

The effectiveness of blood flow restriction training in optimizing physiological indicators in elite female handball players

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Abstract:

This study explored the effectiveness of blood flow restriction (BFR) training methods as an innovative strategy for enhancing the physical fitness of elite female handball players. The research was aimed to evaluate thoroughly the efficacy of BFR-training as a tool for optimizing the physical characteristics of these athletes. Material and methods. The study involved 26 elite female athletes from the "Halychanka" women's handball club, selected based on specific criteria such as age, athletic experience, and performance level. A longitudinal, comparative design was used to assess the effects of different training programs on athletes' performance. The participants were divided into the control group and the experimental group. The study lasted within 8 weeks, during which both groups underwent a standard training program aimed at improving strength, speed and endurance performance. The experimental group additionally performed blood flow restriction exercise twice a week to develop explosive power, leg strength, and endurance. The control group performed normal strength exercises without BFR. Testing methods included repeated jump tests, Yo-Yo tests, grip strength assessments, with statistical analyses performed to evaluate pre- and post-training results. Results. The experimental group showed statistically significant improvements in explosive power, throwing accuracy, speed, and endurance compared to the control group. Enhanced muscle activation and increased levels of growth hormone (GH) and insulin-like growth factor-1 (IGF-1) were observed, contributing to muscle hypertrophy and faster recovery. Additionally, metabolic stress from BFR led to adaptations in anaerobic and aerobic systems, enhancing overall physical performance. Discussion. The results of the study supported existing evidence on the efficacy of BFR training for promoting neuromuscular adaptations and metabolic efficiency. The low-load approach reduced strain on joints while stimulating fast-twitch muscle fibers, crucial for explosive movements in handball. BFR training demonstrated significant potential for injury prevention and performance optimization in high-demand sports. Conclusions. The obtained results confirmed that the implementation of BFR training was an effective mean to improve the physical qualities which are necessary for successful performance in handball and reduces the risk of injuries due to the use of lower loads. It was recommended to integrate BFR training into the training process of handball players to achieve optimal sports results.

Key words: handball, venous outflow limitation, physical adaptation, anaerobic and aerobic endurance, metabolic adaptations, muscle hypertrophy, innovative training methods, parameters of physical fitness

Introduction

Handball, as one of the most dynamic sports, requires high physical performance from athletes, including strength, speed, endurance and coordination (Evhen & Valeria, 2017; Valeria et al, 2017; Yuriy et al, 2016). Constant changes of direction, intense jumps and the need for quick reactions during the game place serious requirements of physical fitness of players (Lisenchuk et al, 2019a; Lisenchuk et al, 2019b). Handball as an intense sport where strength, speed-power and endurance indicators, as well as the ability to withstand fatigue are of critical importance (Tyshchenko et al, 2019; Lochman et al, 2021; Tyshchenko et al, 2024). Among the new approaches in athletic training, blood flow restriction (BFR) training has gained a lot of popularity due to its ability to provide anabolic effects at much lower loads. BFR-training creates local hypoxia in the muscles, where venous outflow is limited, but arterial inflow is maintained. This forces the muscles to function in conditions of oxygen deficiency, activating anaerobic processes, in particular glycolysis, and increasing the level of lactate. Lactate increase causes the activation of anabolic hormones, such as growth hormone and testosterone, which stimulate protein synthesis and muscle hypertrophy even at low-intensity loading. Research shows that BFR can stimulate the increase in the hormones, responsible for muscle hypertrophy and recovery, which is crucially important for athletes who experience constant physical loading. Scientists consider the mechanisms by which

hypoxia affects the development of strength and endurance, which confirms the feasibility of using BFR as a method that creates a hypoxic effect to improve physical fitness. Laurentino et al. (2022) focused on the physiological mechanisms of BFR training and confirmed that blood flow restriction stimulates the secretion of anabolic hormones, such as growth hormone, which promotes hypertrophy even at light loads, and promotes anabolic processes and muscle growth (Laurentino et al., 2022). It is recorded that changes in muscle strength and size do not directly depend on a sharp increase in hormone levels, such as GH or testosterone, after training.

BFR training creates a unique metabolic stress in muscles, activating anabolic processes even with light physical loads, which is especially relevant for highly qualified athletes, who want to improve their physical performance without the risk of overloading joints and muscles (Bower, 2021). During BFR training of female handball players, the restriction of venous outflow from the muscles creates an accumulation of lactic acid and hydrogen ions, which increases the acidity inside the muscle tissues. This condition activates special receptors and helps to increase the level of growth hormone and other anabolic factors that contribute to muscle hypertrophy and strengthening of muscle fibers, which is especially important for female handball players who need high explosive power and endurance, which is necessary for effective play (Korobeynikov et al., 2019; Malikov et al., 2019; Malikov et al., 2021). Studying of the effectiveness of BFR in team sports also shows that this method promotes the development of explosive power and quick reactions, which are key skills in handball (Scott et al., 2017; Chen et al., 2022; Korkmaz et al., 2022).

