrast, RTP effectively promoted muscle hypertrophy but provided no significant advantage in functional performance or antioxidant capacity over low-load RT alone.

The RTH group demonstrated the most pronounced improvements in dynamic knee extension strength and muscular endurance, with gains significantly exceeding those of the RT group. This finding corroborates and extends the work of several previous studies which reported that low-load resistance training in hypoxia enhanced isometric knee extension force and strength endurance more effectively than normoxic resistance training (La-bantao et al., 2025; Manimmanakorn et al., 2013). Similarly, Kurobe et al. (2015) observed greater muscle hypertrophy and strength gains following hypoxic resistance training. The physiological rationale for this adaptation likely centers on the significant amplification of metabolic stress. The markedly elevated post-exercise blood lactate concentration in the RTH group (Figure 4) is a clear biomarker of this intensified metabolic challenge. Under hypoxic conditions, the body compensates for reduced oxygen availability by increasing its reliance on anaerobic glycolysis to sustain ATP production. This leads to an accelerated accumulation of metabolites, including hydrogen ions (H^+), inorganic phosphate (Pi), and lactate. Schoenfeld (2013) has extensively theorized that such metabolic byproducts are not merely waste products but potent mediators of anabolic processes. In essence, the hypoxic environment appears to augment the stimulus per unit of mechanical work, allowing a low-load protocol to elicit a metabolic and hormonal response more characteristic of high-load training.

The RTH and RTP groups exhibited significant hypertrophy of the rectus femoris and biceps femoris. However, the underlying mechanisms likely differed. For the RTH group, the hypertrophy was probably driven by the synergistic combination of metabolic stress (as discussed above) and hypoxia-specific signaling. For the RTP group, the mechanism is more straightforward: the provision of supplemental protein, particularly rich in

the essential amino acid leucine, directly stimulates the mechanistic target of rapamycin complex 1 (mTORC1) pathway, which is the primary regulator of muscle protein synthesis (MPS) (Cermak et al., 2012; Snijders et al., 2015). The critical observation, however, is that the structural gains in the RTP group did not translate into statistically superior strength or performance compared to the RT group. This suggests several possibilities: (1) the quality of the accrued muscle mass (e.g., in terms of architecture or fiber-type composition) may have been different; (2) the 5-week intervention with protein supplementation was insufficient for hypertrophy to be fully expressed as increased force production in a functionally specific manner. This finding underscores that an increase in muscle size is not an automatic guarantee of enhanced athletic performance, a nuance that is crucial for coaches and athletes to consider.

Remarkably, superoxide dismutase (SOD) activity was significantly elevated only in the RTH group. Although the intergroup differences did not reach statistical significance, the within-group elevation in SOD activity exclusively in the RTH group suggests a hypoxia-specific antioxidant adaptive response. SOD is a primary antioxidant that converts superoxide radicals into hydrogen peroxide and oxygen, shielding cells from oxidative damage. This shielding is crucial since exercise naturally drives up reactive oxygen species (ROS) through mitochondrial and Nicotinamide adenine dinucleotide phosphate (NADPH) oxidase activities (Powers & Jackson, 2008). Controlled ROS increases are essential signals for training adaptations, activating kinases that drive mitochondrial biogenesis and glucose transport. Consequently, upregulating antioxidant enzymes like SOD represents a fundamental adaptive response to manage this oxidative stress (Ristow & Schmeisser, 2014). The lack of a significant SOD response suggests low-load RT alone did not induce enough oxidative stress to trigger antioxidant defenses in these trained athletes, who likely possessed a robust baseline capacity (Michailidis et al., 2007). Hypoxia powerfully amplifies oxidative stress, as reduced oxygen tension causes electron leaks in the electron transport chain, paradoxically increasing mitochondrial superoxide production (Burtcher et al., 2021). This ROS signal activates Nrf2, which translocates to the nucleus and binds the antioxidant response element, driving the transcription of cytoprotective genes like SOD (Merry & Ristow, 2016). Consequently, the hypoxic stimulus provided the necessary redox signal to trigger this adaptive antioxidant response, which normoxic training lacked. Meanwhile, the lack of effect in the RTP group indicates that protein supplementation provided no significant antioxidant boost. While some studies, particularly in untrained individuals or using whey protein, show enhanced antioxidant capacity (Goldfarb et al., 2008), the results suggest that protein's antioxidant effects in trained athletes are muted and likely dependent on the protein source and broader dietary context. Simultaneously, the metabolic data highlights each intervention's physiological impact. The RTH group's elevated, prolonged blood lactate confirms a greater reliance on anaerobic glycolysis, aligning with hypoxia's known role in upregulating glycolytic enzymes via HIF-1 α (Mason et al., 2007). Producing, tolerating, and clearing high lactate levels is a hallmark of athletic metabolic fitness. The classic view of lactate as a mere fatigue agent has been replaced by the "lactate shuttle" theory, which establishes lactate as a valuable energy substrate shuttled between cells and tissues (e.g., from glycolytic to oxidative muscle fibers, or to the heart and liver) for oxidation (Brooks, 2009).

