THE EFFECT OF BLOOD FLOW RESTRICTION TRAINING ON MUSCLE STRENGTH AND POWER IN TAEKWONDO ATHLETES

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BO JIN

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THE EFFECT OF BLOOD FLOW RESTRICTION TRAINING ON MUSCLE STRENGTH AND POWER IN TAEKWONDO ATHLETES

BY
BO JIN

HAS BEEN APPROVED BY THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DOCTOR OF PHILOSOPHY
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This study aimed to enhance the performance of high-level athletes through blood flow restriction (BFR) training. Twenty high-level Taekwondo athletes from China were randomly assigned to an experimental and a control group. Experiment 1 tested four types of blood flow restriction at 40%, 50%, and 60% of individual's arterial occlusion pressure (AOP) with varying intervals. Experiment 2 involved 8 weeks of BFR training at 50% AOP, performed three times per week) for the experimental group, while the control group underwent traditional high-intensity resistance training at 70% of 1RM. The experimental group showed significant improvements in body composition, including reduced body fat ($p = 0.035$, Cohen's $d = -0.53$) and increased muscle mass ($p = 0.004$, Cohen's $d = 0.51$), while the control group demonstrated only a weight increase ($p = 0.034$). The experimental group also demonstrated increased thigh circumference ($p < 0.001$, Cohen's $d = 0.771$) and hip circumference ($p = 0.034$), as well as improvements in lower limb explosive power. These findings suggest that BFR training improves body composition, muscle strength, and lower limb explosive power more effectively than traditional resistance training. BFR is a promising training method for high-level athletes seeking to optimize their performance.

Keyword : blood flow restriction training, Taekwondo athlete, Lower limb strength, Explosive power, Muscle activation

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The writing of this article is the last systematic and in-depth study in four years. In the process of writing words and sentences, truly transform the understanding and scattered knowledge points in the first half of the relevant industry into accurate and autonomous knowledge. The completion of a thesis is both a test and a gain.

In these four years of study, I not only gained professional knowledge, but also learned how to think, practice, express, and overcome myself.

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CHAPTER 1
INTRODUCTION

Background

Taekwondo is a globally popular sport and competition program originating from South Korea, and its traditional martial arts spirit contains the important concept of "beginning with etiquette and ending with ritual". The development of Taekwondo has divided into two phases: the International Taekwondo Federation (ITF) and the World Taekwondo Federation (WTF), of which the WTF became a member of the International Sports Federation in 1975 and was officially recognized as an official sport by the International Olympic Committee in 1980 (Yang et al., 2024). After its debut as a demonstration sport, Taekwondo began as a test event at the 1992 Barcelona Olympics, and in 1995 the first National Taekwondo Championships were held in China and the Chinese Taekwondo Association was established, which contributed to the rapid development and popularization of the sport in China (Su et al., 2024).

Taekwondo, as a combat sport that focuses on foot skills, requires a high degree of lower body strength and explosive power. Lower limb strength and explosive power are one of the key factors for Taekwondo athletes to gain an advantage in competitions (Cook et al., 2014). Through systematic training and reasonable training methods, athletes can improve their lower limb strength and explosive power so as to be more competitive in competitions. Lower limb strength includes the anterior thigh muscle group, posterior thigh muscle group, and gluteal muscle group, which are crucial for the production and control of kicking, stomping, and stepping movements. Improving lower limb strength allows athletes to kick more powerfully and aggressively, as well as improve stability and balance (Spranger et al., 2015). Explosive power, on the other hand, refers to an athlete's ability to generate power quickly in a short period of time, which directly affects the speed and effectiveness of the attack. Improving explosive power makes the athlete more sudden and powerful, increases the difficulty of the opponent's defense, and better responds to the opponent's attack (Vehrs & Johnson, 2023). In order to improve and develop lower limb strength and explosive power in

Taekwondo, coaches should emphasize the use of systematic and scientific training methods, such as basic strength training, kicking exercises, explosive power training and balance training, while focusing on nutritional intake and adequate rest. These factors together promote the athletes' competitive level and better performance in the game (Martinez-Rodriguez et al., 2023).

With the continuous progress of science and technology, Blood Flow Restriction Training (BFRT), as an emerging training method, has gradually attracted the attention of Taekwondo athletes and coaches (Sinclair et al., 2022). This training method increases the training effect by restricting the blood flow through applying moderate external pressure around the muscles.BFRT can produce similar effects of muscle hypertrophy and muscle strength increase as the traditional high-intensity training, and it has gradually become a popular way of rehabilitation training for injured and sick athletes. At the same time, BFRT has significant practical applications for the general population, the elderly, and the rehabilitation population in promoting muscle fiber hypertrophy, increasing muscle strength, and preventing muscle atrophy and weakness. Numerous studies support the effectiveness of BFRT. Research indicates that individuals using BFRT show significant improvements in strength and muscle thickness (Loenneke, Fahs, et al., 2011; Takarada et al., 2000). Furthermore, the application of BFRT during rehabilitation has also demonstrated positive effects for the elderly and postoperative patients. (Martinez-Rodriguez et al., 2023).

The primary physiological mechanism of BFRT is to create a hypoxic and ischemic environment for active muscles by restricting blood flow, thereby stimulating sympathetic nerve activity and growth hormone secretion (Segal et al., 2015). In competitive sports, BFRT has become a common approach to strength training and rehabilitation programs for athletes of all levels (Cook et al., 2014). Numerous studies have demonstrated that BFRT can effectively enhance athletes' strength and performance. For instance, Behringer et al. (2018) found that BFRT significantly impacted the strength and muscle thickness of track and field athletes. Additionally, Abe et al. (2010) showed that BFRT can promote strength and muscle growth as effectively as traditional training methods (Cook et al., 2014). However, relatively little research has been conducted on BFRT in a population of healthy high-level athletes, and in particular, the effectiveness of its application and implementation strategies in taekwondo athletes need to be further studied and explored (Abe et al., 2012). Therefore, in order to more widely promote and popularize the use of BFRT in taekwondo sports teams, there is an urgent need for further studies and research on its principles and methods, so as to better standardize the methods and approaches of BFRT to obtain optimal training effects and achieve outstanding athletic performance (Yamada et al., 2004).

Objectives of the Study

This study investigates the effects of blood flow restriction training (BFRT) on lower limb muscle activity and strength gain in outstanding taekwondo athletes, providing guidance for the innovation and development of strength training theories, and develops a training program to improve athletes' competitive level and accelerate the "Science and Technology for the Olympic Games Program". The specific research questions are as follows:

(1) To investigate the immediate effects of blood flow limiting squat exercises at 30% of 1RM intensity on the muscle activity of the lower limbs of good Taekwondo athletes under different conditions of blood flow limiting pressure and intervals. Determine the range of individual relative blood flow limiting pressure values to achieve maximum lower extremity muscle activation levels and compare the characteristic differences in lower extremity muscle activation during continuous and interval training.At the same time,The athletes' exercise intensity is also monitored.

(2) To investigate the characteristics of the immediate changes in lower limb muscle activity and fatigue in good taekwondo athletes before and after performing blood flow-limited deep squat training at 30% 1RM intensity. To analyze the effects of 8-week BFRT intervention on athletes' body composition, body circumference and long-term adaptations in terms of maximal strength, isometric muscle strength and lower limb explosive strength.

The study of the above issues can provide scientific guidance for the training of excellent taekwondo athletes, and enrich the application of blood flow restriction training in high-level athletes, and promote the progress of the "Science and Technology for the Olympic Games Program".

Significance of the Study

(1)Improvement of athletes' competitive level: By studying the effect of BFRT on the lower limb muscle activity and strength gain effect of excellent taekwondo athletes, it can provide a basis for the development of more effective training programmes, help excellent taekwondo athletes to improve their competitive level, and achieve better competition results.

(2) Enriching the training methods of high-level athletes: By studying the application of BFRT in high-level athletes, it can provide more scientific guidance for the training of excellent taekwondo athletes, and at the same time provide reference for other sports to enrich the training methods and means of high-level athletes.

(3) Science and technology for the Olympic program: The results of this study can provide guidance and support for the "Science and Technology for the Olympic Program", promote the application of science and technology in the field of sports training, and further improve the competitiveness of Chinese athletes in the international arena.

In conclusion, by studying the effects of blood flow restriction training on lower limb muscle activity and strength gain in excellent taekwondo athletes, this study is of great significance for the development of theory and the promotion of practice.

Scope of the Study

Population: The participants of this study were 20 outstanding taekwondo athletes, selected based on the following criteria: athletes who ranked in the top 10 in national taekwondo competitions (defined as athletes with high competitiveness at the national level) and those who won gold medals in provincial competitions (considered as athletes who have demonstrated exceptional performance in provincial events). The age range of participants was 18-20 years, and all participants had not undergone any lower limb surgeries and were in good health.

Sample: The athletes' competition levels were: 10 national top taekwondo athletes and 10 national level athletes. Sample selection employed a random sampling method, based on the following formula$n = \frac{Z^2 \cdot p \cdot (1-p)}{E^2}$, where n is the sample size, Z is the confidence level constant (e.g., 1.96), p is the expected proportion (e.g., 0.5), and E is the allowable error (e.g., 0.05) (Michel et al., 2004). Based on the calculation results, a total of 20 athletes were ultimately selected as experimental subjects. All participants had not undergone any lower limb surgeries and were in good health. Prior to the start of the experiment, the researchers conducted a thorough investigation of the participants' health status to ensure that they had no diseases or psychological health issues that could affect the results of the experiment. This study was also subject to the approval of the Ethics Committee of the School of Physical Education and Sports of Henan Normal University.

Grouping: This study employs a simple randomization approach, utilizing IBM SPSS Statistics software to allocate participants into experimental and control groups. This step is designed to ensure an unbiased and randomized grouping process, thereby enabling a more precise evaluation of the effects of blood flow restriction training on athletic performance. Randomization eliminates systematic bias in the grouping process, thereby strengthening both the reliability and validity of the study’s outcomes.

Variable

Independent variables

1.Blood flow restriction training (BFRT) intervention

2.Training intensity and interval mode condition

Dependent Variable

1.Lower limb muscle activity level and fatigue characteristics

2.Lower limb strength gain effect

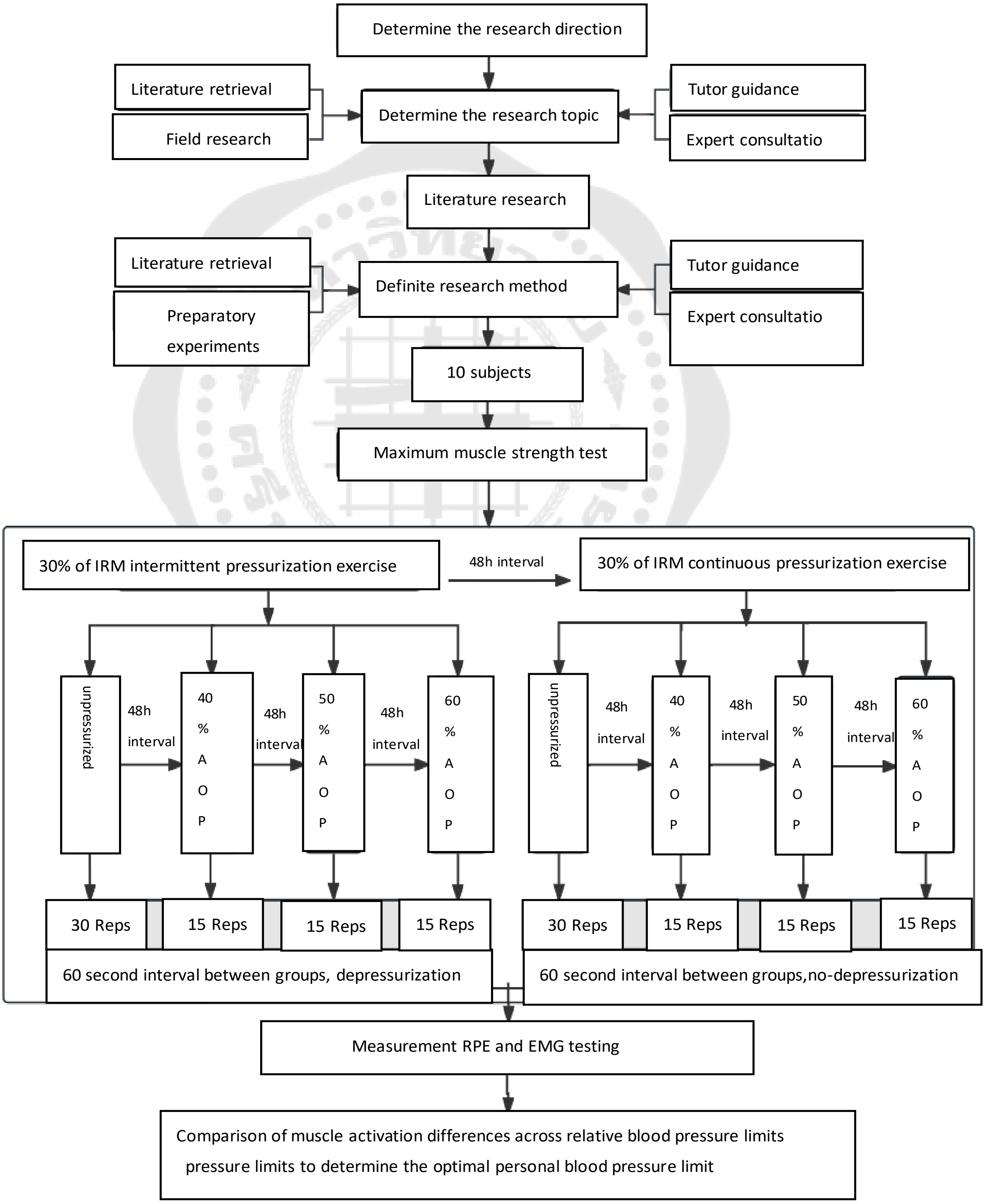
Definition of terms

Blood Flow Restriction Training (BFRT) is an athletic training method that utilizes a technique that restricts blood flow by applying a partial compression device (such as an air bag or band) to a limb (usually an extremity). This training method is designed to induce muscle fatigue by reducing the blood supply to the limb during exercise, thereby promoting muscle growth and strength gains.BFRT is usually performed at lower weights and high repetitions, and can achieve similar results to traditional high-intensity training while reducing loads on joints and soft tissues, making it suitable for use in areas such as rehabilitation, muscular strength gains, and athletic performance optimization.

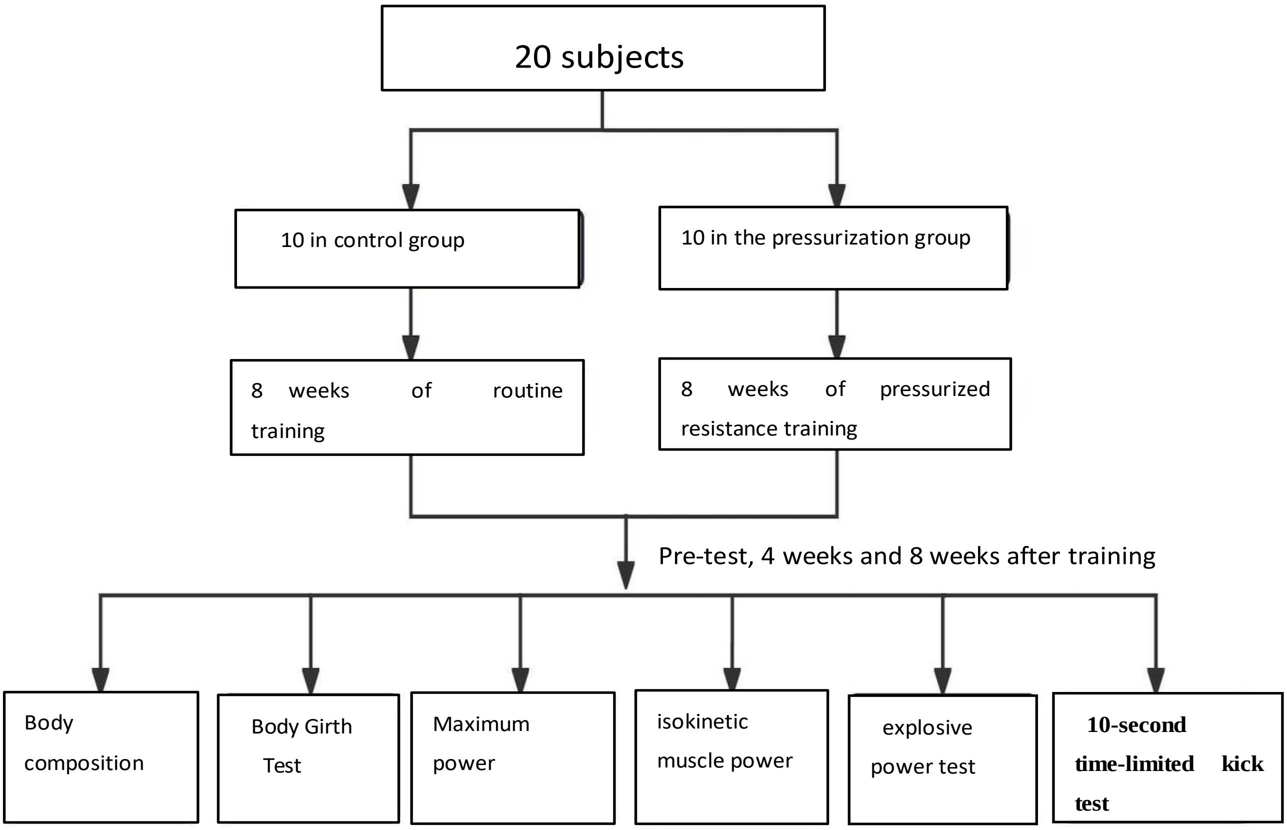
Strength Training: Strength training is a method of physical training designed to increase muscular strength, endurance and explosiveness. This form of training involves repetitive movements using external resistance (one's own body weight, dumbbells, barbells, etc.) to gradually increase the adaptability and strength levels of muscle tissue. Strength training can help improve muscle mass, bone density, metabolic rate, and body posture, as well as help prevent sports injuries and improve athletic performance. Strength training typically involves phased and planned workouts to ensure gradual increases in loading and challenging of the muscles to achieve lasting gains in strength and muscularity.

Conceptual framework

Experiment 1



Experiment2



Research hypotheses

(1) It is hypothesized that the level of lower limb muscle activity will show a gradual increase with the increase of blood flow limitation squatting at 30% 1RM intensity in excellent taekwondo athletes under different conditions of blood flow limitation pressure and intervals, and that the level of maximal lower limb muscle activation will be reached when reaching the range of individual relative blood flow limitation pressure values.

(2) It is hypothesized that before and after performing a 30% 1RM intensity blood flow limiting squat exercise, lower extremity muscle activity will significantly increase in excellent taekwondo athletes, and that fatigue levels will also significantly increase.