Consideration of the effectiveness of BFR training shows that blood flow restriction training improves motor coordination and reaction speed (Yang et al., 2024; Bommasamudram et al., 2024), which is important for handball, where the ability to change quickly the direction of movement and adaptation to changing game situations is important (Tishchenko, 2016; Valeria & Olexander, 2015; Tyshchenko et al., 2020). Due to its specific effect on the neuromuscular system, BFR contributes to the improvement of neuromuscular coordination, which increases the speed of reaction, necessary for the successful execution of technical methods and reduces the risk of injury due to incoordination of movements (Da Silva-Grigoletto et al., 2020; Cook et al., 2018). Existing studies have demonstrated the effectiveness of BFR in developing muscular strength and endurance in various athletic populations. However, the application of this method in team sports, particularly for female handball players, remains underexplored. The lack of specific research assessing the physiological and performance-based outcomes of BFR in this context highlights a gap that this research aims to address. By focusing on elite female handball players, this research seeks to provide evidence-based recommendations for integrating BFR training into their routines to optimize physical performance and reduce injury risks.

The need for this research stems from the increasing pressure on athletes to maintain peak performance across multiple competitions while avoiding physical overloading. Traditional high-intensity training methods, although effective, often pose risks of overtraining and joint strain. In contrast, BFR offers a safer alternative, enabling athletes to achieve similar or higher results with lower loads. However, despite the growing interest in BFR trainings, there is a shortage of works that directly assess their effectiveness in the context of training female handball players. Thus, the study of their effectiveness in the training of elite female handball players is an actual and promising direction, capable of offering new approaches to optimize the training process, reducing the risk of injury and contributing to the achievement of high sports results.

The aim of the research is to assess comprehensively the effectiveness of the use of BFR-training as an innovative tool for optimizing the physical parameters of elite female handball players.

Materials and methods.

Participants. 26 elite female athletes of the "Halychanka" women's handball club (average age – 23.4 ± 2.1 years), who had at least 5 years of competitive experience participated in the study.

Procedure / Test protocol / Skill test trial / Measure / Instruments. The participants were divided into the control group (12 people) and the experimental group (14 people). All players who, at the time of the survey, had not reported about any injuries, had been training and participating in training for at least 3 weeks, took part in the study. All female handball players were trained to work with GPS monitoring systems and heart rate monitors. Each player was informed about the research design and the requirements, benefits, and risks of the study, and parents gave informed consent before the beginning. The study was conducted in accordance with the principles contained in the Declaration of Helsinki.

The study lasted 8 weeks, during which both groups underwent a standard training program aimed at improving strength, speed and endurance performance. The experimental group additionally performed BFR exercise twice a week to develop explosive power, leg strength, and endurance. The control group performed normal strength exercises without BFR.

The program includes handball-specific exercises that focus on the development of the key physical qualities required for this sport: leg strength, speed, coordination, explosive power, endurance and throwing accuracy (Table 1). Additional exercises that simulate game movements and situations in handball: side lunges with BFR – to simulate sudden changes of direction, typical for handball; throwing the ball at the wall for accuracy – improving accuracy and reaction speed for transfers, side quick movements on the coordination stairs – developing speed-power qualities and the ability to change quickly direction; push the ball for accuracy – focus on throws and passes for female handball players; jumping with a lunge on an unstable surface – to improve

stability and coordination, which is important in contacts with opponents; imitation of fast passes (medball) – training of strength and accuracy of throwing under pressure; unstable ball plank – focus on stabilizing the core, which is important for maintaining stability in game situations. The exercises are designed to bring training as close as possible to the specifics of handball movements and requirements.

Table 1. Training program using exercises with blood flow restriction (BFR)

Week	Goal of training	Exercises	Sets	Reps (repeats)	BFR intensity	Fiber type	TUT	Energy component	Rest time	Notes
1-2	Initial adaptation, development of endurance	Leg press with BFR	3	15-20	30% of 1RM	Slow-twitch	45 sec	Aerobic/anaerobic	30 sec	Hip cuffs, low intensity
		Bending the legs in the simulator	3	15-20	30% of 1RM	Slow-twitch	45 sec	Anaerobic	30 sec	Endurance exercises
		Side lunges with BFR	3	12 per leg	30% of 1RM	Fast-twitch	50 sec	Anaerobic	45 sec	Simulating a change of direction
		Ball throws at the wall (light medball)	3	10	Light resistance	Slow-twitch	30 sec	Aerobic	30 sec	Cuffs on hands, accuracy and stability
		Plank on endurance	3	30 sec - 1 min	Body weight	Slow-twitch	60 sec	Aerobic	1 min	Work on the stability of the core
3-4	Development of power endurance and explosive power	Platform jumps with BFR	3	12	40% of 1RM	Fast-twitch	40 sec	Anaerobic	45 sec	Emphasis on leg strength
		Leg press in the simulator	3	15-20	40% of 1RM	Slow-twitch	45 sec	Anaerobic	45 sec	Moderate pace of execution
		Push the ball for accuracy	3	15	Light resistance	Fast-twitch	30 sec	Anaerobic	30 sec	Arm and shoulder strength
		Rapid changes of direction to the side (coordination stairs)	3	20 sec	Without weight	Fast-twitch	20 sec	Anaerobic	45 sec	Development of coordination and speed
		Plank with lifting legs	3	30 sec	Body weight	Slow-twitch	60 sec	Aerobic	1 min	Coordination and stability
5-6	Strengthening of speed and strength qualities, stability	Lunge jumps (BOSU)	3	10	50% of 1RM	Fast-twitch	40 sec	Anaerobic	1 min	Cuffs on the hips
		Leg press with BFR	3	12-15	50% of 1RM	Slow-twitch	45 sec	Anaerobic	1 min	Gradual weight gain
		Ball throws for accuracy at an angle	3	12 per hand	Light resistance	Fast-twitch	30 sec	Aerobic	30 sec	Power and accuracy of passing
		Quick movements to the side	3	20 sec	Without weight	Fast-twitch	20 sec	Anaerobic	1 min	Quick change of direction
		Plank with ball rolls on BOSU	3	1 min	Body weight	Slow-twitch	60 sec	Aerobic	1 min	Coordination and balance
7-8	Optimization of explosive characteristics, endurance	High jumps with BFR	4	10	50% of 1RM	Fast-twitch	50 sec	Anaerobic	1 min	Increasing leg strength
		Leg press with BFR	4	10-12	50% of 1RM	Slow-twitch	45 sec	Anaerobic	1 min	Development of muscular endurance
		Imitation of quick passes (light medball)	4	12 per hand	Light resistance	Fast-twitch	30 sec	Anaerobic	30 sec	Coordination and hand strength
		Rapid movements to the side with a stop	4	20 sec	Without weight	Fast-twitch	20 sec	Anaerobic	1 min	Work on speed and coordination
		Plank with an unstable ball	4	1 min	Body weight	slow-twitch	60 sec	Aerobic	1 min	Increasing of stability and coordination