The RTH group's enhanced lactate production and presumably improved clearance capacity contributed directly to their superior performance in the high-repetition muscular endurance test at 50% 1RM.

A particularly noteworthy outcome was the significant increase in $\dot{V}O_{2\max}$ observed exclusively in the RTH group, with the change being significantly greater than that in the RT group. This finding challenges the conventional paradigm that resistance training has minimal impact on aerobic capacity and suggests that the RTH intervention provided a unique, dual stimulus. The improvement in $\dot{V}O_{2\max}$ indicates that the training induced positive adaptations in the oxygen transport and utilization system, likely through central (e.g., increased plasma volume, stroke volume) and peripheral mechanisms.

The primary peripheral mechanism likely involves hypoxia-inducible factor-1 α (HIF-1 α) activation. Under low oxygen, stabilized HIF-1 α upregulates genes for erythropoietin (EPO) and vascular endothelial growth factor (VEGF). It also interacts with and upregulates PGC-1 α , the central regulator of mitochondrial biogenesis (Mason et al., 2007). An increase in mitochondrial density and efficiency within the trained musculature would enhance oxidative phosphorylation capacity. This improvement in aerobic metabolism provides a more robust bioenergetic foundation for ATP resynthesis during and between bouts of exercise, directly contributing to the enhanced local muscular endurance observed in the RTH group (Ramos-Campo et al., 2018b). Therefore, hypoxic low-load RT can be viewed as an efficient method of concurrent training, simultaneously stimulating both strength oriented and endurance oriented adaptive pathways.

The non-significant changes in resting growth hormone (GH) levels, despite clear structural and functional gains, offer important endocrinological insights. This suggests single, resting measurements of systemic GH are poor biomarkers for training-driven anabolic processes. Unlike studies that reported acute post-exercise GH spikes following hypoxic exercise (Kon et al., 2012), our resting measurements did not capture these transient responses, highlighting that chronic resting GH levels may not reflect the acute anabolic hormonal milieu. Instead, resistance training especially under high metabolic stress is well-known to cause robust but highly transient GH spikes shortly after exercise (Kraemer & Ratamess, 2005). Because our study did

not capture these acute spikes, the observed strength and hypertrophic adaptations were likely governed by local, intra-muscular mechanisms independent of systemic GH fluctuations. These include: (1) Mechanotransduction, where physical tension activates anabolic signaling cascades like the mTOR pathway; and (2) Local IGF-1 Signaling, where mechanical load stimulates autocrine/paracrine production of insulin-like growth factor-1 (IGF-1) directly within the muscle to promote hypertrophy (Adams, 2002). (3) Satellite Cell Activity: Both mechanical strain and metabolic factors can activate satellite cells, which are essential for muscle repair and growth (Snijders et al., 2016; Snijders et al., 2015). The fact that substantial adaptation occurred without a change in resting GH underscores the primacy of these local mechanisms in the training response.