(3) It is hypothesized that in response to the 8-week BFRT intervention, there will be positive effects on body composition, body circumference, and long-term adaptations in excellent taekwondo athletes, including gains in maximal strength, isokinetic muscle strength, and lower extremity explosive strength.

CHAPTER 2

REVIEW OF THE LITERATURE

The research content of this chapter mainly includes the following aspects:

1.Definition and development history of blood flow restriction training (BFRT)

2.Blood flow restriction training (BFRT) on the strength gain effect and neuromuscular activation of the relevant studies

3.Development of blood flow restriction training (BFRT) and metabolic responses

4.Control of training variables in BFRT.

5.Overview of the effects of blood flow restriction training (BFRT) in different populations.

6. Physiological mechanisms and influencing factors of strength training

7.Research Review

Definition and History of Blood Flow Restriction Training (BFRT)

Definition of BFRT

Blood Flow Restriction Training (BFRT) is a form of limb exercise that involves the use of a pressurized tourniquet applied to the "base" of the upper arm and thigh at a specific intensity of pressure (Brunner et al., 2007).The purpose of BFRT is to restrict blood flow and reduce venous return to the restricted limb, thereby creating a specific state that optimizes the environment for muscle movement (Nascimento et al., 2022). The purpose of BFRT is to restrict blood flow and reduce venous return to the restricted limb, thus creating a specific state that optimizes the environment for muscle movement. When the compression band is removed, the blood will be in a better state than before the compression, which can be effectively controlled through the successive repetitions of the "compress-decompress" operation (Kwon, 2016).The core concept of BFRT is to restrict the flow of blood at the end of the body in a short period of time, slowing down its speed and causing it to flow to the poorer circulatory areas, thus achieving similar or similar results to high-load training in a low-load situation. achieving similar or comparable results to high load training (Kwon, 2016). It is important to note that BFRT training requires specific pressurized tourniquets and professional instruction, carries risks, and should be instructed and supervised by professionals with relevant training. During BFRT training, it is important to ensure safety and proper handling to avoid potential risks and injuries. Therefore, it is advisable to consult a professional and receive proper assessment and guidance before undertaking BFRT training (Segal et al., 2015).

In summary, blood flow restriction training is a specific training method that optimizes the muscle movement environment by restricting blood flow and obtains similar results to high-load training at low loads. However, due to the risky nature of BFRT, it should be performed under the guidance of a professional.

Development history of BFRT

In the early BFRT studies, researchers faced a long time problems in formulating "adapted pressure" and "pressurization time", determining "pressurization site" and "safety principles". The researchers faced difficulties for a long time in formulating "adaptation pressure" and "pressurization time", determining "pressurization site" and "safety principle" (Su et al., 2024). It was not until 1983 that Dr. Sato, after 15 years of exploration and practice, basically determined the training principles and methods of BFRT and began to promote them to the Japanese public (Ikezoe et al., 2020). Over the next 30 years, Sato's research team continued to update the equipment, standardize the training principles, explore different training methods, and continue to promote and popularize BFRT worldwide. As the physiological and biochemical aspects of BFRT were thoroughly researched, it began to be used in clinical rehabilitation and athletic training. To date, hundreds of BFRT instructional specialists have been trained and over 200 fitness and training facilities have been established in Japan to provide BFRT instructional services to the general public and patients with diseases (Yasuda et al., 2010).

BFRT was initially started as an innovative thought by the inventor, Dr. Sato, through a kneeling-in-place puja (Abe, Fujita, et al., 2010). During his amateur study of judo, Dr. Sato had the whim to restrict blood flow and chose a judo belt as the starting experimental material. However, this method was eventually scrapped due to the lack of stretch in the judo belt, which made it difficult to maintain a balanced pressure during training, and could even result in sudden and dramatic increases in pressure, risking obstruction of blood flow (Fujita et al., 2008). Subsequently, Dr. Sato chose to replace the judo belt with a bicycle inner tube rubber hose, which was used as a pressurized tourniquet, and successfully solved the danger of obstructing blood flow by regulating the pressure changes in the neck around the muscle. However, there were still some shortcomings in this method, firstly, the problem that the pressurized tourniquet might get caught in the skin had not yet been solved, and secondly, the band was too soft and not easy to bind (Ikezoe et al., 2020).

With continued thought and practice, Dr. Sato processed and modified bicycle inner tubes and added fittings to manually adjust the pressure strength. This improved tourniquet was able to regulate the pressure intensity during movement, and was surprisingly effective (Yasuda et al., 2009). 1973 saw the introduction of the original pressurized tourniquet made of synthetic rubber, called the "Stretchable Pressure Sensing Type Pressurized Tourniquet" (Behringer et al., 2017). This invention was patented in July 2003 by increasing the internal pressure and inflating the tourniquet after tying it, utilizing the mechanism of pressure generation. This invention was patented in July 2003 and has been in use since 2004 under the trade name "KAATSU Master" (Loenneke et al., 2014). The automatic pressurized tourniquet is filled with soft air, making it almost painless to tie. As compression tourniquets have been improved, the range of applications for compression training has become wider, with applications in a variety of fields such as geriatric fitness and clinical rehabilitation (Pope et al., 2013). In addition, miniature pressurized exercise equipment was developed for personal and home use. The final stage of development is a pressurized exercise machine capable of automatically detecting adaptive pressure at the exercise site, the main purpose of which is to prevent and treat major weightlessness syndromes such as muscle atrophy, bone loss and low cardiorespiratory fitness, which may occur in astronauts in a weightless state (Staunton et al., 2015).

Correlative Studies of Blood Flow Restriction Training (BFRT) on Strength Gaining Effects and Neuromuscular Activation

Benefits of BFRT for Muscle Hypertrophy and Strength Gains

Muscle hypertrophy is the result of adaptation to training loads that exceed the capacity of muscle fibers. During resistance training, motor units and muscle fibers are gradually recruited according to the "size principle" (Abe et al., 2012). At lower intensities, type I muscle fibers are recruited first, and as the load intensity increases, type II muscle fibers are gradually recruited (Loenneke, Fahs, et al., 2011). Since type II muscle fibers are more susceptible to hypertrophic response compared to type I muscle fibers, more recruitment and activation of type II muscle fibers can increase muscle size and strength during training. Therefore, increases in muscle size and strength can only be significantly induced when resistance training is used at moderate to high intensities (Ozaki et al., 2011). However, recent studies have shown that Blood Flow Restriction Training (BFRT) can also elicit a muscle hypertrophic response. In particular, when a low-intensity (<50% 1RM) resistance training program combined with blood flow restriction is used, it can produce significant muscle hypertrophy effects (Fujita et al., 2008). Restricting blood flow around the muscle at low loads through the use of tools such as pressurized tourniquets can increase the metabolic demands and adaptations of the muscle, thereby promoting muscle hypertrophy (Shinohara et al., 1998).

The underlying mechanism by which low-intensity pressurized resistance training (BFRT) induces muscle hypertrophy is not well understood, but theoretically, the primary cause may be metabolic stress due to an ischemic or hypoxic environment (Manini & Clark, 2009). This state of stress can induce muscle growth through a variety of factors, including increased recruitment of fast-twitch muscle fibers, a rise in hormone secretion, cellular swelling, and the production of reactive oxygen clusters (ROS) (Drummond et al., 2009).The results of a study by Takarada suggest that low-intensity BFRT can lead to elevated lactate concentrations in blood, plasma, and myocytes.

Increased lactate levels favor growth hormone (GH) secretion, and an acidic intramuscular environment can also increase GH release (Manimmanakorn et al., 2013). Accumulation of metabolites promotes muscle hypertrophy by increasing physiological stresses such as cellular swelling, promotion of intramuscular protein synthesis, and recruitment of muscle fibers. In addition, the intramuscular acidic environment can modulate GH release by stimulating sympathetic nerve activity through chemosensory reflexes and type III and type IV afferent fibers (Karabulut et al., 2013). Since chemosensory pathways play an important role in regulating GH secretion, BFRT may increase GH release by decreasing intracellular pH levels. It should be noted that further studies are still needed to deepen our understanding of the specific mechanism by which BFRT causes muscle hypertrophy (Bugera et al., 2018). However, the results of existing studies suggest that low-intensity BFRT may be an effective training method to promote muscle growth and strength gain at lower loads (Rolnick et al., 2023).

Low-intensity pressurized resistance training (BFRT) may have a greater growth hormone (GH) stress response compared to high-intensity resistance training, although changes in blood lactate levels are not always an accurate predictor of GH secretion (Tian et al., 2022).GH and islet growth factor-I (IGF-I) play a critical role in muscle growth, development, and maintenance of muscle strength. Although the findings of Takarada et al. are controversial in some of the literature, the current findings suggest that the intramuscular acidic environment during BFRT may play a positive role in promoting muscle hypertrophy (Takarada et al., 2000).Reeves et al. also found that BFRT elicited a greater GH stress response compared to traditional high-intensity resistance training, although there was no significant changes in blood lactate levels between the two groups (Reeves et al., 2006).

Adaptations of BFRT to Neural and Muscle Activation

Previous research has shown that there is an interaction between low-intensity pressurized resistance training (BFRT) and neuromuscular adaptations (Velloso, 2008).BFRT combined with training can increase more muscle activity to achieve the same total power output. Researchers Loenneke et al. suggest that muscle hypertrophy may be due in part to the neuromuscular response induced by BFRT, which enhances neural activity and increases Type II motor unit (MU) recruitment (Fleck, 2011). Levels of neuromuscular activity can be measured by surface electromyography (EMG) during low-intensity pressurized and non-pressurized resistance training. A study by researchers Shinohara et al. found that the reduced oxygen supply that occurs during the BFRT condition led to a progressive recruitment of additional MUs. In addition, Takarada et al. recorded integral electromyographic (iEMG) values during unilateral knee extension and found that iEMG values were approximately 1.8 times higher during BFRT relative to non-BFRT (Abe et al., 2012). The BFRT group produced similar force and mechanical work, but with greater muscle activation, compared with the control group. Despite the lower BFRT loading intensity, the relatively low force generation level also recruited more fast-twitch muscle fibers due to the hypoxic intramuscular environment created by BFRT (Wilson et al., 2013). Increasing training load intensity enhances EMG activity and is associated with elevated blood lactate concentrations and greater metabolic demands on the muscle. At the same time, elevated blood lactate concentration is accompanied by increased H+ concentration, which triggers GH release and contributes to the hypertrophic response of fast-twitch muscle fibers. In summary, BFRT has a positive effect on muscle hypertrophy by enhancing neuromuscular activity and recruiting additional Mus (Patterson et al., 2019). This type of training enables higher muscle activation at relatively low loads and promotes muscle growth by creating a hypoxic intramuscular environment and increasing metabolic demand. In addition, BFRT triggers a muscle hypertrophic response through elevated blood lactate concentrations and GH release (Liu et al., 2021).

Many studies have also found that low-intensity pressurized resistance training (BFRT) and traditional high-intensity training can achieve similar results in increasing the effect of fast-muscle fiber recruitment (Rolnick et al., 2023).BFRT recruits more fast-muscle fibers at lower intensities due to the fact that the hypoxic environment resulting from the accumulation of metabolites is unsuitable for the mobilization of slow-muscle fibers.The results of BFRT have been shown to be more effective in increasing fast-muscle fiber mobilization than traditional high-intensity training (Tian et al., 2022). From the perspective of mechanical mobilization of muscle fibers, reduced oxygen supply and accumulation of metabolites can stimulate III and IV afferent nerves and inhibit α-motor neuron activity, thereby increasing the recruitment of fast muscle fibers to maintain muscle strength and prevent conduction failure. Thus, relative to the no-pressure condition, low-intensity BFRT can increase the recruitment and discharge frequency of motor units and activate more fast muscle fibers to participate in muscle activity (Hjortshoej et al., 2023). In addition, increased muscle electrical activity can stimulate the process of muscle protein synthesis through transcription of the Ca2 phosphatase and calmodulin-dependent kinase pathways. However, not all studies have found that BFRT significantly increases the degree of recruitment of fast muscle fibers. The results of some studies have shown similar levels of EMG activity in the quadriceps muscle during knee extension exercises performed under low-intensity BFRT and non-BFRT conditions (De Renty et al., 2023). Also, it has been shown that low-intensity BFRT does not necessarily increase the recruitment of fast-twitch muscle fibers as much as traditional high-intensity resistance training. Thus, the degree of mechanical tension is more important for regulating fast muscle fiber recruitment than metabolic stress in BFRT. Further studies are still needed to clarify the role of neuromuscular factors in the muscle adaptations induced by BFRT (Nascimento et al., 2022). However, it is certain that increased recruitment of fast-twitch muscle fibers is an important manifestation of adaptation to low-intensity BFRT-induced muscle growth (Knezevic et al., 2023).

Research Developments Related to Blood Flow Restriction Training (BFRT) and Metabolic Response

Research Developments Related to the Cardiovascular Effects of Blood Flow Restriction Training (BFR)

Ozaki compared metabolic and cardiovascular responses without and with blood flow restriction (CON) (Ozaki et al., 2017). By performing upright cycle exercise and measuring metabolic and cardiovascular parameters in 10 young men, it was found that in the BFR condition, stroke volume output per beat (SV) decreased by 25% and heart rate (HR) increased by 23%, resulting in an elevated rate pressure product (RPP) (Ozaki et al., 2010). However, mean arterial pressure (MAP) and total peripheral resistance (TPR) were not significantly different. In addition, the oxygen consumption (VO2) observed during BFR conditions presented an increase of approximately 10% per workload. During BFR, stroke volume output (SV) was impaired, but central cardiovascular function was maintained by increasing heart rate (Abe, Fujita, et al., 2010). Findings suggest that the use of BFR leads to greater energy demands and that heart rate and rate pressure product may not be valid indicators of exercise intensity.Staunton et al. compared the hemodynamic responses of young adults (YA) and older adults (OA) during resistance and aerobic flow limiting exercise (BFRE). It was found that BFRE elicited greater increases in blood pressure relative to controlled exercise (CON), especially more pronounced during leg press exercises. Blood flow restriction exercise resulted in an increase in cardiac output (Q) but was accompanied by an increase in heart rate and a decrease in stroke volume output (SV) (only in treadmill walking). The use of aerobic exercise as an appropriate BFRE prescription for limiting the effects of muscle atrophy in the elderly is supported by the observation of similar responses of YA and OA to BFRE. The findings suggest that the effects of aerobic exercise on metabolism may be even more important(Khalilzadeh & Tasci, 2017; Patterson & Brandner, 2018; Sieljacks et al., 2019).

Research developments related to the effects of blood flow restriction training (BFRT) on endocrine hormones

The effects of blood flow restricted training (BFRT) on endocrine hormones have been the subject of much research interest, and a study by Viru et al. compared plasma concentrations of cortisol, growth hormone (GH), insulin, testosterone, thyroid-stimulating hormone (TSH), free thyroxine (fT(4)), and triiodothyronine (T-3) during exercise in normal and blood flow restricted conditions (Viru et al., 1998). The results showed that exercising in an ischemic state increased GH concentrations twice as much as in normal conditions, while cortisol and T-3 also showed reactive increases (Rolnick et al., 2023; Sarfabadi et al., 2023). Another study, conducted by Loenneke et al, emphasized that blood flow restricted exercise had a lesser effect on testosterone but had a positive effect on increases in muscle size and strength (Yuan et al., 2023).A review study by Hjortshoej et al. found that low-load blood flow restricted resistance training (LL-BFRRE) elicited a greater response to growth hormone and testosterone compared to conventional free-flow resistance training (FFRE), with a concomitant attenuation of oxidative stress. while attenuating oxidative stress responses.

A study by Bugera et al. examined the effects of blood flow restricted resistance training (BFR-RE) on systemic myostatin responses (Bugera et al., 2018) and showed no significant effects on myostatin such as IL-6, IL-15, and decorin, while a study by Madarame et al. examined the hemostatic and inflammatory responses induced by blood flow restricted exercise in patients with ischemic heart disease, and showed that BFR applied to low-intensity training did not affect these responses. to low-intensity training did not affect these responses (Madarame et al., 2013). In contrast, Ozaki et al.'s study of walking training with blood flow restriction in older adults found that BFR-walk increased growth hormone levels, but there was no significant correlation with muscle hypertrophy (Ozaki et al., 2011).

Finally, a study by Karabulut et al. performed high-intensity resistance training (HIRT) and low-intensity with vascular restriction resistance training (LIBFR) in older men, and showed that no significant differences were seen between the two training regimens in terms of metabolic hormones, markers of muscle damage, and markers of inflammation, but that LIBFR training was safe and easily tolerated in older men and could be used to improve muscle strength (Karabulut et al., 2013).

In summary, blood flow restriction training has an impact in terms of endocrine hormones, with slight variations in the results observed in different studies, but overall supports the important role of metabolic stress in BFRT and emphasizes its potential role in muscle size and strength, as well as immune response.

Control of Training Variables for Blood Flow Restriction Training (BFRT)

Type of training

BFRT is a type of training that can slow down muscle atrophy when used alone without loading. Takarada et al. found that BFRT alone slowed down muscle atrophy and shortened the rehabilitation time of patients in postoperative rehabilitation after cruciate ligament surgery (Takarada et al., 2000). Therefore, BFRT can be used as a new rehabilitation treatment option for immobilizing the limb during the patient's bed rest period and after injury. However, to promote muscle growth, BFRT must be combined with a certain intensity of training load stimulation. Even when combined with simple walking, BFRT can promote increases in muscle strength and cross-sectional area (CSA).A study by Ozaki et al. found that older adults who performed 10 weeks of BFRT walking exercises 4 days a week, limiting blood pressure to 140-220 mmHg, experienced a 15% increase in maximal knee-extension strength and a 3% increase in thigh CSA. Meanwhile, a study by Abe et al. concluded that BFRT walking exercises performed for 6 weeks, 5 days per week, at 160-220 mmHg enhanced knee extension and flexion moments as well as thigh CSA in older adults, whereas there was no change in the non-BFRT group (Abe et al., 2005). In addition, low-intensity BFRT cycling exercises also increased thigh CSA and maximal strength in young adults. Thus, BFRT walking and cycling exercises can produce small or significant improvements in muscle CSA and strength (J. P. Loenneke, C. A. Fahs, et al., 2012).

Maximum muscle gains can be achieved when performing low-intensity BFRT resistance training. Because external blood pressure restriction limits blood flow between limbs, the muscles of the trunk cannot be trained under equivalent conditions, and studies have focused on the gain effects on limb muscles (Ozaki et al., 2017). Single-joint BFRT exercises produced significant muscle gains in both the arms and legs. Thus, BFRT may slow muscle atrophy in a clinically rehabilitated population. For those who cannot tolerate low-intensity resistance training, muscle atrophy can be slowed and hypertrophy stimulated by resting or walking, respectively. Low-intensity interval BFRT training with a blood pressure limit of 50 mmHg twice daily may also reduce functional muscle decline in untrained populations. In addition, 15-20 min of low-intensity aerobic exercise combined with BFRT exercises can promote muscle growth (Abe et al., 2012; Patterson et al., 2019).