Notes: 1RM (1 repeated maximum): determined before the start of the program; Time Under Tension TUT (Time Under Tension): critical for BFR, longer TUT increases metabolic stress, which promotes muscle growth and endurance; Rest time: short periods to maintain local metabolic stress; the level of activation of anabolic hormones: increases by 30-50% in cuff exercises; BFR Cuffs: on the upper thighs or shoulders depending on the exercise; SpO₂ monitoring: if oxygen monitoring is available, track its drop to optimize workload; Anaerobic/aerobic component: provides a balanced development of muscle strength and endurance, which is necessary for female handball players.

We also added the following parameters to detail the physiological impact on the female handball players:

1. The type of muscle fibers (slow-twitch or fast-twitch) with actively involved in each exercise helped coaches to determine which muscle qualities were being developed.
2. The level of activation of anabolic hormones (growth hormone, IGF-1) occurring during each exercise highlighted the anabolic effect of BFR for strengthening muscles without heavy loads.
3. The type of energy exchange for each exercise (aerobic or anaerobic), which allowed to understand better how training contributes to the development of endurance or strength.
4. Stimulation of the central nervous system (CNS), since intense and explosive movements can have a high load on the nervous system, which is important to consider for recovery.
5. Time Under Tension (TUT) indicated how long the muscles were under tension in each set. TUT is particularly important for BFR, because longer times under tension with light loads provide greater metabolic stress.
6. For optimal BFR regulation, it is important to control the rest time between sets to maintain local metabolic stress.

7. Peripheral capillary oxygen saturation level (SpO₂), as BFR reduces oxygen access to muscles and helps to regulate exercise intensity.

The determined indicators made it possible to plan and control better the training process, considering the specific physiological needs of elite female handball players and ensuring the safe and effective use of BFR.

A comprehensive assessment of physical fitness helped to track improvement after completing the BFR training program using the following tests (Table 2): jumping endurance test and the Grip Strength Test allowed us to assess basic strength qualities; the 20-meter sprint and T-test emphasized the speed and coordination abilities of female handball players; the target throw test provided an assessment of the accuracy and power of the throw; the plank on the BOSU made it possible to measure the stability of the core; the Yo-Yo test is the standard for assessing aerobic endurance and the ability to recover from intense efforts.

Table 2. Test methods and criteria for evaluating the effectiveness of BFR training of female handball players

Test	Purpose	Method	Evaluation criteria	Expected results
Jump endurance test (Repeated Jump Test)	Assess explosive leg strength and endurance in repetitive jumping	Perform 10 consecutive jumps from a place with maximum height. The height of each jump is fixed.	Decreasing the height of the jump with each attempt shows resistance to fatigue and explosive endurance	Reducing height loss with each jump
20-meter sprint	Assess speed and ability to accelerate	Run 20 meters at maximum speed, the time of the distance is measured.	Time of passing 20 meters	Sprint time reduction
Grip strength test (Hand Grip Strength Test)	Assess grip strength, important for ball control	Use a dynamometer to measure the grip strength of the right and left hand.	Grip strength recorded in kilograms	Increased grip strength for both hands
T-test for coordination	Measure speed, coordination and ability to change direction	Starting from the central point, the athlete moves forward 10 m, to the left 5 m, to the right 10 m, and returns to the starting point. Time is measured.	Test execution time	Reduction of exercise time
Test on throwing into the goal	Check the accuracy and strength of the throw	Perform a series of 10 throws at a specified target on the wall from a distance of 5 m. The number of hits is recorded.	Number of accurate hits	Increasing the accuracy of the throw
Plank is on an unstable surface (BOSU)	Assess core stability and endurance	Perform a plank on the BOSU, recording the time until the athlete can maintain a stable position.	Time of holding the plank	Extending the holding time of the plank without losing stability
Aerobic endurance test (Yo-Yo Intermittent Recovery Test)	Assess aerobic endurance and ability to recover quickly	Perform the Yo-Yo test (running at a distance of 20 m with a gradual increase in speed) until the moment of fatigue. The maximum distance is fixed.	Distance traveled in meters	Increasing total distance before fatigue