This study has several limitations. The 5-week intervention may have been too brief to observe full adaptations in body composition or hormonal regulation. The lack of dietary control prevents confirmation of whether protein supplementation provided a true surplus beyond habitual intake. Future studies should employ longer interventions, strict dietary control, and methodologies like muscle biopsies and acute hormone measurements to precisely delineate the molecular mechanisms of hypoxic low-load RT. Research comparing different hypoxic doses, protein sources, and long-term efficacy is also warranted.

Conclusions

This 5-week study demonstrates that low-load resistance training under systemic hypoxia yields superior, multifaceted adaptations in team-sport athletes compared to equivalent normoxic training or protein supplementation. Specifically, the hypoxic stimulus significantly augmented maximal dynamic strength, local muscular endurance, muscle thickness, and antioxidant defense over the intervention period. These enhanced responses were likely mediated by the amplification of metabolic stress, as corroborated by the pronounced elevation of blood lactate concentrations in the hypoxic group. From an applied perspective, when high mechanical loads are contraindicated due to injury or dense competitive schedules, incorporating portable normobaric hypoxic devices during low-load resistance training provides a viable method to compensate for reduced mechanical tension by intentionally increasing metabolic strain. Conversely, although egg-white protein supplementation effectively induced muscle hypertrophy, it did not confer additional functional or antioxidant benefits beyond those achieved with normoxic training alone.

Nevertheless, several avenues warrant further investigation. Future studies should employ longer intervention periods and more diverse athletic cohorts to confirm the sustainability of these findings. Furthermore, integrating molecular methodologies, such as muscle biopsies, will be crucial to directly elucidate the mechanistic pathways, including mTOR signaling and HIF-1 α expression. Evaluating the dose-response relationship of various hypoxic concentrations and exploring alternative protein sources will also be essential for optimizing future training prescriptions. Ultimately, integrating systemic hypoxic stimuli into low-load protocols represents a highly efficient and safe training paradigm to sustain neuromuscular adaptations during periods of load management.

Conflicts of interest The authors declare no conflicts of interest. The results of this study do not constitute the author's endorsement of this hypoxicator.

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References:

- Adams, G. R. (2002). Invited Review: Autocrine/paracrine IGF-I and skeletal muscle adaptation. *Journal of Applied Physiology*, 93(3), 1159-1167. <https://doi.org/10.1152/jappphysiol.01264.2001>
- Bird, S. P., Nienhuis, M., Biagioli, B., De Pauw, K. D., & Meeusen, R. (2024). Supplementation Strategies for Strength and Power Athletes: Carbohydrate, Protein, and Amino Acid Ingestion. *Nutrients*, 16(12), 1886. <https://doi.org/10.3390/nu16121886>
- Brocherie, F., Millet, G. P., D'Hulst, G., Van Thienen, R., Deldicque, L., & Girard, O. (2018). Repeated maximal-intensity hypoxic exercise superimposed to hypoxic residence boosts skeletal muscle transcriptional responses in elite team-sport athletes. *Acta Physiologica*, 222(1), e12851. <https://doi.org/10.1111/apha.12851>