Training Load

The main advantage of low-intensity blood flow restriction training (BFRT) is that using low-intensity exercises at 20-40% 1RM can yield similar results to high-intensity exercises at 70% 1RM or higher (Bridge et al., 2014). Therefore, low-intensity BFRT can be very beneficial for rehabilitation populations and injured athletes. Due to the low mechanical loads, BFRT does not result in skeletal muscle damage, long-term decline in muscle function, or excessive pain levels. Abe et al. found that the minimum resistance training intensities that caused hypertrophy of restricted limb and non-restricted trunk and gluteal muscles were approximately 10% MVC and 20% MVC, respectively. Loenneke et al. found by Meta-analysis that with an intensity of 15-30% 1RM or MVC intensity, BFRT had the greatest effect on muscle hypertrophy and strength. Another study found a 40.1% increase in knee extension 1RM and a 6.3% increase in quadriceps cross-sectional area after 8 weeks of 20% 1RM low-intensity BFRT knee extension training performed twice weekly (Abe, Sakamaki, et al., 2010). In addition, multiple sets of continuous BFRT training produced similar metabolic stimuli as multiple sets of high-intensity resistance training, whereas intermittent BFRT training produced less metabolic stimuli. Metabolite stimulation is one of the most important factors in the development of hypertrophic responses in muscles, and therefore it is recommended that training be performed with appropriate intervals as needed (J. P. Loenneke, T. Abe, et al., 2012). Recent studies have found that lower body BFRT using high intensity (70% 1RM, 5 sets of 5 repetitions) can significantly increase strength in the bench press and deep squat. However, no significant muscle strength and cross-sectional area gains were observed with moderate-intensity (12RM) and high-intensity (6RM) BFRT. This may be due to differences in the study population and 1RM calculation error, and further research is needed to confirm the effects of high-intensity BFRT in high-level athletes (Patterson et al., 2019; Yasuda et al., 2009). Therefore, for common populations considering the generalizability of the study, BFRT using an intensity of 20-40% 1RM or MVC may be the most appropriate intensity to promote muscle hypertrophy and strength gains (Rolnick et al., 2023; Vehrs & Johnson, 2023).

Training Volume

Training volumes of 45 to 75 repetitions per session have been used in some studies, and even some studies have utilized force-exhaustion exercises (De Renty et al., 2023). However, new research suggests that low-intensity BFRT can significantly increase muscle strength and cross-sectional area (CSA) without reaching force exhaustion. As a result, a popular BFRT protocol is to perform four sets of exercises, with 30 target repetitions in the first set and 15 target repetitions in the second through fourth sets, for a total of 75 repetitions (Tian et al., 2022). Although the optimal BFRT protocol has not yet been established, this protocol has been shown to have benefits in rehabilitation from knee injuries, enhancement of acute muscle activation, increases in muscle strength and cross-sectional area, and reductions in muscle fiber tissue damage. In BFRT training, a compression cuff may be used prior to the first set, which allows for more repetitions due to the absence of significant metabolite accumulation. Whereas, the number of repetitions may be reduced in each subsequent set of the exercise due to the accumulation of fatigue metabolites and the effects of metabolic acidosis on muscle contractile function(Loenneke et al., 2015; Teixeira et al., 2018).

However, the study by Wernbom et al. found that under sustained BFRT training conditions (pressurization of 90-100 mmHg), subjects were able to perform only 28 ± 5, 10 ± 2, and 6 ± 1 repetitions in the first, second, and fifth sets. Similarly, 26±1 repetitions were performed only in the group that performed 30% of the 1RM under moderately restrictive blood flow pressure conditions (Wernbom et al., 2012). Thus, in the early stages of BFRT training, the desired number of repetitions may not be achieved, requiring a reduction in exercise intensity (from 30% 1RM to 20% 1RM) or an increase in interval time (from 30 to 45 seconds) (Wernbom et al., 2009). Furthermore, the increased metabolic stress in the high repetition group may be a key factor in the adaptive regulation of BFRT. These findings highlight the importance of individualizing the implementation of BFRT training, and for the general population with no experience of resistance training or athletes who have been out of training for a long period of time, it may be necessary to adjust preset exercise loads to ensure that the workload of a low-intensity BFRT training regimen is comparable to that of traditional high-intensity training. Therefore, care should be taken to avoid overtraining-induced muscle fatigue during the early stages of BFRT training (Schoenfeld, 2010). As the individual gradually adapts to the training stimuli, a progressive approach should be adopted, aiming at a standard BFRT training program of 30-15-15-15 repetitions with 30-second inter-set intervals at 30% 1RM load (Fleck, 2011).

Interval Time

Most low-intensity BFRT studies usually utilize relatively short intervals, typically 30-60 seconds. Short intervals are closely associated with increased metabolic stress, which is a major regulator of physiologic responses in vivo to subsequent BFRT adaptations (Park et al., 2010). Unlike maximal strength training, the recovery time between sets in BFRT is enhancing targeted physiological responses rather than maintaining strength and power output (Ozaki et al., 2011). Additionally, limiting stimuli should be maintained during inter-set rest periods to further augment the degree of metabolic stress. While the accumulation of metabolites will undoubtedly affect exercise performance in subsequent sets, this is the primary adaptive mechanism of BFRT (Shinohara et al., 1998).

Frequency of training

The study by Abe et al. used low-intensity BFRT training at 20% 1RM twice a day and was found to increase 1RM values for the deep squat and leg flexion, as well as the cross-sectional area (CSA) of the thigh and gluteal muscles (Coburn, 1990). This demonstrates the ability to significantly increase strength with just 6 days of twice-daily BFRT training. This effect is comparable to that of traditional resistance training over a longer period of time and at a higher intensity or volume of exercise (Henneman et al., 1965). What's more, muscle damage indicators such as creatine phosphokinase and myoglobin, as well as oxidative stress indicators such as lipid peroxidation, were not elevated during and after training, even when BFRT training was performed at higher training frequencies (Michel et al., 2004). Therefore, short periods of high-frequency BFRT training are beneficial for overload training programs. However, high-frequency BFRT training may increase training monotony in participants, especially in the athlete population. Therefore, the frequency of conventional resistance training and BFRT training should be appropriately scheduled to ensure optimal adaptive responses and timely adjustment of participants' boredom (Chun et al., 2013).

Overview of the effectiveness of blood flow restriction training (BFRT) in different populations

Athletes

Many athletes develop muscular CSA and strength based on specialized qualities required, and training adaptations require athletes to spend extended periods of time before eliciting gains in effectiveness (Bugera et al., 2018). Due to the low intensity and less muscle damage of pressurized training, it can be used as a way for athletes to reduce their training load and also provide physiological stimulation for muscle adaptation. At the same time, low-intensity compression training can be used in place of traditional high-intensity resistance training to reduce the mechanical stresses placed on the muscles, thereby extending the life span of the sport (Kwon, 2016). Pressurization training can produce good adaptations to the athlete's muscles, and these adaptive responses include aspects of maximal strength, squat jump height, maximal and round-trip sprinting ability, agility, and aerobic shuttle running ability back. Therefore, low-intensity pressurized training not only benefits the untrained general population, but also improves athletic performance indices in athletes of all specialties (Behringer et al., 2017). Although low-intensity pressurized resistance training increases maximal strength, the percentage increase in 1RM is less than the percentage increase in muscle CSA (Ozaki et al., 2017). Furthermore, Manini et al. concluded that low-intensity pressurized resistance training does not promote muscle activation and stimulation of high-threshold motor units, suggesting that changes in muscle strength after pressurized training are more closely correlated with a rapid increase in muscle hypertrophy than traditional high-intensity resistance training, which results in an increase in strength through changes in neural stimulation (Khalilzadeh & Tasci, 2017; Kwon, 2016). Therefore, considering the overall development of athletic ability, compression training should not be used as the only means of muscle training, but in combination with traditional high-intensity resistance training, then optimal muscle adaptation may occur (Segal et al., 2015).

A study by Yasuda et al. confirmed that BFRT combined with traditional high-intensity resistance training resulted in better gains (Yasuda et al., 2010). In the study, participants performed low-load BFRT training (30% 1RM), traditional high-load training (75% 1RM), and a combination of the two methods (2 days of BFRT and 1 day of traditional training) for 3 days per week for 6 weeks (Abe, Fujita, et al., 2010). At the end of the training, the rate of increase in 1RM was similar in the high-load and combination training groups and was higher than in the BFRT group (8.7%). In terms of relative exercise intensity, the high-load and combination training groups increased by 10.5% and 6.7%, respectively, whereas the BFRT group showed no significant change (Yasuda et al., 2010). This implies that neural adaptation does not generally occur after BFRT training, but enhancement can be obtained by combining BFRT training with conventional training.

Yamanaka et al. demonstrated that low-intensity BFRT as a supplemental stimulus to traditional strength training significantly increased the 1RM of the bench press and deep squat in American soccer players (Yamanaka et al., 2012).Although this study did not report results in terms of changes in neural adaptations, it is possible that high-intensity resistance training and low-intensity BFRT training during the same training phase may provide a powerful stimulus for neural adaptations and enhance morphological responses (Park, 2020). Due to the low mechanical loading and low muscle damage during BFRT training, there is no negative impact on athletic performance during subsequent training. In addition, athletes' responses to BFRT may vary depending on their sport type. Takada et al. observed that metabolic stress was significantly higher in distance runners than in sprinters during BFRT training (Takada et al., 2012). This is due to the fact that distance runners have a greater aerobic capacity and are more dependent on oxygen delivery and transportation during exercise. As a result, their energy metabolism is more affected during BFRT training. In contrast, sprinters are more adapted to the anaerobic environment triggered by BFRT, so they experience relatively less metabolic stress(Schoenfeld, 2013). The study by Behringer et al. introduced BFRT into 100-meter sprint-specific training by selecting 24 sprinters for a 6-week period of twice-weekly 100-meter training. The athletes performed 6 sets of 100-meter interval training at 60-70% of their personal maximum speed. The results of the study showed that the 100-meter performance improvement was greater in the pressurized group (-0.38 ± 0.24 s) than in the non-pressurized group (-0.16 ± 0.17 s). Also, the rectus femoris muscle thickness and rate of force development (RFD) at knee extension were significantly increased in the pressurized group (Behringer et al., 2017).

Rehabilitation

BFRT training has a positive gain effect on strength synergy and joint immobilization in the elderly or post-operative rehabilitation population. In both young and old people, there is a progressive loss of overall muscle mass and gradual atrophy due to bed rest or prolonged periods of inactivity as a result of disease, surgery or injury (Javier Nunez et al., 2018). Studies have shown that BFRT during immobilization in a cast alone can attenuate these atrophic effects and can limit the functional decline in muscle strength (Bugera et al., 2018). Therefore, BFRT can well promote the rehabilitation of postoperative patients by delaying muscle atrophy and limiting the functional decline of muscles in order to rehabilitate faster and optimize the rehabilitation process (Kim et al., 2017). At the same time, even walking may be difficult in the early stages of rehabilitation as only low external loads can be tolerated. It has also been found that muscle thickness and strength increase after aerobic exercise in older adults, but the relative intensity used is too high, accounting for 60-80% of the heart rate reserve (Liu & Sabatini, 2020; Patterson & Brandner, 2018).

Combining BFRT training with aerobic exercise, such as walking or cycling, can lead to an increase in muscle CSA and strength, which facilitates early recovery after surgery or illness (Patterson et al., 2019). Loenneke et al. proposed a model for the gradual implementation of BFRT training from the early stages of rehabilitation through recovery to high-intensity resistance training, and this model follows four phases as follows:(1) BFRT training alone while bedridden; (2) low-intensity BFRT walking exercise; (3) low-intensity BFRT resistance training; and (4) low-intensity BFRT training combined with traditional high-intensity resistance training (Loenneke et al., 2014). This progressive model is based on sound scientific theories of increasing blood-limiting pressures during training as the participant progresses and implementing BFRT training protocols in the elderly and postoperative populations (Teixeira et al., 2018). Practitioners of BFRT training should also determine appropriate BFRT training protocols based on a rational assessment of the participant's individual functional capacity (Abe et al., 2012).

Physiological Mechanisms and Influences of Strength Training

Strength training is a form of physical activity in which muscle fitness is enhanced through the resistance of a muscle or muscle group against external resistance (Teixeira et al., 2018). Strength training programs are widely used in high school, college, and professional sports around the world as a core element in improving athletes' strength and performance (Sinclair et al., 2022). In addition, strength training is widely used in rehabilitation centers, the fitness industry, hospitals, and various other industries (Witard et al., 2022). Strength training has multiple benefits, including the promotion of muscle hypertrophy, improvement of muscular strength, enhancement of speed, agility, neuromuscular coordination, and localized muscular endurance, among many other qualities. It is important to note that strength training is performed through the use of weights, elastic bands, self-weight, or other forms of resistance (Patterson & Brandner, 2018). This method of training allows the size and form of resistance to be adjusted to meet the specific needs and goals of the individual (Saxton & Sabatini, 2017). Through systematic and consistent strength training, people can achieve significant gains in muscle strength and demonstrate better physical performance in everyday life and in a variety of athletic activities (Gronfeldt et al., 2020).

In conclusion, strength training plays an important role in improving muscular health and is widely used in various fields. Its benefits are not limited to the promotion of muscle hypertrophy and strength gains, but also include the improvement of speed, agility, neuromuscular coordination, and local muscular endurance and other qualities (Saxton & Sabatini, 2017; Sprick, 2018).

Physiological Mechanisms of Muscle Hypertrophy and Activation

(1) Biological factors: Muscle hypertrophy can be described as the growth and enlargement of individual muscle cells, which in adult males account for 45% of the overall mass. Human muscle is a highly plastic tissue capable of responding to appropriate signaling stimuli to promote muscle hypertrophy and strength growth (Liu & Sabatini, 2020). Research has shown that muscle fiber thickening is traditionally responsible for muscle hypertrophy following strength training. When skeletal muscle is overloaded with stimuli, it can cause destruction of muscle fibers or extracellular matrix. This may lead to a series of myogenic responses that ultimately allow for an increase in the total number of contractile protein units such as actin and myosin. In addition, the thickening of individual muscle fibers causes an increase in the cross-sectional area of the entire muscle, and the expansion of the extracellular matrix is a major pathway that promotes muscle hypertrophy (Wilson et al., 2013). Myoplasmic hypertrophy is also another possible mechanism causing muscle hypertrophy. During sarcoplasmic hypertrophy, an increase in various noncontractile elements and fluids may lead to sarcoplasmic growth (Laurentino et al., 2012). Centrifugal, centripetal, and isometric exercise can cause muscle hypertrophy, and the possible mechanisms include increased contractile proteins, extracellular matrix, satellite cells, myogenic pathways, cellular swelling, hypoxia, mechanical tension, damage to the muscle microstructure, and metabolic stress, all of which contribute to muscle growth (Manini & Clark, 2009). Through overload training, expansion of the extracellular matrix can be induced, creating a cascade effect of myogenic responses, leading to an increase in the size and number of contractile proteins in myogenic fibers. In addition, satellite cells can promote muscle hypertrophy in several ways. By exporting additional nuclei to myofibers, satellite

cells can upregulate mRNA production or expression of myogenic regulatory factors. In addition to this, strength training can also induce muscle growth through stimuli such as mechanical tension and hypoxia (Gronfeldt et al., 2020).

In summary, strength training is an effective method to promote muscle hypertrophy and strength growth. Stimuli such as overload, satellite cells, mechanical tension and hypoxia can promote muscle growth and thus improve physical function(Sarfabadi et al., 2023).

(2) Muscle fiber type: Studies have shown that performing more than 15 repetitions of strength training promotes muscle hypertrophy in slow muscle fibers, while muscle hypertrophy in fast muscle fibers is less pronounced (Gronfeldt et al., 2020). Slow muscle fibers have relatively small diameters compared to fast muscle fibers with higher oxidative capacity (e.g., IIa, IIB, and IIX) and therefore do not usually produce a significant muscle hypertrophic response when stimulated with mechanical tension (e.g., strength training) (Sinclair et al., 2022). As muscle fiber cross-sectional area (CSA) selectively hypertrophies from slow muscle fiber type I to IIa, IIX, and IIB, the body's endurance capacity decreases (Teixeira et al., 2018). Additionally, muscle hypertrophy occurs across muscle fiber types (IIa, IIx, and IIB) within the range of 8 to 12 repetitions performed. The researchers also noted that the rate of protein synthesis and catabolism in slow muscle fibers is much higher than in fast muscle fibers, and that the degradation of proteins in slow muscle fibers may be an important factor limiting their ability to produce muscle hypertrophy in response to mechanical tension stimuli (Wernbom et al., 2012). In addition, IGF-1 (insulin-like growth factor-1) concentrations produced different degrees of modulation in both high- and low-oxidizing muscle fibers and stimulated muscle hypertrophy in all four muscle fiber types. However, in the moderate repetition training range, mechanical loading induces changes in intracellular calcium ion concentrations in myocytes and increases growth hormone (GH) secretion, which increases the muscle hypertrophic effect in muscle fibers of types IIa, IIx, and IIB compared with type I muscle fibers. Upon completion of the strength training protocol,

cross-sectional area (CSA) values were greater for type IIa, IIx, and IIB muscle fibers compared to type I muscle fibers (Karabulut et al., 2013).

(3) In addition, the size principle of muscle activation is another factor that explains the muscle hypertrophic response (Nascimento et al., 2022). When exercise intensity or duration increases, the body recruits more muscle fibers to maintain force output. According to the order of activation, smaller slow muscle fibers are activated first before larger fast muscle fibers are activated. Therefore, activation of fast muscle fibers is one of the main causes of muscle hypertrophy (Behringer et al., 2017). To summarize, repetitions above 15 in strength training promote muscle hypertrophy in slow muscle fibers, whereas repetitions in the range of 8 to 12 are capable of causing muscle hypertrophy in different types of muscle fibers (Park et al., 2010). Factors such as mechanical tension, rates of protein synthesis and catabolism, IGF-1 concentration, growth hormone secretion, and the order of muscle activation all play important roles in muscle hypertrophy (Abe et al., 2005).