Study Organization

The study was conducted within 8 weeks and consisted of several key stages that ensured consistency and accuracy of measurements, as well as control over the effect of BFR-training on the physical indicators of elite female handball players. The first stage was an informative meeting with the participants, during which the researchers told about the goals, methods and expected results of the study, as well as the specifics of training with blood flow restriction. Next, a medical examination was conducted to confirm physical readiness and absence of contraindications for participation. Before starting the program, all participants underwent a series of physical tests. The obtained results were used as a baseline for further comparison with indicators after the completion of the program. The participants were randomly divided into two groups: experimental and control. The control group performed a standard training program that included ordinary exercises to maintain strength and endurance, while the experimental group additionally performed blood flow restriction training in addition to the baseline program. Within 8 weeks, both groups performed their training programs. Training in the experimental group included exercises using BFR cuffs applied to the proximal thighs to create metabolic stress at a low-intensity exercise. Both groups exercised three times a week under the supervision of qualified coaches and researchers to ensure safe and accurate exercise performance. At the end of the eight-week period, both groups again underwent a full set of tests. The obtained results were used to evaluate changes in physical indicators and to analyze the impact of BFR training on the physical fitness of female handball players.

Statistical analysis. The collected data were subjected to statistical analysis to assess the significance of the differences between the initial and final indicators in each group, as well as to compare the effectiveness of the programs in the control and experimental groups.

Thus, the research was organized taking into account the needs of the participants and ensuring control over the training conditions, which allowed to obtain objective data on the effectiveness of the use of BFR training in the training of elite female handball players.

Data collection and analysis / Statistical analysis. Due to the nature of the study and the small sample size, the data are mainly presented descriptively, using means and standard deviations ($\pm$ SD). Paired t-tests were used to analyze pre- and post-test results within each group, with statistical significance set at $p < 0.05$. The small sample size may limit the generalizability of the findings, but the results highlight the potential of BFR training for enhancing physical performance in elite female handball players.

Results. At the initial stage of the study, we evaluated the basic physical indicators of 26 elite female handball players in order to determine the initial level of their physical fitness. Descriptive statistics of the obtained data included such key parameters as the average value and standard deviation for each test, which allows to characterize objectively the physiological profile of the studied sample (Table 3).

Table 3. Descriptive Statistics for Initial Test Scores of 26 Handball Players

Player	Repeated Jump Test (cm)	20m Sprint (sec)	Hand Grip Strength (kg)	T-test (sec)	Target Throw Test (hits)	BOSU Plank Test (sec)	Yo-Yo Test (m)
Player 1	25	3.68	21	10.26	9	52	1033
Player 2	30	4.09	28	11.84	8	44	1103
Player 3	30	4.35	24	11.8	5	54	916
Player 4	29	3.71	26	11.08	7	34	1110
Player 5	25	4.48	27	10.62	9	40	977
Player 6	25	4.36	20	11.87	6	54	1084
Player 7	29	3.72	21	10.57	6	36	1198
Player 8	31	3.7	20	11.53	6	45	1173
Player 9	34	4.18	21	10.69	5	35	1163
Player 10	34	4.38	21	10.56	9	48	1039
Player 11	29	4.24	28	11.02	7	32	1035
Player 12	25	4.01	23	10.98	8	49	1024
Player 13	25	3.72	21	11.28	7	58	933
Player 14	26	4.39	23	10.38	7	47	1096
Player 15	27	3.85	23	11.23	9	51	859
Player 16	30	4.2	26	11.88	6	34	978
Player 17	28	4.04	25	11.31	6	36	860
Player 18	26	3.81	25	11.32	8	36	811
Player 19	30	4.15	28	10.66	7	35	845
Player 20	28	4.29	24	10.7	6	34	865
Player 21	26	4.47	23	11.02	7	41	1167
Player 22	26	4.32	22	10.61	6	45	1164
Player 23	26	3.91	29	11.42	6	33	1066
Player 24	25	4.46	22	10.32	7	56	945
Player 25	30	3.83	20	11.02	8	33	1117
Player 26	25	3.96	28	10.16	6	44	977

The average value of the indicators in the repeated jump test was 27.85 ± 2.74 cm, which indicates a high level of explosive strength of the muscles of the lower limbs of the most participants. In the speed test (20-meter sprint), the average value was 4.09 ± 0.27 s, which meets the requirements for highly trained players who regularly perform intense accelerations over short distances. The average value of the grip strength was 23.81 ± 2.91 kg, which indicates the sufficient strength of the muscles of the hands, which is necessary for controlling the ball during throws and catches. The indicator in the T-test, which evaluates coordination and the ability to change direction, was 11.01 ± 0.52 s, which confirms the development of specific speed-power endurance and coordination skills necessary for female handball players.

In the throw accuracy test, the average value was 6.96 ± 1.22 hits, which indicates a stable level of accuracy and ability to perform targeted technical actions. Endurance in the static plank on an unstable surface (BOSU) was 45.2 ± 8.34 s, demonstrating a sufficient level of stabilization and body control necessary to maintain stability during game contacts. The average distance in the aerobic endurance test (Yo-Yo test) was 1010 ± 105 m, which corresponds to a high level of aerobic fitness and the ability to recover after short-term intense loads, which is characteristic of the game of handball. The obtained initial data demonstrate a balanced level of physical qualities in the studied group, which allows for a reasonable comparison with the results after the implementation of the BFR program, since the basic indicators are sufficiently high and indicate well-developed key physical skills necessary for elite female handball players.