-
- Brocherie, F., Millet, G. P., Hauser, A., Steiner, T., Rysman, J., Wehrin, J. P., & Girard, O. (2015). "Live high–train low and high" hypoxic training improves team-sport performance. *Medicine and Science in Sports and Exercise*, 47(10), 2140-2149. <https://doi.org/10.1249/MSS.0000000000000630>
- Brooks, G. A. (2009). Cell–cell and intracellular lactate shuttles. *Journal of Physiology*, 587(23), 5591-5600. <https://doi.org/10.1113/jphysiol.2009.178350>
- Brzycki, M. (1993). Strength testing—predicting a one-rep max from reps-to-fatigue. *Journal of Physical Education, Recreation & Dance*, 64(1), 88-90. <https://doi.org/10.1080/07303084.1993.10606684>
- Burtscher, J., Mallet, R. T., Burtscher, M., & Millet, G. P. (2021). Hypoxia and brain aging: Neurodegeneration or neuroprotection? *Ageing Research Reviews*, 68, 101343. <https://doi.org/10.1016/j.arr.2021.101343>
- Cermak, N. M., Res, P. T., de Groot, L. C., Saris, W. H., & van Loon, L. J. (2012). Protein supplementation augments the adaptive response of skeletal muscle to resistance-type exercise training: a meta-analysis. *American Journal of Clinical Nutrition*, 96(6), 1454-1464. <https://doi.org/10.3945/ajcn.112.037556>
- Chelly, M. S., Fathloun, M., Cherif, N., Ben Amar, M., Tabka, Z., & Van Praagh, E. (2009). Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *Journal of Strength and Conditioning Research*, 23(8), 2241-2249. <https://doi.org/10.1519/JSC.0b013e3181b86c40>
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Medicine*, 41(2), 125-146. <https://doi.org/10.2165/11538500-000000000-00000>
- De Smet, S., van Herpt, P., D'Hulst, G., Van Thienen, R., Van Leemputte, M., & Hespel, P. (2017). Physiological Adaptations to Hypoxic vs. Normoxic Training during Intermittent Living High. *Frontiers in Physiology*, 8, 347. <https://doi.org/10.3389/fphys.2017.00347>
- Figueiredo, V. C., & Cameron-Smith, D. (2013). Is carbohydrate needed to further stimulate muscle protein synthesis/hypertrophy following resistance exercise? *Journal of the International Society of Sports Nutrition*, 10(1), 42. <https://doi.org/10.1186/1550-2783-10-42>
- Goldfarb, A. H., Garten, R. S., Chee, P. D. M., Cho, C., Reeves, G. V., Hollander, D. B.,...Kraemer, R. R. (2008). Resistance exercise effects on blood glutathione status and plasma protein carbonyls: influence of partial vascular occlusion. *European Journal of Applied Physiology*, 104(5), 813-819. <https://doi.org/10.1007/s00421-008-0836-1>
- Griffen, C., Duncan, M., Hattersley, J., Weickert, M. O., Dallaway, A., & Renshaw, D. (2022). Effects of resistance exercise and whey protein supplementation on skeletal muscle strength, mass, physical function, and hormonal and inflammatory biomarkers in healthy active older men: a randomised, double-blind, placebo-controlled trial. *Experimental Gerontology*, 158, 111651. <https://doi.org/10.1016/j.exger.2021.111651>
- Kerksick, C. M., & Leutholtz, B. (2005). Nutrient Administration and Resistance Training. *Journal of the International Society of Sports Nutrition*, 2(1), 50-67. <https://doi.org/10.1186/1550-2783-2-1-50>
- Kon, M., Ikeda, T., Homma, T., & Suzuki, Y. (2012). Effects of Low-Intensity Resistance Exercise Under Acute Systemic Hypoxia on Hormonal Responses. *Journal of Strength and Conditioning Research*, 26(3), 611-617. <https://doi.org/10.1519/JSC.0b013e3182281c69>
- Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Medicine and Science in Sports and Exercise*, 36(4), 674-688. <https://doi.org/10.1249/01.mss.0000121945.36635.61>
- Kraemer, W. J., & Ratamess, N. A. (2005). Hormonal responses and adaptations to resistance exercise and training. *Sports Medicine*, 35(4), 339-361. <https://doi.org/10.2165/00007256-200535040-00004>
- Kurobe, K., Huang, Z., Nishiwaki, M., Yamamoto, M., Kanehisa, H., & Ogita, F. (2015). Effects of resistance training under hypoxic conditions on muscle hypertrophy and strength. *Clinical Physiology and Functional Imaging*, 35(3), 197-202. <https://doi.org/10.1111/cpf.12147>
- La-bantao, K., Manimmanakorn, A., Hamlin, M. J., Manimmanakorn, N., Huang, Q., Namboonlue, C.,...Nithisup, P. (2025). Hypoxia and venous occlusion improve muscular performance but no effect on growth hormone in athletes. *Retos*, 73, 1076-1089. <https://doi.org/10.47197/retos.v73.117374>
- Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: a systematic review, qualitative analysis and meta-analysis. *British Journal of Sports Medicine*, 52(24), 1557-1563. <https://doi.org/10.1136/bjsports-2018-099078>
- Manimmanakorn, A., Hamlin, M. J., Ross, J. J., Taylor, R., & Manimmanakorn, N. (2013). Effects of low-load resistance training combined with blood flow restriction or hypoxia on muscle function and performance in netball athletes. *Journal of Science and Medicine in Sport*, 16(4), 337-342. <https://doi.org/10.1016/j.jsams.2012.08.009>
- Mason, S. D., Rundqvist, H., Papandreou, I., Duh, R., McNulty, W. J., Howlett, R. A.,...Poellinger, L. (2007). HIF-1 α in endurance training: suppression of oxidative metabolism. *American Journal of Physiology*:
-