(4) Activation of fast muscle fibers: According to the "size principle", the order of recruitment of muscle fiber motor units is usually from small to large, from slow to fast. Small motor units are composed of smaller slow type 1 muscle fibers, which have a lower activation threshold (chan-Mo, 2008). Whereas large motor units consist of larger type II fast muscle fibers with a higher activation threshold (Sforzo & Touey, 1996). This order of recruitment allows the body to fine-tune and coordinate movements at different loads and speeds. However, in strength training, larger and harder-to-activate motor units can only be recruited by using heavy loads to produce maximum force (Madarame et al., 2013). Previously, the notion that "heavier is better" has been popular, but there is limited research to support this claim. In fact, under hypoxic conditions, fast muscle fibers can be recruited and activated in large numbers, even under low load conditions (Agorastos & Chrousos, 2022). Hypoxic conditions may result in restricted blood flow with accumulation of metabolites. Vascular obstruction increases lactate accumulation while decreasing lactate clearance. Reduced oxygenated arterial blood flow supplying working muscles limits oxygen delivery and creates an anaerobic

environment (Bugera et al., 2018). In addition, increased metabolites and decreased clearance may result in cellular swelling, and cessation of venous return retains these metabolites, preventing blood flow from the working muscle to remove metabolic byproducts. This process provides an optimal environment for the recruitment and replenishment of fast-twitch muscle fibers (Yamanaka et al., 2012). Therefore, the use of heavy loads in strength training can be effective in recruiting and activating fast muscle fibers, thereby increasing strength levels (Sarfabadi et al., 2023). At the same time, training in an anoxic environment also helps to promote the mobilization and replenishment of fast muscle fibers. These principles apply to the planning and execution of strength training and help optimize muscle hypertrophy and strength gains(Wilson et al., 2013).

Components of a strength training program

(1) Choice of exercise forms: generally single joint exercises such as elbow bends and knee extensions that Strength training is a training method that strengthens the muscular and skeletal systems through the use of heavy loads (De Renty et al., 2023). This training method consists of two forms of exercises: core exercises and assistance exercises. Core exercises require the mobilization of more than one large muscle group and more than two major joints to participate in the exercise to achieve the complexity of multi-joint coordination and neural activation. In the primary phase, core exercises require the use of heavier loading weights due to the involvement of multiple muscle groups (Jeremy P. Loenneke et al., 2012). Core exercises primarily include exercises such as squats, bench presses and upward thrusts. Also, assistance exercises are an integral part of this training modality. Assistive exercises are focus on specific muscles (Jeremy P. Loenneke et al., 2012). Complementary exercises help promote the development of core exercises and prevent muscle injuries from occurring. The main benefit of strength training is its ability to effectively enhance the health of the muscular and skeletal systems, as well as improve the body's endurance and stability (Sarfabadi et al., 2023). When performing strength training, it is important to pay attention to the balance of loading weight and training frequency. Appropriate loading weights are effective in recruiting and activating fast muscle fibers, thereby increasing strength levels (Yang et al., 2024). At the same time, proper training frequency ensures adequate muscle recovery and protection. In summary, strength training is a highly effective method of muscle building, and its combination of core and assistive exercises helps to promote healthy growth and prevent potential muscle damage (Schoenfeld, 2013).

(2) Exercise Sequence: The choice of exercise sequence and mode has a close relationship with the effect of strength training (Sarfabadi et al., 2023). A scientifically sound exercise sequence should consider the impact of each exercise on the others and prevent certain exercises from negatively affecting the technique or quality of the others. It was found that performing assistance exercises (e.g., elbow flexion and leg extension) first in the same training session resulted in a 75% decrease in the quality of bench press exercises and a 22% decrease in deep squat exercises (Takada et al., 2012). Additionally, Speuwenberg et al. found that performing assistance exercises targeting similar muscle groups before multi-joint core exercises also led to a decrease in the quality of core exercises (Knezevic et al., 2023). The correct sequence of exercises should be based on core exercises and assisted exercises. In practice, multi-joint core exercises such as squats, bench presses and overhead presses should be performed first in order to maximize the activation of multiple muscle groups and joints. This ensures that appropriate loading weights are used early in the workout to increase strength levels (Yuan et al., 2023). Only then perform single joint assistance exercises such as elbow flexion and knee extension to focus on specific muscles. This will help the muscles recover and protect better and prevent potential muscle injuries. In summary, the correct sequence of exercises is critical to the effectiveness of strength training (Schoenfeld, 2013). Core exercises should be prioritized over assistance exercises, and you should avoid performing assistance exercises that are similar to core exercises first. This will ensure that training results are maximized while preventing potential muscle injury (Yang et al., 2024).

(3) Training frequency: training frequency refers to the number or distribution of training programs completed, usually in the training process of athletes, coaches will develop an annual training plan, the annual plan is divided into several phases, i.e., "big cycle" (Wilson et al., 2013). During this period of time, according to the competition time nodes and goals, to achieve certain training goals, such as the pre-competition period, inter-competition period, the rest of the adjustment period, etc.. (Fahs, 2013)The macrocycle is then further subdivided into "microcycles", which are usually weekly training programs during which three to seven days of training take place. The choice of training frequency depends on the macrocycle in which the team is training.Kraemer et al. conducted a study of soccer training programs in the United States and found that teams that trained 4-5 days per week typically achieved better training results than teams that trained 3 or more days per week. Kraemer et al. found that teams that trained 4-5 days per week typically achieved better training results than teams that trained 3 or more days per week (Kraemer & Ratamess, 2005). These types of training programs typically use "split" training, alternating upper and lower body strength training with 1-2 days of rest prior to training days for the same muscle group (Ratamess et al., 2009). For example, in a four-day strength training program, upper body training is scheduled on Monday and Thursday, and lower body training is scheduled on Tuesday and Friday, with two days of rest and recovery for each of the consecutive training sessions. The relationship between training frequency and training intensity should also be considered. According to NASM (National Academy of Sports Medicine) recommendations, strength training for the same muscle group should not be performed again until 48 hours later in order to give the muscle adequate time for recovery and growth. Therefore, a reasonable training frequency in strength training should be 2-3 times per week to ensure adequate muscle recovery time and optimal training results (Kraemer et al., 1990). In summary, the choice of training frequency should be based on the macrocycle in which the training team is located, with appropriate rest periods scheduled in a timely manner, and the relationship between training intensity and muscle recovery should be considered. In strength training, a training frequency of 2-3 times per week is a reasonable choice to ensure that the training effect is maximized.

(4) Training intensity and number of repetitions: The intensity of strength training refers to the weight used or resistance overcome during training. The choice of intensity has a significant impact on immediate metabolic, hormonal, neurological and cardiovascular responses to training. Research has shown that by implementing high-intensity strength training at 80% to 85% of repetition maximum (1RM), neural adaptations can be further facilitated to improve motor unit recruitment, discharge frequency, and synchronization, which are critical for muscle hypertrophy and maximal strength development (Rolnick et al., 2023). In strength training, the pattern of motor unit recruitment has specific characteristics; high threshold motor unit recruitment is achieved when lifting at maximal or sub-maximal intensities, which cannot be achieved at small to moderate intensities. Only with a maximum number of motor units recruited can the muscle exert maximum strength, explosiveness, and muscle hypertrophic response (Yang et al., 2024). The number of repetitions is inversely related to intensity, and studies have shown that up to 6 repetitions using >85% 1RM intensity is effective in developing maximal muscular strength; 1-5 repetitions using 80%-85% 1RM intensity is effective in developing explosive power in single and multi-joint movements; 6-12 repetitions using 67%-85% 1RM intensity is effective in promoting the hypertrophic response of the muscle More than 12 repetitions using less than 67% 1RM intensity can be effective in developing muscular endurance levels (Segal et al., 2015).

(5) Training Volume: The training volume in strength training refers to the total amount of activity accomplished during the training process, which is usually expressed by the product of training intensity, number of sets and repetitions. In practice, training volume can be adjusted by changing the number of training sessions, increasing training density, adjusting the number of repetitions per session, and increasing or decreasing the number of training sets (Yang et al., 2024). However, too much training volume may lead to overtraining and reduced athletic performance, so specific adjustments need to be made on an individual basis and for training purposes

(Loenneke et al., 2015). Studies have shown that high training volume significantly improves muscular strength under similar conditions of training intensity, whereas low and moderate training volumes have no significant effect on the development of muscular strength (Su et al., 2024; Yuan et al., 2023). For example, Robbins et al. implemented a strength training program with three different training volumes, low (1 set), medium (4 sets) and high (8 sets), on athletes, and found that after 6 weeks, the high training volume group was able to significantly increase the 1RM values of the lower extremities, while the low and medium training volume groups showed no significant changes (Staunton et al., 2015). Therefore, training volume is crucial for the development of muscle strength. It should be noted that the increase in training volume should take into account the effects of repetitions and training load. In strength training, it is usually performed with high intensity and low repetitions, i.e., 1-5 repetitions using 80% to 85% of the repetition maximum (1RM) to develop explosive power in uni- and multi-joint movements, and up to 6 repetitions using greater than 85% of the 1RM intensity to efficiently develop maximal muscular strength. Additionally, training can be performed using less than 67% 1RM intensity when performing more than 12 repetitions to effectively develop muscular endurance levels (Bridge et al., 2014; Ratamess et al., 2009). In summary, training volume is critical to the effectiveness of strength training, but specific adjustments need to be made based on individual conditions and training objectives, and a comprehensive strength training program should be implemented to achieve better strength gains. In general, strength training is usually performed with high intensity and low repetition to achieve the best training effect.

(6) Intervals: Intervals are specific intervals of passive or active rest given during a series of strength training exercises (Sougiannis & Wallace, 2012). The length of the interval is related to metabolism and has a strong influence on the adaptive response induced by training. The purpose of any interval rest is to replenish the appropriate energy substrate for various types of strength training programs. In traditional high-load strength training, a 2-4 minute interval rest period is typically used to allow the anaerobic metabolic and neuromuscular systems to recover enough to train at a high intensity again. Research has shown that for different training purposes, a typical rest duration of 2-5 minutes is recommended for strength and explosive training, 30-90 seconds for muscle hypertrophy training, and less than 30 seconds for muscular endurance training (Kim et al., 2017; Marston et al., 2017). It should be noted that the length of intervals is also influenced by factors such as training intensity, training frequency, personal health and training experience. For example, for beginners, longer intervals (3-5 minutes) are recommended to allow the body to fully recover and to avoid overexertion. Meanwhile, as the training level increases, the interval time can be gradually shortened to enhance the challenge and effect of training (Loenneke et al., 2014; Manini & Clark, 2009). To summarize, interval time is one of the important and indispensable factors in strength training, and its length needs to be adjusted according to the individual situation and training purpose in order to obtain the best training effect.

Research Review

Numerous studies have shown that high-intensity resistance training at loads of 65% to 85% of 1RM can significantly promote muscle hypertrophy and strength gains. This effect is primarily triggered by the application of high mechanical tension stimuli to trigger constitutive changes such as biokines and muscle fiber types within muscle cells. The effects of high-intensity resistance training are influenced by several factors, including the right combination of exercise modality, sequence, frequency, intensity and number of repetitions, training volume, and intervals. However, despite the positive effects of high-intensity resistance training on muscle hypertrophy and strength gains, it may be more difficult to implement for specific groups such as the elderly and clinical rehabilitation patients. In addition, for the general population lacking training experience, performing high-intensity resistance training may lead to subjective discomfort and sports injuries. Therefore, when performing high-intensity resistance training, individual characteristics and ability levels need to be considered to ensure the safety and effectiveness of the training program.

Currently, blood flow restriction training (BFRT) has become a widely used training modality in postoperative rehabilitation and the elderly population, and has also produced some results in the general population who have not received systematic strength training, as well as in the athlete population. Studies have shown that the physiological mechanism of BFRT is mainly to trigger a series of adaptive responses through local hypoxic stimuli. In addition, metabolite accumulation combined with a hypoxic environment can stimulate the activation of group III and IV afferent fibers, which in turn promotes the recruitment of fast-twitch muscle fibers. Recruited fast-twitch muscle fibers may be associated with intramuscular protein synthesis and muscle adaptation (Madarame et al., 2013). However, the hypoxic environment created by varying degrees of blood flow restriction varies in the degree of promotion of fast-twitch muscle fibers. Therefore, it is critical to create a hypoxic environment that maximizes the recruitment of fast-twitch muscle fibers.

With the wide application of blood flow restriction training (BFRT) in strength training, rehabilitation therapy and other fields, the understanding of its physiological mechanisms and practical effects has been deepening. Scholars generally agree that BFRT can be safely and effectively applied in physical training programs for specialized athletes. Currently, there has been an increase in the literature on muscle adaptation, and the focus of research has gradually shifted to the appropriate range of blood flow limiting pressures. However, there are still many unanswered questions regarding the immediate effects of BFRT on neuromuscular responses as well as long-term adaptations, particularly in the following areas: (1) no studies have been reported on lower extremity neuromuscular adaptations during low-intensity blood flow-limited squat training; (2) the application of the percentage of arterial occlusion pressure (AOP%) determined by the individual's lower extremity circumference to study its effects on muscle activity is still relatively few, and its application in squat training maneuvers has not yet been reported; (3) existing studies have mainly focused on ordinary males and college students, while relatively few studies have been conducted on high-level athletes, especially on outstanding taekwondo athletes, which have not yet been covered by research (Bridge et al., 2014; Carpinelli, 2008). Therefore, further studies on BFRT are needed, especially on lower limb neuromuscular adaptation to low-intensity blood flow-limited deep squat training, the effect of AOP% on muscle activity as determined by individual lower limb circumference, and the application to outstanding taekwondo athletes. These studies will contribute to a more comprehensive understanding of the effects and mechanisms of BFRT (Su et al., 2012).

Based on the above background, the topics of this study were as follows: (1) to investigate the effects of different blood flow restriction pressure percentages (AOP%) and intervals on the lower limb muscle activity of excellent taekwondo athletes in order to determine the optimal range of AOP% and intervals to improve muscle activation; (2) to investigate the effects of implementing a low-intensity blood flow restriction weighted squat exercise program under the appropriate conditions of blood flow restriction pressures before and after on the immediate changes of lower limb muscle activity and fatigue indexes in excellent Taekwondo athletes; (3) to investigate the effects of 8 weeks of blood flow restriction training on the gain effects of body composition, circumference, maximal strength of upper and lower limbs and core muscles, isometric muscle strength, and lower limb explosive strength in excellent Taekwondo athletes. Through this study, we gained an in-depth understanding of the application of BFRT in excellent taekwondo athletes to provide a basis for developing a more scientific training program and to further promote the development of BFRT in the field of athletic training.

CHAPTER 3
RESEARCH METHODOLOGY

In this study, the investigators performed the following steps:

1.Research Design

2.Ethical Consideration

3.Participants in the Study

4.Research Instruments

5.Data collection

6.Data Analysis

Research Design

Basis of experimental design

This study explores the mechanisms underlying long-term adaptations in muscle strength, attributed to the cumulative impact of individual training sessions on muscle activation. Therefore, the study emphasizes the cumulative influence of individual training sessions on muscle activation. Initially, we examined the acute effects of pressurized squat exercises on lower-limb muscle activation, identifying the optimal blood-flow restriction pressure range and interval types that maximize muscle activation. We further analyzed acute changes in lower-limb muscle activation and fatigue before and after varying intervals within the pressurized exercise protocol. These investigations aim to establish the optimal blood-flow restriction pressure and interval strategies, enabling the design of lower-limb-focused pressurized training interventions. These interventions will further elucidate long-term adaptations in athletes’ body composition, circumferential measurements, and diverse strength enhancements.

In Experiment 1, we will investigate the immediate effects of the pressurised squat exercise on the activation of lower limb muscle groups and attempt to identify the optimal interval modality that elicits maximal activation of lower limb muscle groups. At the same time, the study will analyse the immediate changes in lower limb muscle activation and fatigue levels before and after different intervals of the pressurised exercise protocol.

In Experiment 2, we will use the optimal pressurised exercise protocol derived from Experiment 1 to carry out a lower limb-based pressurised training intervention programme and investigate its long-term adaptive effects on athletes' body composition, body circumference, and the effects of various strength gains. Through this experiment, we aim to provide a scientific basis for optimising athletes' training programmes.

Experiment 1: The effects of different arterial occlusion pressures (AOP%) and interval modalities on the surface electromyographic activity of the lower limb muscles of good taekwondo athletes in weighted deep squatting exercises.

Experimental design

1.The blood flow limiting pressure conditions in this study were categorized into four groups: no pressurization, 40% AOP, 50% AOP, and 60% AOP; and the interval mode was divided into an intermittent group (pressure removed during the intervals between groups) and a continuous group (pressure maintained during the intervals between groups). With this design, we will conduct a systematic study on the effects of different blood flow limiting pressures and intermittent modalities on the lower limb muscle activity of good Taekwondo athletes. In the experiment, this study will train participants in deep squats with different blood flow limiting pressures and interval modalities. The blood restriction pressures will be set as no pressurization, 40% AOP, 50% AOP and 60% AOP to observe the changes of muscle activities under different pressure conditions. Meanwhile, the intervals will be set as intermittent and continuous groups to compare the effects of different intervals on muscle activity. After each pressurized weight training session, we used a 6-20-point Borg RPE scale (Borg's Rating of Perceived Exertion Scale) to give a subjective perception rating to assess the athlete's perceived exercise intensity during training while monitoring heart rate and blood pressure. Through this experimental design, in a comprehensive understanding of the effects of different blood flow limiting pressures and intervals on the lower limb muscle activity of excellent taekwondo athletes, and It also monitors the exercise intensity of good taekwondo athletes and provides a scientific basis for developing more effective training programs.

Intervention Procedure

Before the start of the experiment, subjects will receive a detailed introduction to the experiment, including the concept and use of RPE (Rating of Perceived Exertion). Each subject will be asked to fill out a basic personal information form and take measurements of physical indicators, such as heart rate and blood pressure, before performing the exercise task. Subjects underwent 1RM test and thigh circumference measurement 72 hours before the EMG test experiment. On the day of the EMG test, after the subjects arrived at the laboratory, a 10-minute warm-up activity was performed, and then the experimental procedure was explained to the subjects in detail, and the electrode pads and electrode wires required for BFRT were installed. After the installation of the EMG electrodes, the Maximum voluntary contraction (MVC) test was performed on 8 muscles of the lower limb, and the surface EMG signal data were collected and recorded.After the MVC test, a warm-up experience with progressively increasing blood flow restriction was performed for 3 minutes, and finally, the BFRT weight-bearing squatting exercise test was performed.

Subjects completed 4 sets of BFRT weighted squat training programs under intermittent and continuous conditions, each program was four sets, the repetitions of the first set to the fourth set were 30time、 15time、 15time、 15time repetitions, each time squatting upward at maximal speed, with a break of 60 s between sets, and de-pressurization between sets of intermittent practice programs, and no de-pressurization between sets of continuous practice programs. 4 sets of external blood pressure limiting settings were set as follows in the order of the four sets of programs: ① No BFRT: ② 40% AOP relative value: ③ 50% AOP relative value: ④ 60% individual AOP relative value. The external blood pressure limiting conditions were selected according to the correspondence table of the relationship between arterial occlusion pressure and thigh circumference drawn by Loenneke et al. to select the relative value of individual blood pressure limiting (as shown in Table 1). Electromyography (EMG) of eight muscle surfaces of the lower limbs was recorded during deep squatting, and the EMG was analyzed to explore the differences in muscle activation of the lower limbs with different external blood pressure limitations, and to find out the relative values of individual blood pressure limitations that caused the maximum muscle activation. The four sets of interval and continuous training programs under different external blood pressure-limiting conditions were performed sequentially at the same time and place at intervals of 48 hours or more, After the subjects performed the exercise tasks of different intensities, the subjects were given subjective perception ratings according to Borg's Rating of Perceived Exertion Scale (RPE) to assess the intensity perception of each exercise task. At the same time, heart rate, blood pressure and other physiological indicators were measured again to assess the intensity of the exercise, and the whole process took about 2 weeks.