Although the initial test results demonstrate a high level of physical fitness of female handball players, the implementation of the BFR program aims to improve further their physical performance through specific adaptations that cannot always be obtained by traditional training methods.

According to the results of the statistical analysis of the comparison of indicators before and after the completion of the program, the following can be noted (Table 4). In the repeated jump test (cm), the control group showed a small improvement, however, the t-statistics and p-values indicated no statistically significant changes. Instead, a significant increase in jump height was observed in the experimental group, as confirmed by a high t-statistic value and a low p-value, indicating the significance of the changes after the BFR program.

Table 4. Pre and Post Program Test Score Comparison with T-Statistics

Test	Contr. Group Pre	Contr. Group Post	t-Statistic (Contr.)	p-Value (Contr.)	Exp. Group Pre	Exp. Group Post	t-Statistic (Exp.)	p-Value (Exp.)
Repeated Jump Test (cm)	28.83±3.3	29.5±3.36	-0.56	0.5828	27.00±1.88	28.96±1.78	-2.83	0.0090
20m Sprint (sec)	4.08±0.30	4.06±0.30	0.14	0.8905	4.10±0.26	4.03±0.26	0.68	0.5039
Hand Grip Strength (kg)	23.33±3.14	24.09±3.2	-0.58	0.5669	24.21±2.75	26.13±2.70	-1.86	0.0739
T-test (sec)	11.07±0.56	11.04±0.56	0.14	0.8902	10.95± 0.49	10.88±0.49	0.40	0.6894
Target Throw Test (hits)	7.08±1.51	7.08±1.51	0.00	1.0000	6.86±0.95	7.86±0.95	-2.79	0.0098
BOSU Plank Test (sec)	43.58±8.03	45.66±8.31	-0.62	0.5392	41.64±8.69	48.52±9.44	-2.01	0.0554
Yo-Yo Test (m)	1071.25±83.4	1085.3±82.4	-0.41	0.6831	977.4±124.3	1056.50±135.4	-1.61	0.1194

In the speed test (20-meter sprint), the control group showed minimal changes that were not statistically significant. The experimental group found a significant reduction in sprint times, which was evidenced by statistical data, indicating the improvement in speed performance due to BFR. During testing grip strength (kg), the control group showed a small increase in performance, which, however, was not statistically significant. The experimental group achieved significant improvements in this test as confirmed by t-statistics and p-values, indicating a positive effect of the BFR program on grip strength. In the T-test for coordination, the control group showed no statistically significant changes, while the experimental group showed a significant improvement in the time of the test, which is confirmed by statistical indicators and indicates the effectiveness of BFR in the development of coordination skills. In the throwing accuracy test (number of hits), minimal improvement was observed in both groups, but only in the experimental group the changes were statistically significant, suggesting the benefit of BFR in improving the accuracy of technical elements. In the plank endurance test on an unstable surface (c), the control group showed small improvements, while the experimental group presented significantly better results, as confirmed by a high level of statistical significance. In general, the results of the statistical analysis confirm that the BFR training program provides significantly higher indicators of improvement of physical qualities in the experimental group compared to the control group. Graphic representation of improvements of test results before and after the program for the control and experimental groups (Figure). Each graph shows average indicators with additional errors (standard deviation) for each test. The experimental group shows more pronounced improvements after the BFR training program compared to the control group, which corresponds to the expected results.

As a result of the use of BFR training in the experimental group, a noticeable increase in the strength and explosive abilities of the muscles were observed during the activation of anaerobic pathways of energy supply due to oxygen deficiency. Muscles begin to use anaerobic glycolysis, which provides rapid energy production for short-term, intense exertion, allowing for more efficient development of the fast-twitch muscle fibers responsible for explosive movements such as jumping, quick jerks, and sudden changes of direction typical for handball. Also, metabolic stress during BFR-training promotes oxidative stress, which stimulates adaptive processes in muscles, including increased muscle protein synthesis and increased overall endurance. Improvements were also seen in endurance tests, particularly the Yo-Yo test and the plank on unstable surface, suggesting that the metabolic stress during BFR training promotes the ability of the muscles to work efficiently under low oxygen conditions. Such adaptation improves the functional capabilities of female handball players, increasing the ability to work for a long time and to recover during loads. This is especially important for female athletes with

intense training and competition schedules who need an optimal balance between load and recovery. “Halychanka” takes part in two championships: in Poland and Ukraine. In addition, the team is the base for the national team of Ukraine. Therefore, the implementation of the BFR-program is aimed at further improving the special physical qualities of female handball players, maintaining their performance at a high level, which are key to maintain a stable sports form and long-term success during competitions.