-
- Regulatory, Integrative and Comparative Physiology*, 293(5), R2059-R2069.
<https://doi.org/10.1152/ajpregu.00242.2016>
- Merry, T. L., & Ristow, M. (2016). Do antioxidant supplements interfere with skeletal muscle adaptation to exercise training? *Journal of Physiology*, 594(18), 5135-5147. <https://doi.org/10.1113/jp270654>
- Michailidis, Y., Jamurtas, A. Z., Nikolaidis, M. G., Fatouros, I. G., Koutedakis, Y., Papassotiriou, I., & Kouretas, D. (2007). Sampling time is crucial for measurement of aerobic exercise-induced oxidative stress. *Medicine and Science in Sports and Exercise*, 39(7), 1107-1113.
<https://doi.org/10.1249/01.mss.0b013e318053e7ba>
- Morton, R. W., Murphy, K. T., McKellar, S. R., Schoenfeld, B. J., Henselmans, M., Helms, E.,...Phillips, S. M. (2018). A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. *British Journal of Sports Medicine*, 52(6), 376-384. <https://doi.org/10.1136/bjsports-2017-097608>
- Namboonlue, C., Hamlin, M. J., Sirasaporn, P., Manimmanakorn, N., Wonnabussapawich, P., Thuwakum, W.,...Manimmanakorn, A. (2020). Optimal degree of hypoxia combined with low-load resistance training for muscle strength and thickness in athletes. *Journal of Physical Education and Sport*, 20(2), 828-838. <https://doi.org/10.7752/jpes.2020.02119>
- Nimphius, S., McGuigan, M. R., & Newton, R. U. (2010). Relationship between strength, power, speed, and change of direction performance of female softball players. *Journal of Strength and Conditioning Research*, 24(4), 885-895. <https://doi.org/10.1519/JSC.0b013e3181d4d41d>
- Powers, S. K., & Jackson, M. J. (2008). Exercise-induced oxidative stress: cellular mechanisms and impact on muscle force production. *Physiological Reviews*, 88(4), 1243-1276.
<https://doi.org/10.1152/physrev.00031.2007>
- Radak, Z., Chung, H. Y., & Goto, S. (2005). Exercise and hormesis: oxidative stress-related adaptation for successful aging. *Biogerontology*, 6(1), 71-75. <https://doi.org/10.1007/s10522-004-7386-7>
- Ramos-Campo, D. J., Scott, B. R., Alcaraz, P. E., & Rubio-Arias, J. A. (2018a). The efficacy of resistance training in hypoxia to enhance strength and muscle growth: a systematic review and meta-analysis. *European journal of sport science*, 18(1), 92-103. <https://doi.org/10.1080/17461391.2017.1388850>
- Ramos-Campo, D. J., Martínez-Guardado, I., Olcina, G., Marín-Pagán, C., Martínez-Noguera, F. J., Carlos-Vivas, J.,...Rubio, J. (2018b). Effect of high-intensity resistance circuit-based training in hypoxia on aerobic performance and repeat sprint ability. *Scandinavian Journal of Medicine and Science in Sports*, 28(10), 2135-2143. <https://doi.org/10.1111/sms.13221>
- Ristow, M., & Schmeisser, K. (2014). Mitohormesis: Promoting Health and Lifespan by Increased Levels of Reactive Oxygen Species (ROS). *Dose-Response: A Publication of International Hormesis Society*, 12(2), 288-341. <https://doi.org/10.2203/dose-response.13-035.Ristow>