Correspondence between arterial occlusion pressure (AOP) and thigh circumference：

thigh circumference	pressure value(60%AOP)	pressure value(50%AOP)	pressure value(40%AOP)
<45-50.9cm	120mmHg	100mmHg	80mmHg
51-55.9cm	150mmHg	130mmHg	100mmHg
56-59.9cm	180mmHg	150mmHg	120mmHg
≥60cm	210mmHg	180mmHg	140mmHg

The test movement was a 30% 1RM weighted BFRT squat, with the subject standing on the Smith squat rack, eyes level, toes naturally separated, squatting to a knee angle of 60~70° after (thighs parallel to the ground), squatting requires simultaneous hip and knee extension, and finally a heel lift. A linear sensor was used to monitor the peak velocity of the barbell bar at each squat and to make it above 1.1m/s, which was determined to be the speed range for the development of rapid lower limb strength. A joint goniometer was used to determine and monitor the knee angle in real time during the squat exercise and to verbally cue the subject. A metronome was used to control the rhythm of the movements when the experiment was formally started, and this study specified that the test movements were 3 seconds/repetition, centrifugal squat for 2 seconds and centripetal squat for 1 second. Subjects controlled the timing and rhythm of each movement according to the metronome.

Measurement indicators

(1) Lower Extremity 1RM Test: Maximum static force during the half-squat was measured by the Load Incremental Test method using a linear sensing device, Gymaware (Australia, Kinetic Performance Technology Pty Ltd, standard model). Since load and velocity have a highly negative correlation, the athlete's maximal muscular strength can be predicted using the statistical method of linear regression (Load = m+b 土Z, with Load being the maximal force, m being the velocity, b being the intercept, and Z being the error value) . The incremental load maximal strength test based on force-velocity curves can well circumvent the risk of injury, and the maximal strength of an athlete can be predicted more accurately with 4-6 incremental loads of movement velocity. This method is safer and more efficient. During the test, the load of the athlete's squat is monitored against the velocity displayed by the sensor, and the load-velocity relationship is utilized to determine the athlete's maximal strength.

Figure 1 Linear Sensing Devices Gymaware

Source:baidu retrieved from https://ris.sogou.com/ris?flag=1&from=pic_result_list&query=http%3A%2F%2Fimg01.sogoucdn.com%2Fapp%2Fa%2F100520146%2Fb750042eef60a7cb202f07759ef1604b

(2) Thigh circumference test: Subjects separated their legs shoulder-width apart, placed a tape measure at the transverse line behind the pelvis, and measured the circumference of the thighs horizontally around one week. Three measurements were taken on each of the left and right legs, and the average value was taken as a reference. Each blood pressure limit level was set according to the right and left thigh circumference.

(3) Surface electromyography test: during exercise, we used an Italian Wave Plus electromyograph and 3M silver-silver chloride electrode pads to capture the subjects' rectus abdominis (RA), external abdominal obliques (ObliqusExternus Abdominis, OE), erector spinae (Erector spinae. ES), Gluteus Maximus (GM), Rectus Femoris (RF), Vastus Medialis Oblique (VMO), Semitendinosus (SM), and Biceps Femoris Muscle (BF). BF) myoelectric signals. We used dual electrode sheets for testing and aligned them with the muscle fiber orientation. Before the start of each test maneuver, we debugged the EMG acquisition system so that it was in a ready state. After the subject started to perform the movement, we turned on the acquisition system for EMG signal acquisition. Based on the experimental synchronized video recording, we selected all EMGs from group 1 to group 4 exercises. We rectified, filtered, smoothed and normalized the raw EMG data using the accompanying Emgserver analysis software. On the raw EMG, we selected the range of muscle exertion and calculated the RMS (root mean square) average. The RMS value of each muscle at maximum active contraction (MVC) was defined as the maximum RMS value for that subject, i.e., RMS MVC.To achieve standardization across subjects, we divided the EMG RMS values obtained throughout the experiment by the RMS MVC to obtain the RMS standardized value (%MVC).

(4) RPE (Rating of Perceived Exertion) is a scale for subjective assessment of exercise intensity, typically used to assess the perceived exercise intensity of athletes during training or competition.

While performing the exercise activity, try to maintain a steady intensity and pace of movement; ask the participant at intervals during the exercise (e.g., every 5-10 minutes) about their subjective perception of how they feel while exercising; and using an RPE scale, usually a 6-20-point Borg RPE scale, ask the participant to choose a number to describe their perceived intensity of the exercise. Typically, 6 indicates very easy exercise and 20 indicates very strenuous exercise. Subjects could choose the appropriate number to reflect their perceived level of exercise intensity based on how they felt about the exercise. The RPE value chosen by the subject each time is recorded for subsequent analysis and evaluation. The RPE test provides a more objective understanding of the subject's perceived intensity during exercise, which helps to adjust the training program and monitor the athlete's exercise condition. In practical application, we also combine the objective indicators of heart rate monitoring and blood pressure monitoring to more comprehensively assess the exercise load and effect. In this case, heart rate is measured using a heart rate monitoring device (e.g., heart rate watch, heart rate belt, or heart rate monitor) on the subject; when starting the measurement, make sure that the heart rate monitoring device has been calibrated and starts recording heart rate data. Blood pressure was measured using a standard sphygmomanometer (stethoscope or electronic sphygmomanometer); the subject should be sitting or lying down in a comfortable and relaxed position, with the arm placed flat at the level of the heart, and the cuff should be secured to the upper arm and adjusted to the appropriate size, with care taken to ensure that the subject did not talk or move, and that he or she remained quiet. After starting the measurement, the systolic (high pressure) and diastolic (low pressure) values are recorded and expressed in millimeters of mercury (mmHg).

Experiment 2: Study of the effects of 8 weeks of pressurised resistance training on the improvement of body composition and strength in outstanding taekwondo athletes

Experimental design

A two-factor repeated-measures experimental design was used, in which time was divided into pre-test, mid-test and post-test, and groups were divided into the pressurized group and the control group, to compare and analyze the changes in the indicators of body composition, body circumference, and lower limb and core strength of athletes of the two groups before and after 8 weeks of training.

Intervention process

The pressurized training equipment (KAATSU Master, made in Japan) was used to perform low-intensity resistance training for the lower limbs during the athletes' BFRT training. The training consisted of movements such as deep squats, hard pulls, weighted lunges, and resistance running to meet the requirements of the taekwondo team's daily training program. Prior to pressurization, athletes were required to perform a pressurized warm-up. The width of the pressurization band was 5 cm and the dress pressure was 40 mm Hg. During training, the pressure intensity was set at 50% of the individual maximum blood flow limiting pressure (AOP), and the optimal relative value of the individual blood pressure limiting pressure was selected according to the table corresponding to the relationship between the predicted value of blood flow obstruction and thigh circumference plotted by Loenneke et al. The BFRT training was carried out for 8 weeks, with 3 workouts performed per week. Four sets of each type of training were performed, with 30 repetitions in the first set and 15 repetitions in each of the remaining sets, with a 60-second interval between sets, and no depressurization during training. The load was reset 4 weeks after training based on the 1RM value from the midterm test.BFRT training is an alternative to traditional high-intensity resistance training.The control group of athletes performed traditional high-intensity resistance training at 70% of the 1RM, with 4 sets of 8-12 repetitions of each type of exercise, with a 3-minute inter-set interval, and the same duration and number of sets as in the BFRT workout.The BFRT group and control group The training components were identical except that four intervention training components were performed: deep squat, hard pull, weighted lunge and resistance running. Diet and rest periods were also the same.BFRT training was performed for 4 and 8 weeks, with mid- and post-testing of relevant indicators at the end of the training. Pre, mid, and post-test content, testers, and testing instruments were identical.

Measurement Indicators

(1) Body Composition Test: Before, during and after BFRT training, subjects were measured for body composition indicators using the Inbody720 instrument in the early morning in a fasted state. These metrics included body weight, muscle mass, body fat, percent body fat, and skeletal muscle mass.

(2) Body Circumference: Body circumference tests were performed during the same time period in the morning and were measured using a circumference scale. All tests were performed by two identical testers, the first tester was responsible for measuring chest and upper arm circumference and the second tester was responsible for measuring hip, thigh and calf circumference.

(3) Maximum Strength Test

Deep Squat/Hard Pull/Bench Press: Before and after the training interventions of Deep Squat, Bench Press and Hard Pull, we performed load incremental testing using Gymaware, an Australian linear sensing device, in order to test the athlete's maximal strength during Bench Press, Deep Squat and Hard Pull. During testing, we monitored the load of the athlete squatting or pushing up and combined this with the velocity displayed by the sensor to determine the athlete's maximal strength through the relationship between load and velocity. For bench press, we required that the speed of the first set of push-ups be greater than 1m/s, and the speed of the last set of push-ups be below 0.5m/s. For deep squatting or hard pulling, the speed of the first set of squatting or pulling-ups should be greater than 1m/s, and the speed of the last set of squatting or pulling-ups should be below 0.5m/s. The number of test sets for each movement is about 3-5 sets, and the incremental load of each set is between 10-30kg, depending on the athlete's body weight and strength.

Core area muscles: In this study, a core area strength test assessment system (V22801) made in Germany was used to test the maximum isometric contraction strength of the core area muscles of the abdominal and dorsal muscle groups in four modes, namely, flexion, extension, lateral flexion and rotation. The system is effective in assessing the level of core muscle strength in athletes. We took the best of the test results as the experimental results to accurately measure the core muscle group strength of the athletes.

(4) Isokinetic muscle strength test: A German-made isokinetic muscle strength training test system (ISOMED2000 model) was used to determine the muscle strength produced by isokinetic contractions. During the test, we used an angular velocity of 60% for knee extension and flexion peak moments, with eight measurements each at maximum effort on the right and left legs, respectively. During testing, the athlete's limb was placed on a chair seat and secured to the upper body, hip, and the thigh of the measured foot by means of specialized straps that adjusted the center of rotation of the knee joint in conjunction with the axis of rotation and secured the upper part of the ankle joint using specialized pads. The range of mobility is taken as 0° for the maximum extension position and can be rotated 90° in the direction of flexion. The test system can accurately assess the muscle power generated by the athlete's isometric contraction.

(5) Lower extremity explosive power: The vertical jump test is used to assess the vertical jump height of athletes by performing a half squat jump (SJ) and a lower squat jump (Counter movement jump, CMJ) on a vertical jumping mat. In the semi-squat jump test, the knee is held at a 120 angle with no counter movement to allow the athlete to jump as high as possible. The squat jump test, on the other hand, starts from a standing position and utilizes a squat reverse motion to jump as high as possible. To limit the impact of the swinging arm, the athlete is asked to jump with their arms crossed. Sufficient rest is required between each jumping exercise to eliminate the effects of fatigue. Each vertical jump test needs to be performed 3 times and the highest jump height is taken as the best performance. This method of testing provides an accurate assessment of the athlete's vertical jumping ability.

(6) 30-meter sprint run: On the athletic field, we use a tape measure to measure the 30-meter distance. An infrared timer was placed at the starting and finishing points. After ensuring that the instrument is zeroed, the athletes themselves adopt a standing start and sprint with all their strength. At the same time, the instrument

automatically records the sprint time. This measurement method can accurately obtain the sprint time of the athletes.

(7) 10-second time-limited kick test (FSKT10s): The FSKT10s test is an effective tool for evaluating the performance of Taekwondo athletes, and it can be used as one of the indicators of specialized anaerobic capacity testing for Taekwondo athletes. Relevant studies have shown that Wingate test results correlate with the FSKT10s test. In taekwondo competition, the ATP-CP system is mainly relied upon to provide energy to support high-intensity kicking and punching maneuvers. Anaerobic capacity is considered critical for taekwondo performance due to the 2-minute duration of each round of taekwondo competition, which requires explosive muscular exertion for offense and defense in a short period of time with multiple consecutive takedowns and pace adjustments of low intensity.The FSKT10s test is performed using sandbags and requires a maximal test of a horizontal kicking kick to be completed in 10 seconds, with alternation between the left and right legs . This test method is effective in assessing the level of explosive and anaerobic capacity of taekwondo athletes.

Ethical Considerations

The following ethical considerations need to be kept in mind when conducting the study:

Informed Consent: the researcher should ensure that all Taekwondo athletes participating in the study fully understand the purpose, process, and risks of the study and participate voluntarily. They should sign an informed consent form confirming that their participation is based on a voluntary and informed decision.

Respect for privacy: researchers should ensure that all personal information and data collected are treated confidentially and used only for research purposes. They should take appropriate measures to ensure data security and privacy.

Research Ethics Review: Researchers should submit the research plan and undergo ethical review in accordance with relevant regulations. They should comply with the recommendations and requirements of the ethics committee and ensure that the study design is in accordance with ethical principles.

Minimization of harm: Researchers should make every effort to minimize possible harm or discomfort to Taekwondo athletes. They should design a reasonable training program to ensure the safety of participants and provide the necessary rescue equipment and emergency treatment.

Interpretation and reporting of results: Researchers should interpret and report the results of the study honestly and objectively, avoiding manipulation of data or misrepresentation of facts. They should respect scientific ethics and follow the principles of academic integrity.

Participants of the Study

Participants in the study were mainly outstanding taekwondo athletes from the School of Physical Education and Sports, Henan Normal University, China. Inclusion criteria included: aged between 18-20 years, having experience in national or provincial competitions, being in good health, and not having undergone any lower limb surgeries. Exclusion criteria included: history of lower limb surgeries, recent injuries, or any diseases affecting athletic performance. A total of 20 excellent taekwondo athletes participated in the study.

Experimental equipment

Experiment 1 myoelectricity experimental equipment: Japan-made automatic air pressurization trainer and pressurized belt, the trade name of KAATSUMASTER; Italy-made Wave plus wireless surface myoelectricity tester and surface electrode tablets; Panasonic HC-V100 digital video camera; Australia-made linear sensor equipment Gymaware a unit; joint angle meter; A set of barbell bars and barbell plates, a Smith squat rack, a tape measure, a laptop computer, a metronome, etc. (Some of the instruments and equipment are shown in Figure).

Figure 2 Surface electrode sheet, Surface electromyography tester, Digital camera *figure by researcher

Main instrumentation for Experiment 1 section

Experiment 2 training intervention experimental equipment: Japan-made KAATSU Master pressurized training equipment; Australia-made Gymaware linear sensing equipment; Inbody720 body composition measuring instrument; Germany-made V22801 core area strength testing and evaluation system perimeter scale; Germany-made ISOMED2000 isokinetic plyometric training test system; longitudinal jump tester (Jianmin brand GMCS-11 type); infrared timer, markers, Smith's squat rack, barbell pieces, etc. (some of the instruments and equipment in Figure).

Figure 3 Tape measure, composition measuring instrument, Isokinetic muscle strength test system *figure by researcher

Overall hypothesis: blood flow restriction training (BFRT) significantly increases the activation of lower limb muscle groups relative to unpressurized training under equivalent loading conditions and can induce transient fatigue in the anterior thigh group after a single sustained session. After 8 weeks of BFRT training, athletes will experience long-term adaptive improvements in lean body mass, maximal strength, isometric muscle strength, and explosive qualities.

Subhypotheses:

(1) Relative to the no-pressurization training condition, continuous and intermittent BFRT weighted deep squat exercises will simultaneously increase motor unit discharge rates in the anterior and posterior thigh muscle groups and stimulate activation of the quadriceps and posterior femoral muscle groups in Excellent Taekwondo athletes. The optimal individual blood pressure limiting range was 40% to 50% AOP and the activation was greater with continuous practice than with interval training, but there was no significant difference between the two.

(2) Activation of the anterior and posterior thigh muscle groups increased significantly by the end of both the one-time continuous and intermittent BFRT weighted squat training protocols. However, at the end of the training session, activation of the anterior thigh muscle group decreased, whereas activation of the posterior thigh muscle group increased, with no significant change in the calf muscle group. Continued training resulted in a transient fatigue response in the anterior thigh muscle groups.

(3) After 8 weeks of lower extremity BFRT resistance training, the athletes showed improved body composition, increased body weight, decreased percent body fat, and increased maximal strength in the thigh circumference, hip circumference, and core area muscle groups. In addition, BFRT training was comparable to, if not better than, traditional resistance training in improving maximal strength, isometric muscle strength, and lower extremity explosive strength.

Data collection

According to the experimental design described above, data collection was mainly carried out in the following ways:

Lower Extremity 1RM Test: A linear sensing device, Gymaware (Australia, Kinetic Performance Technology Pty Ltd, Standard), was used to measure maximal static force during the half-squat by the load-escalation test method, which predicted the athlete's maximal muscular strength.

EMG signal data acquisition: the subjects' rectus abdominis (RA), external abdominal oblique (ObliqusExternus Abdominis, OE), erector spinae (ES), gluteus maximus (GS), rectus femoris (RF), vastus medialis Oblique (VMO), semibondus (VMO), and vastus medialis Oblique (VMO) muscles were analyzed by using the Wave Plus EMG meter made in Italy and the 3M Silver-Silver Chloride Electrode Sheets. Gluteus Maximus, GM), Rectus Femoris, RF), Vastus Medialis Oblique, VMO), Semitendinosus, SM), and Biceps Femoris Muscle, BF) were the eight muscles for which the EMG signal data were acquired.

Exercise intensity monitoring: the RPE Subjective Assessment of Exercise Intensity scale was collected, and subjects gave subjective perception ratings based on Borg's Rating of Perceived Exertion Scale (Borg's RPE Scale). Heart rate was measured using a heart rate monitoring device (e.g., heart rate watch, heart rate belt, or heart rate monitor); blood pressure was measured by using a standard sphygmomanometer or an electronic sphygmomanometer.

4. Body Composition Testing: Measurements of body composition metrics including body weight, muscle mass, body fat, body fat percentage and skeletal muscle mass are performed using the Inbody720 instrument.

5. Body Circumference Measurement: Measurements are taken using a circumference scale, including chest circumference, upper arm circumference, hip circumference, thigh circumference, and calf circumference.

6. Maximum Strength Test: Load incremental testing of movements such as deep squat, hard pull and bench press using a linear sensing device, Gymaware, to test the athlete's maximum strength in these movements.

7. Core Zone Muscle Strength Test: The Core Zone Strength Test Evaluation System (V22801) made in Germany was used to test the maximum isometric contraction strength of the core zone muscles of the abdominal and dorsal muscle groups in four modalities: flexion, extension, lateral flexion, and rotation.

8. Isometric muscle Strength Test: The Isometric Strength Training Test System (Model ISOMED2000) made in Germany was used to determine the muscle strength generated by isometric contraction.