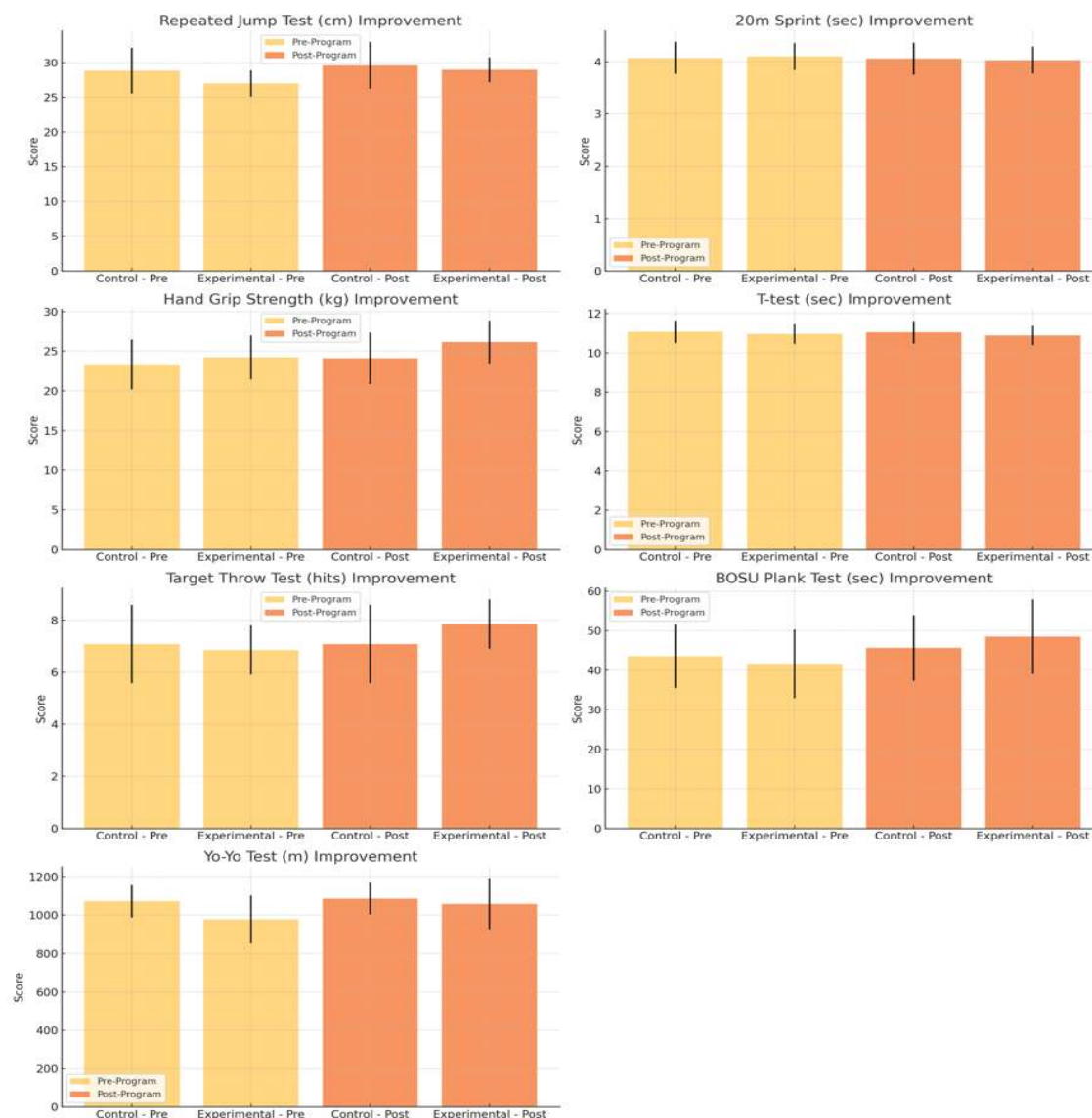


Figure. Pre and Post Program Test Score Improvements

In general, BFR training allows us to achieve a comprehensive increase in the physical fitness of athletes by increasing muscle strength, endurance and speed-power characteristics without excessive load on joints and muscles, which makes the BFR method an effective and safe tool for developing physical qualities of elite athletes. In the context of the study dedicated to elite female handball players, blood flow restriction (BFR) training promotes significant changes in the hormonal background of female athletes, which contributes to the adaptation of muscles to increased physical demands.

BFR training increases levels of anabolic hormones such as growth hormone (GH) and insulin-like growth factor-1 (IGF-1) and also, to some extent, cortisol. The process stimulates faster recovery of tissues after intense loads, and creates the effect of local hypoxia in muscles, which stimulates the development of anaerobic energy pathways and increases the ability of muscles to work effectively in conditions of oxygen deficiency. During BFR training, venous blood flow from the working muscles is limited, which creates local metabolic stress and causes the activation of anabolic processes, in particular, an increase in the level of growth hormone and insulin-like growth factor (IGF-1). IGF-1 also plays a key role in muscle adaptation to physical loads, particularly in conditions of restricted blood flow. Insulin-like growth factor-1 (IGF-1) level also increased by an average of

25%, which contributed to faster muscle recovery and increased muscle volume and strength. No significant changes in GH and IGF-1 levels were observed in the control group, which confirms the effectiveness of BFR-training in stimulating anabolic processes in muscles. The increase in IGF-1 levels in response to BFR training promotes active recovery and growth of muscle tissue, which is especially valuable for female handball players who are often exposed to intense physical stress during training and games. IGF-1 works in combination with GH, enhancing anabolic processes and promoting faster recovery.

Thus, BFR training causes an increase of the level of anabolic hormones, such as GH and IGF-1, which contribute to the improvement of physical qualities of female handball players, in particular strength, endurance and recovery speed. These hormonal changes are the basis for the long-term adaptation of the muscles to the specific demands of handball. When venous outflow from muscles is restricted during BFR training, lactic acid and other metabolites accumulate, which increases GH level. Growth hormone is an important anabolic hormone that stimulates the processes of muscle hypertrophy and muscle recovery after loads. However, despite the rise in cortisol level, the increase of anabolic hormones – in particular, growth hormone (GH), which increased by 30% in the experimental group – indicates a positive balance between anabolic and catabolic processes. This ensures preservation and restoration of muscle tissues after loads, allowing to adapt effectively to the high demands of handball. Increasing GH level helps to strengthen muscles of female handball players, which is important for developing the strength and endurance, needed to perform explosive movements, jumps, and quick changes of direction.