- Schoenfeld, B. J. (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Medicine*, 43(3), 179-194. <https://doi.org/10.1007/s40279-013-0017-1>
- Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and hypertrophy adaptations between low-vs. high-load resistance training: a systematic review and meta-analysis. *Journal of Strength and Conditioning Research*, 31(12), 3508-3523. <https://doi.org/10.1519/JSC.0000000000002200>
- Scott, B. R., Slattery, K. M., & Dascombe, B. J. (2015). Intermittent hypoxic resistance training: is metabolic stress the key moderator? *Medical Hypotheses*, 84(2), 145-149.
<https://doi.org/10.1016/j.mehy.2014.12.001>
- Snijders, T., Nederveen, J. P., Joannis, S., Leenders, M., Verdijk, L. B., van Loon, L. J. C., & Parise, G. (2016). Muscle fibre capillarization is a critical factor in muscle fibre hypertrophy during resistance exercise training in older men. *Journal of Cachexia, Sarcopenia and Muscle*, 8(2), 267-276.
<https://doi.org/10.1002/jcsm.12137>
- Snijders, T., Res, P. T., Smeets, J. S. J., van Vliet, S., van Kranenburg, J., Maase, K.,...van Loon, L. J. C. (2015). Protein Ingestion before Sleep Increases Muscle Mass and Strength Gains during Prolonged Resistance-Type Exercise Training in Healthy Young Men. *Journal of Nutrition*, 145(6), 1178-1184.
<https://doi.org/10.3945/jn.114.208371>
- Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. *Sports Medicine*, 46(10), 1419-1449. <https://doi.org/10.1007/s40279-016-0486-0>
- Thuwakum, W., Hamlin, M., Manimmanakorn, N., Leelayuwat, N., Wonnabussapawich, P., Boobpachatt, D., & Manimmanakorn, A. (2017). Low-load resistance training with hypoxia mimics traditional strength training in team sport athletes. *Journal of Physical Education and Sport*, 17(1), 240-247.
<https://doi.org/10.7752/jpes.2017.01036>
- Vollaard, N. B., Shearman, J. P., & Cooper, C. E. (2005). Exercise-induced oxidative stress: myths, realities and physiological relevance. *Sports Medicine*, 35(12), 1045-1062. <https://doi.org/10.2165/00007256-200535120-00004>
-

- Whitehouse, G., & Lawlis, T. (2017). Protein supplements and adolescent athletes: A pilot study investigating the risk knowledge, motivations and prevalence of use. *Nutrition & Dietetics*, 74(5), 509-515. <https://doi.org/10.1111/1747-0080.12367>
- Willoughby, D. S., Stout, J. R., & Wilborn, C. D. (2006). Effects of resistance training and protein plus amino acid supplementation on muscle anabolism, mass, and strength. *Amino Acids*, 32(4), 467-477. <https://doi.org/10.1007/s00726-006-0398-7>
- Zheng, M., Manimmanakorn, A., Huang, Q., La-bantao, K., Choocheepwatana, P., Chotipinit, T.,...Yang, G. (2026). Muscle Adaptations to Hypoxic Resistance Training Occur Independent of Hematological Shifts. *Journal of Exercise Physiology Online*, 29(2), 69.