9. Lower Extremity Explosive Strength Test: Athletes' vertical jumping ability and explosive strength were evaluated by vertical jumping ability test and 30-meter sprint run.

10.Seconds Limited Time Kick Test (FSKT10s): used to assess the level of explosive power and anaerobic capacity in Taekwondo athletes.

Data Analysis

Experiment 1: The data collected were analyzed using IBM SPSS Statistics 26 software. The study employed descriptive statistics, including mean ± standard deviation, to summarize and describe the data. To assess the normal distribution of the variables, we utilized the Shapiro-Wilk test; additionally, to check the homogeneity of variances, we conducted the Levene test. To evaluate the effects of different blood flow restriction pressures on RMS standardized values (%MVC) of large and calf muscle groups, we performed a two-way ANOVA. The factors analyzed included blood flow restriction pressure (50% APO) and training modality (intermittent and continuous training). This analysis allowed us to identify significant differences between groups and their interactions. For the data presented in Tables 2 and 3, we utilized repeated measures ANOVA to examine the changes in RMSMVC values (μV) and RMS standardized values (%MVC) before and after the intervention across different groups (intermittent and continuous training). This analysis helped us determine the effect of the time factor on each group and assess the significance of the intervention effects. In Table 4, we also employed repeated measures ANOVA to assess the changes in subjective fatigue scores before and after the intervention across different groups (Continuous pressorization (A), Intermittent pressor (B), No pressurization (C)). This analysis allowed us to identify the effects of different training modalities on fatigue perception and evaluate their statistical significance.In addition, we used analysis of covariance to control for confounding variables (e.g., height, BMI, and age) and to compare outcome indicators between groups using the Bonferroni method. In addition, effect size indicators, such as ηp^2 and Cohen's d, can be calculated to measure the size of the intervention effect. Typically, small effect sizes are 0.01/0.20, medium effect sizes are 0.06/0.50, and large effect sizes are 0.14/0.80 (Khalilzadeh & Tasci, 2017). The significance level was set at $p < 0.05$.

Experiment 2: A two-way repeated-measures ANOVA was conducted to examine the effect of the intervention across two groups (pressurized and control) at three different time points (pre-test, mid-test, and post-test). This ensures clarity and consistency in the statistical methods employed. Confounding variables (baseline, sex, BMI, and age) were controlled for by analysis of covariance, and outcome indicators were compared between groups using the Bonferroni method. In addition, statistically significant effect sizes were calculated, expressed as η p^2 and Cohen's d, with a small effect of 0.01/0.20, a medium effect of 0.06/0.50, and a large effect of 0.14/0.80 (Khalilzadeh & Tasci, 2017). The level of significance was set at $p < 0.05$.

CHAPTER 4

DATA ANALYSIS AND RESULTS

Experiment 1: Effects of different AOP% and interval modes on the surface electromyographic activity of the lower limb muscles of good taekwondo athletes during weighted deep squatting exercises

1. Effects of different blood restriction pressures and intervals on the activation level of thigh and calf muscles in taekwondo athletes

Table 1 demonstrates the effects of different blood restriction pressures and intervals on the RMS standardized values (%MVC) of the large and calf muscle groups. The results were tested for statistical significance by two-way ANOVA (F-value and p-value). For the rectus femoris, there was no significant difference in the effect of blood restriction pressure on muscle group RMS between the intermittent and continuous training scenarios (p=0.04 for the main effect of pressure), whereas neither the intermittent modality (p=0.09) nor its interaction effect (p=0.95) reached the level of statistical significance. The effect of blood-limiting pressure in the medial femoral muscle was significant (p=0.002), but the intermittent modality (p=0.42) and its interaction effect (p=0.70) were not significant. Analysis of the lateral femoral muscle showed a significant effect of blood-limiting pressure on RMS (p=0.007), but the intermittent modality (p=0.55) and interaction effect (p=0.80) were not significant. Biceps femoris also showed significance in blood-limiting pressure (p=0.008), but the intermittent modality (p=0.14) and its interaction effect (p=0.99) were not significant. The results for the semitendinosus muscle showed the effect of blood-limiting pressure to be close to significant (p=0.04), while the intermittent modality (p=0.81) and the interaction effect (p=0.72) were not significant. Blood-limiting pressure on gluteus maximus had a significant effect on RMS (p=0.03), but the intermittent modality (p=0.61) and interaction effect (p=0.93) did not reach the level of statistical significance. In summary, blood restriction pressure had a significant effect on RMS standardized values of the thigh muscle groups, especially in the medial and lateral femoral muscles, whereas the effect of the intermittent approach was more limited. For the gastrocnemius muscle, the main effect of blood restriction pressure was significant (p=0.03), indicating that different levels of blood restriction pressure had a significant effect on RMS standardized values for the gastrocnemius muscle. Specifically, RMS criterion values were significantly different between no pressurization and 40% AOP (p=0.03), 40% AOP and 50% AOP (p=0.03), but not between 50% AOP and 60% AOP (p=0.14). Under continuous training, although RMS criterion values varied between stress levels, the differences did not reach significant levels. For the tibialis anterior muscle, the analysis showed that blood-limiting pressure (p=0.39), intermittent modality (p=0.21), and its interaction effect (p=0.99) did not reach the level of statistical significance. The effect of each blood-limiting pressure level on the RMS criterion values of the tibialis anterior muscle was not significant under either intermittent or continuous training. In conclusion, the RMS standardized values of the gastrocnemius muscle were significantly affected by blood-limiting pressure, whereas the RMS standardized values of the tibialis anterior muscle did not respond significantly to changes in blood-limiting pressure and interval mode.

Multiple comparisons revealed significant effects of different blood restriction pressures and intervals on the RMS standard values of the thigh and calf muscle groups. Regarding the thigh muscle groups, the RMS standardized values of the rectus femoris, medial femoris, lateral femoris, biceps femoris, semitendinosus, and gluteus maximus under interval training were significantly elevated with the increase of blood-limiting pressures, with the effects of 50% AOP and 60% AOP being particularly significant (p<0.05), especially in the medial femoris and lateral femoris muscles. The overall effect was weaker (p<0.05) under continuous training conditions than under interval training, although the stress level had a significant effect on the RMS standardized values of some muscle groups such as the lateral femoral and biceps femoris. For calf muscle groups, gastrocnemius responded significantly to different blood-limiting pressures under interval training, whereas RMS standardized values of tibialis anterior did not show a significant difference in response to blood-limiting pressures (p>0.05). Overall, blood-limiting pressure had a significant effect on the RMS standardized values of the thigh muscles under interval training, while the effect on the calf muscles was more limited.

Table 1 Effect of different blood restriction pressures and intervals on RMS standardized values (%MVC) of large and calf muscle groups (n=20)

Position	Interval mode	Blood restriction pressure				Two-factor ANOVA-F value (p-value)		
		No pressurization	40%AOP	50%AOP	60%AOP	Pressure	Intermittent mode	Interaction effect
Rectus	Interval	36.5±7.5	43.5±10.5*	44.5±9.5*	41.1±6.8	2.89	2.70	0.10
femoris	continued	34.1±6.9	40.5±9.8	40.6±7.8	39.3±9.5	(0.04)	(0.09)	(0.95)
Medial	Interval	47.5±5.1	52.9±9.1	56.5±8.2*	58.6±4.0*	5.21	0.72	0.47
femoral muscle	continued	47.9±6.7	54.8±10.2	57.8±7.2*	55.7±3.7	(0.002)	(0.42)	(0.70)
Lateral	Interval	40.8±10.9	45.8±9.7	48.9±9.2*	45.5±4.7	4.40	0.43	0.34
femoral muscle	continued	38.9±6.2	45.4±3.0*	49.5±1.9*	44.2±5.9*	(0.007)	(0.55)	(0.80)
Biceps	Interval	25.0±10.9	31.3±8.9	34.5±7.6*	32.1±13.8	4.20	2.24	0.025
femoris	continued	25.8±9.9	32.8±8.2	32.1±13.8*	27.9±8.7	(0.008)	(0.14)	(0.99)
semitendin	Interval	14.5±6.8	17.8±5.5	19.9±6.1*	23.7±13.8*	2.85	0.06	0.45
osus	Interval	15.2±12	18.8±9.0	20.5±7.9*	20.11±7.8	(0.04)	(0.81)	(0.72)
Gluteus	Interval	32.3±8.5	31.3±8.7	36.6±7.1	38.4±4.8*	3.26	0.20	0.15
maximus	continued	31.3±6.5	32.7±8.3	37.6±6.4*	37.0±5.2*	(0.03)	(0.61)	(0.93)
Gastrocne	Interval	32.1±9.5	35.1±7.9	39.5±7.2	36.2±7.8	2.43	0.03	0.004
mius	continued	31.3±9.8	35.9±8.1	35.8±7.9	39.4±5.8	(0.03)	(0.86)	(0.68)
Tibialis	Interval	44.2±12.5	40.4±10.8	39.1±10.9	38.4±11.5	1.02	1.58	0.01
anterior	continued	41.1±7.5	36.4±13.2	36.3±11.9	34.5±11.1	(0.39)	(0.21)	(0.99)

Note: * indicates significant differences compared to the unpressurized state ($p<0.05$)

2. Immediate effects of pressurized weighted squatting exercises on lower limb muscle activation and fatigue in taekwondo athletes

(1) Characteristics of changes in RMSMVC values of lower limb muscle groups before and after pressurized squatting exercises

The results of the effects of pressurized squat training on the RMSMVC values of the lower limb muscles are shown in Table 2, which shows that the difference in RMSMVC values of the rectus femoris muscle under intermittent pressurization was -23.32 μV (95% CI: -64.24 to 17.60), with a p-value of 0.27, which did not reach significance, whereas the difference was -52.94 μV (95% CI: -113.45 to -7.58) under continuous pressurization with a p-value of 0.27. 7.58), with a p-value of 0.002, showing a significant reduction and a Cohen's d of -0.43, with a moderate effect size. The difference in intermittent pressurization of the medial femoral muscle was -23.00 μV (95% CI: -60.65 to 58.65), with a p-value of 0.58, which was not significant, and the difference in continuous pressurization was -57.05 μV (95% CI: -159.20 to 45.10), with a p-value of 0.26, which was also not significant. The lateral femoral muscle had a difference of -8.00 μV (95% CI: -105.83 to 89.83) with a p-value of 0.85 under intermittent compression and -30.63 μV (95% CI: -92.59 to 31.33) with a p-value of 0.34 under sustained compression, which also did not show significance. The difference for biceps femoris under intermittent pressurization was 108.10 μV (95% CI: 87.30 to 303.50), with a p-value of 0.01, a significant increase, and Cohen's d of 0.38; the difference for continuous pressurization was 61.36 μV (95% CI: -56.88 to 179.60), with a p-value of 0.30, which was not significant. The difference for the semitendinosus under interval pressurization was 66.55 μV (95% CI: 20.12 to 183.22), with a p-value of 0.23 and a Cohen's d of 0.39 for a moderate effect size; the difference for continuous training was 11.12 μV (95% CI: -55.12 to 77.36), with a p-value of 0.73, which was not significant. The gluteus maximus had a difference of -25.08 μV (95% CI: -110.90 to 60.74) with a p-value of 0.57, non-significant, with interval training, and a difference of -69.66 μV (95% CI: -186.95 to -47.63) with a p-value of 0.004, significantly lower, and a Cohen's d of -0.41, with a moderate effect size, with continuous training. The difference in the gastrocnemius muscle was -37.29 μV (95% CI: -96.88 to 22.30) with a non-significant p-value of 0.23 under intermittent pressurization, and -18.72 μV (95% CI: -76.54 to 39.10) with a non-significant p-value of 0.51 for continuous training, again non-significant. The difference for the tibialis anterior was -14.94 μV (95% CI: -87.58 to 57.70) with a non-significant p-value of 0.70 for intermittent pressurization, and -8.31 μV (95% CI: -46.65 to 30.03) with a p-value of 0.67 for continuous pressurization, also non-significant. These results suggest that pressurized deep squat training has different effects on RMSMVC values for different muscle groups under different pressurization training modalities.

Table 2 Characteristics of changes in $_{\text{RMSMVC}}$ values (μV) of lower limb muscle groups before and after pressurized deep squat exercise (n=20)

Position	Interval mode	Pre-training	Post-training	Difference(95%CI)	p	Cohen's d
Rectus femoris	Interval (50%APO)	598.43±107.65	575.11±125.6	-23.32 (-64.24, 17.60)	0.27	—
	Continuous (50%APO)	601.15±144.31	548.21±101.56	-52.94 (-113.45, -7.58)	0.002	-0.43
Medial femoral muscle	Interval (50%APO)	504.25±148.65	481.25±198.25	-23.00 (-60.65, 58.65)	0.58	—
	Continuous (50%APO)	498.25±186.25	441.20±175.55	-57.05 (-159.20, 45.10)	0.26	—

Table 2 (Continued)

Position	Interval mode	Pre-training	Post-training	Difference(95%CI)	p	Cohen's d
Lateral femoral muscle	Interval (50%APO)	405.15±117.25	397.15±175.60	-8.00 (-105.83, 89.83)	0.85	—
	Continuous (50%APO)	399.78±105.25	369.15±111.25	-30.63 (-92.59, 31.33)	0.34	—
Biceps femoris	Interval (50%APO)	514.15±197.15	622.25±253.31	108.10 (87.30, 303.50)	0.01	0.38
	Continuous (50%APO)	531.25±143.25	592.61±124.01	61.36 (-56.88, 179.60)	0.30	—
semitendinosus	Interval (50%APO)	478.65±171.53	545.20±96.15	66.55 (20.12, 183.22)	0.23	0.39
	Continuous (50%APO)	440.51±137.89	451.63±87.12	11.12 (-55.12, 77.36)	0.73	—
Gluteus maximus	Interval (50%APO)	437.20±127.15	412.12±101.11	-25.08 (-110.90, 60.74)	0.57	—
	Continuous (50%APO)	427.31±170.12	357.65±212.15	-69.66 (-186.95, -47.63)	0.004	-0.41

Table 2 (Continued)

Position	Interval mode	Pre-training	Post-training	Difference(95%CI)	p	Cohen's d
Gastrocnemius	Interval (50%APO)	349.51±123.15	312.22±81.51	-37.29 (-96.88, 22.30)	0.23	—
	Interval (50%APO)	340.13±110.11	321.41±80.42	-18.72 (-76.54, 39.10)	0.51	—
Tibialis anterior	Interval (50%APO)	576.51±141.13	561.57±110.15	-14.94 (-87.58, 57.70)	0.70	—
	Continuous (50%APO)	589.20±99.20	580.89±122.89	-8.31 (-46.65, 30.03)	0.67	—

(2) Characteristics of changes in RMS standard values of lower limb muscle groups before and after pressurized squatting exercise

The results of the changes in the RMS standard values of the lower limb muscle groups before and after the pressurized squat exercise are shown in Table 3: Continuous pressurized training was performed on the rectus femoris muscle (RMS standard value increased from 49.60% to 58.24%, p=0.003, Cohen's d=1.05), biceps femoris muscle (increased from 33.40% to 38.93%, p=0.075, Cohen's d=0.75), gluteus maximus (from 48.30% to 58.98%, p=0.009, Cohen's d=1.16) muscle groups showed significant gains. In contrast, interval compression training showed significant improvement in the rectus femoris (RMS criterion values increased from 48.40% to 55.23%, p=0.007, Cohen's d=0.62), biceps femoris (increased from 29.68% to 39.35%, p=0.003, Cohen's d=0.87), gastrocnemius (increased from 49.00% to 55.67%, p=0.031, Cohen's d=0.65) were significant in the muscle groups. The lateral femoral muscles decreased significantly during continuous compression training (from 54.67% to 42.20%, p=0.007, Cohen's d=-1.48), whereas the change was not significant during interval compression training. Comparison between groups revealed significant differences between Interval and Continuous groups in Rectus femoris, Lateral femoral muscle, Biceps femoris, Gluteus maximus, and Gastrocnemius (p<0.05).

Table 3 Characteristics of the change in RMS standardized values (%MVC) of lower limb muscle groups before and after pressurized deep squat exercise (n=20)

Position	Interval mode	Pre-training	Post-training	Difference(95%CI)	p	Cohen's d
Rectus femoris	Interval	48.40±4.25	55.23±9.89*	6.83 (2.19, 11.47)	0.007	0.62
	Continuous	49.60±7.52	58.24±5.68	8.64 (3.83, 13.45)	0.003	1.05
Medial femoral muscle	Interval	55.12±5.23	57.53±6.23	2.41 (-0.32, 5.14)	0.083	0.27
	Continuous	53.57±5.78	57.73±5.98	4.16 (0.34, 7.98)	0.029	0.51
Lateral femoral muscle	Interval	54.33±6.00	55.33±5.66**	1.00 (-2.34, 4.34)	0.564	0.13
	Continuous	54.67±6.45	42.20±11.86	-12.47 (-21.77, -3.17)	0.007	-1.48
Biceps femoris	Interval	29.68±10.70	39.35±4.63**	9.67 (3.95, 15.39)	0.003	0.87
	Continuous	33.40±3.89	38.93±7.28	5.53 (-0.53, 11.59)	0.075	0.75
semitendinosus	Interval	34.75±11.54	41.70±13.18	6.95 (-1.04, 14.94)	0.093	0.49
	Continuous	47.30±8.87	53.00±10.71	5.70 (-0.53, 11.93)	0.066	0.53
Gluteus maximus	Interval	49.60±7.64	52.48±9.40**	2.88 (-3.82, 9.58)	0.419	0.24
	Continuous	48.30±4.24	58.98±9.97	10.68 (2.97, 18.39)	0.009	1.16

Table 3 (Continued)

Position	Interval mode	Pre-training	Post-training	Difference(95%CI)	p	Cohen's d
Gastrocnemius	Interval	49.00±6.09	55.67±8.90*	6.67 (0.50, 12.84)	0.031	0.65
	Continuous	48.05±13.04	53.98±10.65	5.93 (-4.65, 16.51)	0.275	0.40
Tibialis anterior	Interval	46.53±12.38	52.35±9.87	5.82 (-0.60, 12.24)	0.077	0.52
	Continuous	44.10±13.34	50.25±9.75	6.15 (-2.29, 14.59)	0.146	0.55

Note: * indicates significant difference in results between intermittent and continuous group comparisons (*p<0.05, **p<0.01)

(3) Characteristics of Subjective Fatigue Scores before and after Pressurized Squat Exercise

This study compared the effects of continuous pressurization training, interval pressurization training and no pressurization training on subjects' subjective fatigue scores. The results showed that continuous pressurization training significantly increased fatigue scores from 3.23±0.56 to 7.26±0.79 (difference 4.03, 95% CI: 3.68-4.38, p<0.001, Cohen's d=5.93), demonstrating a very high effect size. Intermittent pressurization training also significantly increased fatigue scores from 3.21±0.47 to 7.09±0.72 (difference 3.88, 95% CI: 3.62-4.14, p<0.001, Cohen's d=6.69), with a high effect size. Fatigue scores increased from 3.56±0.41 to 5.48±0.56 (difference 1.92, 95% CI: 1.67-2.17, p=0.017, Cohen's d=4.00) for the no-pressure training, and between-group comparisons showed significantly lower subjective fatigue scores than those of the pressure training group (p<0.05).