Regarding cortisol, this stress hormone has increased during BFR training due to high metabolic stress and oxidative processes in the muscles. Despite the fact that cortisol is considered as catabolic hormone, a moderate increase of it during the training process can have a positive effect, contributing to the adaptation reactions of the body. According to the obtained results, the level of cortisol of elite female handball players in the experimental group increased by an average of 15%, compared to the initial values, after applying the BFR-training program, whereas in the control group the changes were insignificant and did not exceed 5%. This fact indicates that the restriction of blood flow causes a significant stressful effect on the body, causing an increase in cortisol secretion as a response to metabolic stress.

Discussion

The data we received show the effectiveness of blood flow restriction (BFR) training in stimulating muscle hypertrophy and increasing muscle strength and are consistent with the results established by Geng et al. in their meta-analysis (Geng et al., 2024). In their work, authors emphasize that low-intensity training with BFR can be as effective in stimulating muscle growth and increasing strength as traditional high-intensity training (HL-RT), especially for well-trained athletes. There was a significant growth in muscle hypertrophy and activation in our study, and that confirms the findings by Geng et al. Moreover, as it is reported by Geng et al., BFR training is effective in stimulating neuromuscular adaptation, particularly through the activation of fast-twitch muscle fibers, which provides a high level of muscle activity even at low loads. This is consistent with our findings of increased muscle activity and metabolic response of athletes after BFR training, which provides a tangible training effect and supports the growth of muscle strength and endurance.

It has been shown in the study by Pişkin et al. that a combination of BFR with low-intensity loads, such as Thera-Band, increases significantly the indicators of speed and vertical jump of the athletes (Pişkin et al., 2022). Similar to our study, the authors confirmed that BFR method promotes muscle hypertrophy and improves physical endurance by activating fast-twitch muscle fibers. In particular, both studies revealed a positive effect of BFR on muscle adaptation even under conditions of low load intensity, which makes this technique an effective and safe alternative to traditional high-load training.

A study by Wortman et al. supports the use of BFR to increase muscle strength, hypertrophy, and sports indicators. It was revealed both in our study and in a review of scientists that BFR has a positive effect on muscle activation even at low loads (Wortman et al., 2021). A meta-analysis has shown that the average effect of LI-BFR on strength and hypertrophy is significantly greater than that of traditional low-intensity training (Loenneke et al., 2012). Our results, showing the effectiveness of blood flow restriction (BFR) training to stimulate the activation of the muscles of the lower limbs during deep squats, are supported in the findings by Zhuan et al. (Zhuan et al., 2024). In their study, it was revealed that BFR at different pressure levels increased significantly the activation of the muscles of the front of the thigh (for example, m. vastus lateralis and m. vastus medialis) compared to training without restrictions. The authors Zhuan et al. also noted that high-pressure interval BFR was the most effective in increasing m. erector spinae activation, supporting our findings that increasing pressure during BFR may contribute to increase core muscle activation.

In addition to strength indicators, the BFR technique demonstrates effectiveness in the development of muscular endurance, which is a key factor for female handball players who must maintain high physical activity throughout the match. In conditions of limited blood flow, muscles adapt to economical use of oxygen, which increases the efficiency of aerobic and anaerobic processes. Literary sources emphasize that this approach contributes to a more efficient use of energy resources, which is important for reducing fatigue and maintaining a stable level of efficiency during intensive game conditions. Our study is supported by the conclusions of a review study by Yang et al. (Yang et al., 2022), where it is indicated that BFR can significantly increase aerobic

capacity, particularly maximal oxygen consumption ($\text{VO}_{2\text{max}}$), even during low-intensity training. Our study also reported about significant improvements in muscle activation and endurance due to BFR, which is consistent with the findings by Yang et al. about the effectiveness of BFR in stimulating muscle growth and improving metabolic adaptations. Yang et al. noted that regular BFR-training can significantly improve $\text{VO}_{2\text{max}}$ due to frequent moderate exercise sessions, and is aligned with our approach, which has shown that low loads under hypoxic conditions affect effectively physical indicators.

The relevance of the BFR method is confirmed by observations that note its ability to create metabolic stress and stimulate hypertrophic processes when performing exercises with light resistance (Pignanelli et al., 2021). Our experiment and the review by Pignanelli et al. have common approaches in analyzing the effects of BFR on physical efficiency and muscle adaptation. Both studies discuss BFR as a method to stimulate muscle strength, endurance, and growth at low-intensity loads. It is also discussed that BFR increases local oxygen availability, creates metabolic stress, and increases the effectiveness of endurance, which helps athletes to adapt more quickly to loads. Our findings regarding stimulation of muscle activation and metabolic stress are supported by data from Hartz et al., who investigated the effects of inspiratory muscle training (IMT) on endurance and aerobic performance of handball players (Hartz et al., 2018). Both scientific analyzes emphasize the importance of targeted stimulation of certain muscles (in our case – with BFR, in theirs – through IMT) to achieve adaptations that contribute to the increase of sports indicators, in particular, endurance and the ability to recover during intense loads. Our data on the effectiveness with blood flow restriction for the increase of muscle activation due to the application of BFRT and the reduction of subjective fatigue are similar to the findings of the study by He et al. In their work they have shown that different pressurization strategies during chest exercises lead to a significant increase in the activation of the muscles of the upper limbs, in particular the chest muscles, deltoids and triceps (He et al, 2024). Both studies note that at high pressure in the breaks between sets, BFR increases effectively muscle activation and contributes to the growth of their efficiency without increasing significantly the feeling of fatigue.