Table 4 Characteristics of subjective fatigue score changes in subjects before and after pressurized deep squat exercise (n=20)

Group	Before training	After training	Difference(95% CI)	p	Cohen's d
Continuous pressorization	3.23±0.56	7.26±0.79##	4.03 (3.68,4.38)	<0.001	5.93
Intermittent pressor	3.21±0.47	7.09±0.72##	3.88 (3.62,4.14)	<0.001	6.69
No pressurization	3.56±0.41	5.48±0.56	1.92(1.67, 2.17)	0.017	4.00

Note: # indicates that the results of the intermittent and continuous groups compared with the No pressurization group are significantly different (#p<0.05, ##p<0.01).

3.The discussion of experiment one

The purpose of this chapter was to investigate the effects of different blood limiting pressures (AOP%) and interval modes on the surface electromyographic activity of the lower limb muscles of excellent taekwondo athletes. By systematically analyzing the weighted squat exercise under different pressure conditions, it was found that blood-limiting pressure had a significant effect on the activation level of the thigh and calf muscle groups, especially under interval training conditions. Specifically, the results showed that the RMS standardized values of the thigh muscles, including rectus femoris, medial femoris, lateral femoris, and biceps femoris, were accompanied by increased RMS standardized values under different blood restriction pressure conditions, and the performance was particularly significant at 50% AOP and 60% AOP ($p<0.05$), suggesting that an increase in the blood restriction pressure effectively promotes the activation of these muscle groups. This finding has important implications for understanding the physiological mechanisms of blood flow restriction training, especially for applications in enhancing athletic performance and muscle strength. In addition, the study revealed the different effects of interval training versus continuous training on lower limb muscle activation. Under interval pressurization training, muscle activation was relatively high, especially in terms of RMS normative values of the lateral femoral muscles and biceps femoris. This result may be attributed to the fact that interval training permits the muscles to have some recovery time after the application of stress, thus reducing the effects of muscle fatigue, which in turn improves the activation of the muscle groups. In contrast, continuous compression training, while having a significant activation effect on certain muscle groups (e.g., lateral femoral and gluteus maximus), also showed some fatigue effect, which was particularly evident in the change in RMSMVC values under continuous training. Therefore, the selection of appropriate training modalities and pressurization intensities is crucial for the design of training programs for taekwondo athletes. In addition, this study showed that the gastrocnemius muscle responded significantly to different blood-limiting pressures under interval training, whereas the tibialis anterior muscle did not show significant changes in RMS criterion values. This result suggests the need to consider the sensitivity of different muscle groups to blood-limiting pressures when developing training strategies. The performance of the gastrocnemius may be directly related to its functional role in taekwondo, showing its more active state during high-intensity exercise. In contrast, the tibialis anterior muscle was less activated during weighted deep squat training, which may have a different mechanism of action than its role in dynamic exercise, thus affecting its response to pressurization training. This point provides an important direction for further research in the future, as well as a basis for coaches and athletes to select target muscle groups during training (Schoenfeld, 2013). In terms of subjective fatigue scores, both continuous and intermittent pressurization training significantly enhanced the subjects' fatigue perception, and the effect of intermittent pressurization training was more pronounced. This finding is consistent with our observations of muscle activation, further emphasizing that during high-intensity training, athletes may experience higher physiological loads in a short period of time. The findings suggest that although pressurized training can significantly increase muscle activation levels, it can also result in athletes feeling fatigued more quickly. Therefore, in actual training, coaches should consider how to balance training intensity and recovery time to maximize athletes' fitness levels without causing excessive fatigue.

In conclusion, this study provides an important experimental basis for understanding the effects of different blood restriction pressures and intervals on lower limb muscle activation and fatigue levels in taekwondo athletes. The results of the study not only help to enrich the theory of blood flow restriction-based training, but also provide scientific guidance for application in practical training (Ozaki et al., 2011).

(1) Effects of different blood flow restriction pressures and interval modes on the activation level of thigh and calf muscle groups in taekwondo athletes

This study first investigated the effects of blood flow restriction (BFR) training on the electromyographic activity (RMS values) of thigh and calf muscle groups in taekwondo athletes under different pressure levels and training modes. The results of the study revealed that BFR training significantly altered muscle activation levels, especially in the thigh muscle group. By experimentally setting multiple blood-limiting pressure points (40%, 50%, 60% AOP), this study provides a scientific basis for adjusting BFR intensity to optimize training effects in practical applications (Ben Kibler et al., 2006).

BFR training induces a muscle growth mechanism similar to that of high-load training by limiting blood flow to the limb and increasing the metabolic stress of muscles under low-load conditions. Studies have shown that BFR can increase muscle protein synthesis while decreasing protein degradation by activating the mTOR signaling pathway, promoting increases in muscle size and strength (Fujita et al., 2008) .In addition, BFR has also been found to enhance neuromuscular activation in muscle, which may be achieved through increased recruitment and synchronization of motor units (Ben Kibler et al., 2006).

Consistent with the results of the present study, Patterson & Brandner's study also found that even low-load training under BFR conditions significantly increased muscle activity, especially in the thigh muscle group (Kraemer et al., 1990). However, in contrast to the novel findings of the present study, they failed to differentiate in detail the differences in response between the different muscle groups and did not consider the effects of interval versus continuous training modes. The present study adds to these knowledge gaps and provides a more comprehensive view of BFR application (Andersen, 2003). In addition, the present study found that interval training modalities were not as effective as continuous training in BFR applications, contrary to the findings of Laurentino et al. who reported that interval training was more effective in improving muscle strength and endurance in BFR applications. This difference may be due to differences in training intensity, training duration and physical condition of the subjects (Javier Nunez et al., 2018; Tan, 1999).

The results of this study emphasize the importance of adjusting BFR training parameters according to individual differences (Schoenfeld, 2010). In order to achieve optimal training results, it is recommended to implement an individualized BFR training program, which includes precise blood-limiting pressure settings and optimization of the training cycle. For example, the initial training phase could start with a low blood-limiting pressure (e.g., 40% AOP) and gradually increase to higher levels (e.g., 60% AOP), with adjustments made based on the athlete's adaptation to training and feedback. Additionally, while BFR training offers the potential for muscle strength enhancement, safety is always a primary concern. Any discomfort or health issues that may arise during training, such as symptoms of muscle pain, numbness, or poor circulation, should be monitored. Athletes should undergo a health assessment prior to BFR training to ensure that there are no circulatory or neurological related contraindications(J. P. Loenneke, C. A. Fahs, et al., 2012; Ozaki et al., 2011). According to the results of this study, there are differences in the effects of interval training and continuous training modes on muscle RMS. Therefore, the choice of training mode should be based on the specific needs and goals of the athlete. For example, in order to enhance muscular endurance, interval training may be more suitable, while in order to improve muscular strength, continuous training may be more effective (Behringer et al., 2017; Saxton & Sabatini, 2017). In addition, combining BFR with traditional strength training can be considered to further optimize the training effect. In conclusion, this study suggests that BFR training is an effective way to increase muscle mobility at lower physical loads, especially in the thigh muscle group. By adjusting the blood restriction pressure and training pattern, the training effect can be optimized to provide a more individualized and effective training program for athletes(Vehrs & Johnson, 2023).

(2) Characteristics of changes in RMSMVC values of lower limb muscle groups before and after pressurized deep squat exercise

This study investigated the effects of pressurized deep squat training on the maximum voluntary contraction voltage ($_{\text{RMSMVC}}$) of the lower limb muscle groups, and the findings revealed the differential effects of different modes of pressurization on the electromyographic activity. The study design included both intermittent and continuous modes of pressurization to assess the potential benefits of these training modalities in improving muscular strength and muscular endurance(Tian et al., 2022; Yang et al., 2024).

Pressurization training, or blood flow restriction (BFR) training, has been shown to produce similar effects of muscle gains and strength increases during low- to moderate-intensity training as high-intensity training. In this study, continuous pressurization demonstrated a significant reduction in RMSMVC values for the rectus femoris and gluteus maximus muscles, which may be indicative of an increase in muscle fatigue, thereby contributing to long-term gains in muscle strength(Khazaei et al., 2023; Spranger et al., 2015). In contrast, while intermittent pressurization did not significantly alter RMSMVC values for most muscle groups, the biceps femoris showed a significant increase, possibly reflecting the initial manifestation of muscle adaptation [18]. These results provide important practical applications for clinical rehabilitation and athletic training, especially in situations where training intensity needs to be controlled to avoid joint overload(Weakley et al., 2021).

In exploring the effects of blood flow restriction (BFR) training on muscle strength and myoelectric activity (RMSMVC), it is crucial to understand the underlying physiological mechanisms. By reducing muscle blood flow and oxygen supply while increasing intramuscular metabolic stress, blood flow restriction training is capable of triggering a range of physiological and biochemical responses that are strongly associated with increased muscle strength, improved endurance, and growth in muscle adaptations [19, 20]. The application of pressurized belts significantly reduces blood flow during exercise, limiting the supply of oxygen and nutrients while promoting the accumulation of metabolic waste products (e.g., lactic acid). This low oxygen environment and high metabolic stress increases the acidic environment within the muscle, which in turn stimulates the autonomic nervous system in the muscle via chemoreceptors and increases the activity of muscle fibers, especially those type II muscle fibers that are more important for strength production(Liu & Sabatini, 2020). Muscles under conditions of low oxygen and high metabolic stress activate the mTOR (mammalian target of rapamycin protein complex 1) pathway, which is a key signaling pathway that promotes protein synthesis and muscle growth (Loenneke et al., 2014). In addition, muscle cells under stress conditions increase the expression of heat shock proteins and other stress proteins, which contribute to cell maintenance and repair, further promoting adaptive muscle growth (Schoenfeld, 2010; Wilson et al., 2013).In addition, blood flow restriction may also affect the efficiency of neuromuscular junctions. By restricting blood flow and increasing metabolic stress in the muscle, the efficiency of neuromuscular activation can be enhanced, which is particularly important during anaerobic training [24]. This enhanced neural activation can improve muscle contraction efficiency and force output(Schoenfeld, 2010; Wilson et al., 2013).

In contrast to the existing literature, the results of the present study support the effectiveness of continuous pressurization in increasing muscle fatigue and promoting adaptive muscle growth. According to Loenneke et al(Laurentino et al., 2012; Marston et al., 2017).BFR combined with low-intensity training can promote significant muscle growth, which is consistent with the results of the present study. They noted that BFR was effective in increasing muscle size and strength even at low loads (approximately 30% of one repetition maximum). The present study further validated this finding and observed that even at lower loads, training combined with BFR was still able to stimulate muscle growth, which may be due to the fact that BFR enhances the metabolic stress response and neuromuscular activation within the muscle.Abe et al. demonstrated that BFR training increased the accumulation of lactic acid in the muscle, which is similar to the results observed in the present study, i.e., BFR can significantly increase muscle metabolic stress [27]. Additionally, Cook et al. reported in their study that despite the fact that BFR training triggered higher muscle fatigue, the long-term adaptation of the training participants demonstrated significant endurance and strength improvements (Cook et al., 2014). In contrast to these findings, the present study further explored the role of fatigue management and recovery strategies in BFR training and found that appropriate recovery and periodized training methods can significantly reduce fatigue accumulation while improving training sustainability(Cook et al., 2014).

To summarize, pressurized squat training had variable effects on lower limb muscle groups through different training modes, showing that sustained pressurization may be better suited to promote muscle fatigue and increase training intensity, whereas intermittent pressurization may contribute to muscle recovery and adaptive growth. These findings have important implications for the design of safe and effective training programs and their application in rehabilitation and physical training.

(3) Characteristics of changes in RMS standard values of lower limb muscle groups before and after pressurized deep squat exercise

This study also examined the changes in electrophysiological activity (RMS standard values) of the major lower extremity muscle groups before and after blood flow restricted (BFR) deep squatting exercises, as well as the effects of intermittent and continuous pressurized training modes on muscle responses. By accurately controlling the percentage of AOP, this study provides empirical support for the role of BFR training in improving muscle strength and muscle activity (Sarfabadi et al., 2023; Tian et al., 2022). The results of the study showed that the continuous compression training mode significantly increased RMS normals in the rectus femoris, biceps femoris, and gluteus maximus muscles, whereas intermittent compression training demonstrated significant effects in the rectus femoris, biceps femoris, and gastrocnemius muscles. These findings highlight the differential response of BFR training across muscle groups and training modalities, providing an important physiological basis for the design of future training protocols (Loenneke et al., 2014; Martinez-Rodriguez et al., 2023).

BFR training increases metabolic stress in muscle groups by limiting blood flow to the limb, which in turn promotes the release of muscle growth factors and muscle protein synthesis. In addition, the lower oxygen supply state exacerbates metabolic accumulation in the muscle, thereby triggering a physiological response similar to that of high-intensity training at lower external force demands. For example, Loenneke et al. noted that blood flow-restricted low-load training can produce similar gains in muscle strength and volume as traditional high-intensity training, which may be due to type switching of muscle fibers and changes in the intracellular environment of muscle cells [26]. In comparison to the study by Abe et al. we found that the effects of interval pressurization were more pronounced on the rectus femoris and biceps femoris muscles, which is consistent with the findings of Abe, who reported that interval pressurization significantly increased strength and muscle activity in these muscle groups (Aslam et al., 2013; Hjortshoej et al., 2023; Manimmanakorn et al., 2013). However, the significant decrease in the lateral femoral muscles during continuous compression training in the present study differs from previous findings and may be due to differences in compression intensity and duration. This finding suggests the need for individualized consideration of the responses of different muscle groups when implementing BFR training(Weakley et al., 2021). In addition, a study by Park et al. suggested (Pope et al., 2013) that BFR training could improve muscle function by increasing lactate concentration within the muscle and promoting growth hormone release, which is consistent with our findings, especially that the significant improvements in the rectus femoris and gluteus maximus muscles during sustained pressurization training could be explained in part by these biochemical mechanisms (Abe, Fujita, et al., 2010).

Based on the findings of this study, it is recommended that individualized training protocols be used when implementing a BFR training program. Coaches and athletes should select the appropriate mode and intensity of pressurization based on the specific response of the muscle group (Patterson & Ferguson, 2010). In addition, the physiological and health status of the athlete should be monitored regularly, especially if high pressurization intensities or prolonged training periods are used. In order to maximize the training effect and ensure safety, it is recommended that BFR training be performed under the guidance of a professional (Patterson & Ferguson, 2010). In conclusion, this study provides empirical data on the changes in RMS standardized values of lower limb muscle groups by BFR deep squat training and validates the effects of different pressurized training modes on muscle activity. The findings emphasize the potential application of BFR training in sports training and rehabilitation, and provide a basis for future research on training methods and physiological mechanisms. Through further research and application, BFR training is expected to be an effective means to improve sports performance and promote health recovery (Andersen, 2003; Behringer et al., 2017).

(4) Characteristics of subjective fatigue score changes in subjects before and after pressurized deep squat exercise

Finally, this study analyzed the effects of continuous pressurized, intermittent pressurized and unpressurized deep squat training on subjects' subjective fatigue perception, as well as subjective fatigue response to blood flow restriction (BFR) training (Drummond et al., 2009; Marston et al., 2017). The results showed that both continuous and intermittent pressurization training significantly increased subjects' fatigue scores, with a more significant increase in fatigue with pressurization training compared to no-pressurization training. These findings are important for understanding the physiological and psychological effects of BFR training, and also provide important guidance on how to apply BFR training safely and effectively(Schoenfeld, 2010).

BFR training increases metabolic stress in the muscles by restricting blood flow to the limb, and this metabolic accumulation increases muscle and nervous system sensibility, which may lead to higher subjective fatigue perception. The perception of fatigue is multifaceted and involves a composite of psychological, physiological, and neurological factors (Kraemer & Ratamess, 2004; Viru et al., 1998). Increased subjective ratings of fatigue may be associated with lactate accumulation, inadequate oxygen supply, decreased intramuscular pH, and increased pain perception. In addition, blood flow restriction may further exacerbate this perception by affecting the sensitivity of muscle pain receptors and chemoreceptors(Kraemer & Ratamess, 2004; Viru et al., 1998)·

According to previous studies, blood flow restriction can significantly increase muscle fatigue even under low-load conditions, as shown by Fujita et al.Our findings are consistent with these observations, especially the significantly increased fatigue scores observed during continuous and interval pressurization training (Fujita et al., 2008). However, our effect size was greater compared to the study by Cook et al. which may be due to differences in pressurization intensity (AOP%), training frequency and duration (Cook et al., 2014). In addition, subjective fatigue perception was significantly lower in the non-pressurized training than in the pressurized group in the present study, which is in line with the findings of P. Sieljacks et al. who noted that lower fatigue perceptions with low-load training without blood flow restriction may be related to less metabolic accumulation and lower muscle stimulation(Marston et al., 2017; Rolnick et al., 2023).

Given that BFR training may cause higher subjective fatigue, it is recommended that such training be carefully monitored when implemented and that training intensity and frequency be adjusted according to individual response (Ikezoe et al., 2020; Knezevic et al., 2023). Coaches and athletes should focus on fatigue management to avoid overtraining, especially when training with BFR. In addition, to safely and effectively utilize the benefits of BFR training, it is recommended that it be performed under the guidance of a professional (Witard et al., 2022). In summary, this study demonstrated the significant effects of blood flow restriction training on subjective fatigue perception, providing a valuable perspective for understanding the physiological and psychological effects of BFR training. With proper monitoring and modification, BFR training can be used as an effective tool for improving muscular strength and endurance, while attention needs to be paid to its potential impact on fatigue management (Agorastos & Chrousos, 2022; Staunton et al., 2015).

4. Research limitations and perspectives regarding Experiment 1

Although this study provides an important experimental basis for the effects of different blood limiting pressures (AOP%) and interval training modalities on lower limb muscle activation and fatigue in taekwondo athletes, there are still some limitations in the study design and implementation (Ikezoe et al., 2020; Yamanaka et al., 2012).

First, the study sample size was small (20 athletes), which may affect the generalizability of the results. Sample size is closely related to statistical significance and effect size in sports science; therefore, future studies should increase the sample size and cover athletes of different genders, ages, and training levels to improve the external validity of the findings (Fahs, 2013). Secondly, this study focused on lower limb muscle activation and fatigue, but did not fully consider other influencing factors such as psychological state, training experience and nutritional intake. Athletes' psychological state plays an important role in high-intensity training, and future studies should comprehensively assess these factors to obtain a more holistic picture of training outcomes. In addition, the study only explored specific training patterns and did not address variables such as training duration, frequency and recovery time (Velloso, 2008; Wilson et al., 2013). Different training parameters had significant effects on muscle adaptation and fatigue, and it is recommended that future studies explore diverse training protocols including training cycle optimization and pressurized intensity adjustment (Andersen, 2003; Wernbom et al., 2009).