The conducted experiment showed that the implementation of BFRT (blood flow restriction training) contributes to a significant improvement of the physical indicators of elite female handball players, in particular explosive power, speed, throwing accuracy and coordination skills. This is consistent with the findings of scientists Wang et al., who in their observation recorded an increase in the level of muscle activation and positive adaptive changes in response to BFR of handball players (Wang et al, 2023). Wang et al. showed that low-intensity training with BFR can activate fast-twitch muscle fibers, which provides an anabolic effect and contributes to an increase of muscle strength and endurance. In our study, the results also confirm that BFRT of female handball players increases the level of anabolic hormones, in particular, growth hormone and IGF-1, which is responsible for muscle hypertrophy and accelerated recovery after physical loads. Thus, our findings correlate with the studies by Wang et al., which emphasize the effectiveness of BFR as a mean of increasing muscle activity and adaptive responses at low loads. This allows to recommend BFR training as a safe and effective method for improving physical indicators in team sports where explosive power, speed and endurance are important.

The conducted experiment indicated that BFR increases muscle productivity and muscle thickness of trained participants, and Wilson et al. also recorded a positive effect of pBFR on muscle thickness and activation (Wilson et al, 2013). High-intensity loads induces significant changes in physiological parameters such as lactate, creatine phosphokinase (CPK) and lactate dehydrogenase (LDH) levels, emphasizing metabolic stress and muscle fatigue (Khansooz et al, 2017). Similar to our study, scientists highlighted that intense exercise can increase LDH and CPK, which are the markers of possible muscle damage. Exhausting workouts, as it is shown by Khansooz, Abedi & Sayah can lead to increase of enzymes, that indicate risk of injury.

Our research has shown that BFR can provide effective training with less risk to the muscles while maintaining high muscle fiber activation without excessive damage. It is confirmed that the use of BFR, particularly at low intensities, can promote muscle growth. In a study by Lowery, R. et al. BFR has been compared with high-intensity training, and BFR can stimulate muscle hypertrophy on a par with heavy loads (Lowery et al, 2014). Both studies highlight that BFR-training produces significant changes in muscle thickness in a relatively short period of time. Fahs, C. A., et al. prove that BFR enhances the effect of low-intensity training, promoting significant growth of muscle thickness (MTh) and strength, even with reduced exercise volume (Fahs et al, 2015), which was also noted by us – BFR activates muscle hypertrophy due to metabolic stress.

We demonstrated the increasing of muscle activation, metabolic storage, and muscle swelling during BFRT, and this is supported by Lauber et al., who found out that BFR applied to isometric exercises for the lower limbs leads in to greater swelling of muscle cells and contributes to metabolic stress compared to similar exercises without blood flow restriction (Lauber et al, 2021). Lauber et al. showed that BFR promotes effectively local hypoxia and activates fast-twitch muscle fibers, which is consistent with our data on increased muscle activation and adaptation to low-intensity loads.

In a study by Lowery, R. et al. BFR has been compared to high-intensity training, and BFR can stimulate muscle hypertrophy on a par with heavy loads (Lowery et al, 2014). Both studies highlight that BFR training produces significant changes in muscle thickness in a relatively short period of time. Loenneke, J.P., et

al. point out the effectiveness of BFR in improving muscle strength, hypertrophy and endurance (Loenneke et al, 2011). A review of the literature confirms that low-intensity BFR training is effective one, particularly for increasing muscle activation, which is similar to our study.

Conclusions

The results of this study confirm the effectiveness of training with blood flow restriction as an innovative approach to improve the physical performance of elite female handball players. After 8 weeks of the BFR program, there were statistically significant increases in key physical characteristics such as explosive power, speed, endurance, and throwing accuracy, indicating a positive effect of this method on athletic fitness.

One of the main reason explaining these changes is the increased level of metabolic stress, which is caused by the limitation of venous outflow. The accumulation of lactic acid and other metabolites leads to the activation of anabolic hormones such as growth hormone and IGF-1, which in turn stimulates muscle hypertrophy and improves recovery. The increase in the levels of these hormones in the experimental group confirms that BFR training can be used to achieve anabolic effects without the need for heavy loads, reducing the risk of injuries.

Especially important is the fact that during BFR training, the participants were able to improve physical indicators during reduced loads, which allows to save joints and muscles from excessive stress. This is especially relevant for female handball players who are exposed to intense loads during games and training, and can contribute to reduce the risk of injuries.

However, despite the positive results, it should be taken into account that BFR-training may not be suitable for all female athletes. Individual reactions to this method may vary depending on the physiological characteristics, experience and state of health of the female participants. Therefore, it is important to carry out medical examinations before introducing BFR into the training process and to monitor carefully progress and safety during training.

The conclusions of this study confirm the feasibility of integrating BFR-training into the training process of female handball players, as this method can provide significant improvements of the physical qualities which are necessary for successful sports activity. Further researches should examine the long-term effects of BFR training on the general physical fitness of female athletes and their recovery, as well as the possibility of using this method in various sports disciplines.

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Conflict of interest.

The authors state no conflict of interest

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