Looking forward, based on the limitations of this study, it is recommended that a long-period comprehensive training intervention program be designed to systematically assess the effects of pressurized resistance training on body composition, muscle strength, and hormone levels in athletes (Tan, 1999; Yuan et al., 2023). Focusing on changes in hormones such as growth hormone, testosterone, and cortisol associated with muscle growth and recovery will help to gain a deeper understanding of the effects of blood flow restriction training on the physiological mechanisms of muscle adaptation. This will not only reveal the comprehensive effects of training on the physiological state of athletes, but also provide a more scientific basis for fitness and performance enhancement (Knezevic et al., 2023; Spranger et al., 2015).

Experiment 2: Study on the effects of 8 weeks of pressurized resistance training on body composition, muscle strength and hormone effects in excellent taekwondo athletes

1. Changes in body composition before and after intervention

The changes in body composition before and after the intervention are shown in Table 5. In this study, the weight of the pressurized group increased slightly from 75.24 ± 8.96 kg to 76.24 ± 8.99 kg, an increase of 1.00 kg (95% CI: -8.08 to 10.08), but this change was not statistically significant (p = 0.809; Cohen's d = 0.11) . In contrast, body weight in the control group increased from 74.98 ± 9.25 kg to 76.99 ± 8.98 kg, an increase of 2.01 kg (95% CI: 1.21 to 3.23) and showed statistical significance (p=0.034; Cohen's d=0.22). In terms of body fat mass, the pressurized group embodied a significant reduction from 9.58 ± 2.25 kg to 8.45 ± 1.99 kg, a decrease of 1.13 kg (95% CI: -3.28 to -1.02; p=0.035; Cohen's d=-0.53). In contrast, the control group showed a non-significant reduction in body fat mass. Both muscle mass and skeletal muscle mass increased significantly in the pressurized group, from 65.14±7.56 kg to 69.25±8.56 kg (4.11 kg increase, 95% CI: 2.06 to 12.28; p=0.004; Cohen's d=0.51) and from 46.68±5.04 kg to 47.97±4.27 kg (increase of 1.29 kg, 95% CI: 0.44 to 6.02; p=0.002; Cohen's d=0.28). Body fat percentage decreased significantly in the pressurized group, from 15.25±4.68% to 13.51±3.99%, a decrease of 3.74% (95% CI: -6.14 to -2.66; p=0.004; Cohen's d=-0.40). These data suggest that pressurized training is effective in improving muscle mass and skeletal muscle mass while reducing body fat and body fat percentage, whereas changes in the control group were not significant.

Table 5 Changes in body composition before and after intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
Weight (kg)	Pressurized group (50%APO)	75.24±8.96	76.24±8.99	1.00 (-8.08, 10.08)#	0.809	0.11
	Control group (No pressure applied)	74.98±9.25	76.99±8.98	2.01 (1.21, 3.23)	0.034	0.22
Body fat (kg)	Pressurized group (50%APO)	9.58±2.25	8.45±1.99	-1.13 (-3.28, -1.02)	0.035	-0.53
	Control group (No pressure applied)	9.65±2.98	8.99±2.20	-0.66 (-3.31, 1.99)	0.587	-0.25
Muscle mass (kg)	Pressurized group (50%APO)	65.14±7.56	69.25±8.56	4.11 (2.06, 12.28)##	0.004	0.51
	Control group (No pressure applied)	65.29±8.12	67.25±7.99	1.96 (-6.19, 10.11)	0.600	0.24
skeletal muscle mass (kg)	Pressurized group (50%APO)	46.68±5.04	47.97±4.27	1.29 (0.44, 6.02)#	0.002	0.28
	Control group (No pressure applied)	46.59±5.55	47.05±5.02	0.46 (-4.89, 5.81)	0.850	0.09
Body fat rate (%)	Pressurized group (50%APO)	15.25±4.68	13.51±3.99	-3.74 (-6.14, -2.66)##	0.004	-0.40
	Control group (No pressure applied)	15.77±4.98	14.01±4.01	-1.76 (-6.33, 2.81)	0.407	-0.39

Note: # indicates a difference in comparison between groups (p<0.05); ### indicates a highly significant difference between groups (p<0.001)

2. Changes in body circumference before and after the intervention

In this study, we assessed the effect of the intervention by comparing the body circumference measurements of the pressurized group and the control group at different time points. The results showed that in terms of increase in left thigh circumference, the pressurized group showed a significant increase from 61.41 ± 4.23 cm to 64.99 ± 4.10 cm at baseline, with a change of 3.58 cm (95% confidence interval: 2.24 to 4.92 cm) and a very high statistical significance (p<0.001, Cohen's d = 0.771), which showing a significant difference between the groups. In addition, hip circumference also showed a statistically significant increase in both groups, with an increase of 1.56 cm in the pressurized group and 1.70 cm in the control group, both statistically significant (p<0.05). However, for the chest and calf circumference measurements, the changes did not reach statistical significance in either group. These results suggest that specific physical training interventions may have a significant enhancement effect on muscle circumference in specific regions of the lower extremity, especially most significantly on left thigh circumference.

Table 6 Changes in body circumference before and after the intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen’s d
Chest circumference (cm)	Pressurized group (50%APO)	96.27±8.54	97.06±8.15	0.79 (-0.50, 2.08)	0.189	0.086
	Control group (No pressure applied)	97.11±4.45	97.79±5.21	0.68 (-0.67, 2.02)	0.304	0.089

Table 6 (Continued)

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen’s d
Hip circumference (cm)	Pressurized group (50%APO)	101.63±4.98	103.19±5.47	1.56 (0.12, 3.00)	0.034	0.317
	Control group (No pressure applied)	103.24±5.51	104.94±3.86	1.70 (0.16, 3.24)	0.032	0.352
Left thigh circumference (cm)	Pressurized group (50%APO)	61.41±4.23	64.99±4.10	3.58 (2.24, 4.92)##	<0.001	0.771
	Control group (No pressure applied)	62.76±3.00	64.30±3.34	1.54 (0.11, 2.97)	0.036	0.239
Right thigh circumference (cm)	Pressurized group (50%APO)	61.90±3.79	63.84±3.95	1.94 (0.56, 3.32)#	0.007	0.301
	Control group (No pressure applied)	63.04±2.47	64.51±2.61	1.47 (0.03, 2.91)	0.045	0.211
Left calf circumference (cm)	Pressurized group (50%APO)	40.31±3.14	40.13±2.88	-0.18 (-1.08, 0.72)	0.708	-0.057
	Control group (No pressure applied)	40.61±1.48	40.34±1.77	-0.27 (-1.11, 0.57)	0.511	-0.097
Right calf circumference (cm)	Pressurized group (50%APO)	40.46±2.76	40.16±3.08	-0.30 (-1.12, 0.52)	0.472	-0.109
	Control group (No pressure applied)	40.73±1.79	40.51±2.00	-0.22 (-0.93, 0.49)	0.545	-0.079

Note: # indicates a difference in comparison between groups (p<0.05); ### indicates a highly significant difference between groups (p<0.001)

3. Changes in muscle strength before and after intervention

(1) Changes in maximum strength of upper and lower limbs before and after intervention

The changes in maximal strength of upper and lower limbs before and after intervention are shown in Table 7. The results showed that the pressurized group significantly improved their maximal strength in the deep squat, bench press and hard pull programs. Specifically, the deep squat increased from 198.25±19.25 kg at baseline to 209.19±11.32 kg, a change of 10.94 kg (95% confidence interval: 5.54 to 16.34 kg), with a p-value of less than 0.001 and a Cohen's d-value of 0.606. In the bench press program, strength increased from 105.15 ± 11.16 kg to 113.69 ± 10.21 kg with a change of 8.54 kg (95% confidence interval: 4.23 to 12.85 kg), again showing a significant improvement ($p<0.001$, Cohen's d = 0.534). Hard pull strength also increased from 198.60 ± 31.25 kg to 211.37 ± 25.20 kg, a change of 12.77 kg (95% confidence interval: 7.53 to 18.01 kg) and highly statistically significant ($p<0.001$, Cohen's d = 0.664). In contrast, strength gains in the control group, while reaching statistical significance, were smaller in magnitude. These data suggest that targeted pressurization training can significantly increase maximal strength in the upper and lower extremities, especially in the pressurized group.

Table 7 Changes in maximum strength of upper and lower limbs before and after intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
Squat (kg)	Pressurized group (50%APO)	198.25±19.25	209.19±11.32##	10.94 (5.54, 16.34)##	<0.001	0.606
	Control group (No pressure applied)	200.48±18.25	204.99±9.10	4.51 (0.10, 8.92)	0.045	0.208

Table 7 (Continued)

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
Bench Press (kg)	Pressurized group (50%APO)	105.15±11.16	113.69±10.21	8.54 (4.23, 12.85)##	<0.001	0.534
	Control group (No pressure applied)	106.98±8.15	110.79±7.51	3.81 (0.25, 7.37)	0.034	0.196
Hardpull (kg)	Pressurized group (50%APO)	198.60±31.25	211.37±25.20##	12.77 (7.53, 18.01)##	<0.001	0.664
	Control group (No pressure applied)	207.31±39.14	210.99±16.98	3.68 (-4.34, 11.70)	0.352	0.089

Note: # indicates that there is a difference in comparison between groups (p<0.05); ### indicates that the difference between groups is highly significant (p<0.001)

(2) Changes in core muscle groups before and after intervention

In this study, we assessed the effect of pressurization training on core muscle group strength in adult males and compared it with the control group. The results of the study showed that the pressurized group showed significant improvement in all the tested indexes. Specifically, in the flexor strength test, the mean strength of the pressurized group increased from 276.22 Nm pre-intervention to 318.00 Nm, a change of 41.78 Nm (95% confidence interval: 28.25 to 55.31), with a Cohen's d-value of 0.785 showing a high degree of statistical significance (p<0.001). Extensor strength likewise showed a significant increase from 530.19 Nm to 612.78 Nm with a change of 82.59 Nm (95% confidence interval: 68.72 to 96.46) and a Cohen's d value of 1.095 (p<0.001). In tests of lateral flexion and rotation, the pressurized group also showed more significant increases in strength than the control group. For example, lateral flexion strength to the left increased from 142.31 Nm to 214.17 Nm, a change of 71.86 Nm (95% confidence interval: 56.15 to 87.57), with a Cohen's d value of 1.327 (p<0.001). These results suggest that pressurization training can significantly strengthen the core muscles and is an effective method to improve muscle function and athletic performance.

Table 8 Changes in core muscle groups before and after intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
Body bend (Nm)	Pressurized group (50%APO)	276.22±20.12	318.00±33.98	41.78 (28.25, 55.31)##	<0.001	0.785
	Control group (No pressure applied)	280.37±12.33	308.19±60.12	27.82 (5.14, 50.49)	0.015	0.379
Stretch (Nm)	Pressurized group (50%APO)	530.19±71.25	612.78±49.99	82.59 (68.72, 96.46)#	<0.001	1.095
	Control group (No pressure applied)	512.20±69.85	582.12±49.25	69.92 (51.41, 88.43)	<0.001	0.800
Left lateral flexion (Nm)	Pressurized group (50%APO)	142.31±21.23	214.17±24.65	71.86 (56.15, 87.57)##	<0.001	1.327
	Control group (No pressure applied)	143.22±19.19	168.74±16.66	25.52 (10.55, 40.49)	0.002	0.530

Table 8 (Continued)

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
Right lateral flexion (Nm)	Pressurized group (50%APO)	150.51±18.12	199.15±31.81	48.64 (30.88, 66.40)##	<0.001	0.875
	Control group (No pressure applied)	153.19±21.25	172.15±21.98	18.96 (3.92, 34.00)	0.014	0.338
Left lateral flexion (Nm)	Pressurized group (50%APO)	164.25±21.98	192.12±29.29	26.96 (8.13, 45.79)##	<0.001	0.525
	Control group (No pressure applied)	162.15±19.19	168.74±12.16	8.02 (-16.61, 32.65)	0.014	0.113
Rotation to the left (Nm)	Pressurized group (50%APO)	165.19±24.25	192.15±24.29	36.22 (19.90, 52.54)##	0.006	0.720
	Control group (No pressure applied)	164.19±22.65	172.21±35.49	3.62 (-14.73, 21.97)	0.511	0.051
Rotation to the right (Nm)	Pressurized group (50%APO)	155.49±30.19	191.71±19.56	41.78 (28.25, 55.31)#	<0.001	0.785
	Control group (No pressure applied)	157.79±34.16	161.41±34.19	27.82 (5.14, 50.49)	0.684	0.379

Note: # indicates that there is a difference in comparison between groups (p<0.05); ### indicates that the difference between groups is highly significant (p<0.001)

4. Changes in isokinetic muscle strength test indexes of knee joint before and after intervention

The changes in knee joint isometric muscle strength test indexes before and after intervention are shown in Table 9. The data showed that the left knee extension muscle strength in the pressurized group increased significantly from 279.59±30.12 Nm before intervention to 312.41±26.15 Nm after intervention (change of 32.82 Nm, 95% CI: 20.65 to 44.99, $p<0.001$, Cohen's d=0.899), showing a significant improvement, whereas the control group also showed an increase (from 271.12±29.25 Nm to 293.12±21.51 Nm, change of 22.00 Nm, 95% CI: 8.25 to 35.75, $p=0.003$, Cohen's d=0.561), but to a lesser extent than the pressurized group. Right knee extension also showed a statistically significant enhancement in the pressurized group (from 293.22±19.69 Nm to 306.59±27.42 Nm, a change of 13.37 Nm, 95% CI: 1.25 to 25.49, $p=0.035$, Cohen's d=0.313), while enhancement was not significant in the control group. Left and right knee flexion showed similar improvements in the pressurized group, with a significant increase in left knee flexion (from 150.74±40.17 Nm to 169.17±19.99 Nm, a change of 18.43 Nm, 95% CI: 4.82 to 32.04, $p=0.010$, Cohen's d=0.461), and an increase in right knee flexion was smaller (from 155.75±21.15 Nm to 163.79±21.16 Nm, a change of 8.04 Nm, 95% CI: 1.96 to 18.04, $p=0.029$, Cohen's d=0.254) but still significant. None of the control group's changes in the flexion test reached statistical significance. The results of this study suggest that compression training can significantly increase isometric muscle strength of the knee, especially more effective in extension maneuvers, and that the compression group performed better than the control group in most of the indices in the between-group comparisons ($p<0.05$).

Table 9 Changes in indicators of isometric muscle strength test of knee joint before and after intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen’s d
Left knee extension (Nm)	Pressurized group (50%APO)	279.59±30.12	312.41±26.15	32.82 (20.65, 44.99)#	<0.001	0.899
	Control group (No pressure applied)	271.12±29.25	293.12±21.51	22.00 (8.25, 35.75)	0.003	0.561
Right knee extension (Nm)	Pressurized group (50%APO)	293.22±19.69	306.59±27.42	13.37 (1.25, 25.49)#	0.035	0.313
	Control group (No pressure applied)	286.12±21.21	294.61±30.55	8.49 (-4.57, 21.55)	0.198	0.185
Left knee flexion (Nm)	Pressurized group (50%APO)	150.74±40.17	169.17±19.99	18.43 (4.82, 32.04)##	0.010	0.461
	Control group (No pressure applied)	149.31±19.11	160.11±25.68	10.80 (-1.43, 23.03)	0.080	0.269
Right knee flexion (Nm)	Pressurized group (50%APO)	155.75±21.15	163.79±21.16	8.04 (1.96, 18.04)	0.029	0.254
	Control group (No pressure applied)	152.19±19.87	159.11±19.89	6.92 (-2.32, 16.16)	0.136	0.206

Note: # indicates that there is a difference in comparison between groups (p<0.05); ### indicates that the difference between groups is highly significant (p<0.001)

5. Changes in lower limb explosive strength before and after intervention

The changes in lower limb explosive strength before and after intervention are shown in Table 10. The results of the study showed that the pressurized group improved significantly more than the control group in all the tested indices. Specifically, the pressurized group increased from 34.10±2.97 cm to 40.19±4.99 cm (change of 6.09 cm, 95% CI: 4.13 to 8.05, p<0.001, Cohen's d=1.055) in standing long jump (SJ) after the intervention, while the control group increased from 33.98±3.01 cm to 37.35±5.61 cm (change of 3.37 cm, 95% CI: 0.84 to 5.90, p=0.010, Cohen's d=0.576). On the reactive stress test, the pressurized group showed an increase in counted motor jump height (CMJ) from 42.14±4.15 cm to 50.17±3.19 cm (change of 8.03 cm, 95% CI: 6.07 to 9.99, p<0.001, Cohen's d=1.592), and the control group showed a smaller increase (from 41.95±1.99 cm to 45.99±7.18 cm, change of 4.04 cm, 95% CI: 1.32 to 6.76, p=0.004, Cohen's d=0.490). In the 30-meter sprint run test, the pressurized group demonstrated significant time reduction (from 4.15±0.12 to 3.90±0.11 seconds, change -0.25 seconds, 95% CI: -0.30 to -0.20, p<0.001, Cohen's d=1.250), and the control group showed less improvement (from 4.12± 0.16 seconds to 4.01±0.11 seconds, change -0.11 seconds, 95% CI: -0.20 to -0.02, p=0.015, Cohen's d=0.303). Additionally, standing long jump performance was also significantly improved in the pressurized group, from 251.20 ± 8.96 cm to 263.12 ± 7.25 cm (change of 11.92 cm, 95% CI: 8.68 to 15.16, p<0.001, Cohen's d=1.433), with less improvement in the control group (from 252.11 ± 10.15 cm to 259.14±8.99 cm, change of 7.03 cm, 95% CI: 3.02 to 11.04, p=0.001, Cohen's d=0.505).The FSKT10s test also showed a significant increase before and after the intervention in the pressurized group and the control group (p<0.05), and the between-group comparison of pressurized group showed better improvement than the control group (p<0.05). These results confirm that pressurization training has a significant effect on improving the explosive strength of the lower limbs, especially in the test of explosive strength and speed of movement.

Table 10 Changes in lower limb explosiveness before and after intervention

Indicator (unit)	Group	Pre	Post	Change(95%CI)	p-value	Cohen's d
SJ (cm)	Pressurized group (50%APO)	34.10±2.97	40.19±4.99	6.09 (4.13, 8.05)#	<0.001	1.055
	Control group (No pressure applied)	33.98±3.01	37.35±5.61	3.37 (0.84, 5.90)	0.010	0.576
CMJ (cm)	Pressurized group (50%APO)	42.14±4.15	50.17±3.19	8.03 (6.07, 9.99)##	<0.001	1.592
	Control group (No pressure applied)	41.95±1.99	45.99±7.18	4.04 (1.32, 6.76)	0.004	0.490
30M sprint run (s)	Pressurized group (50%APO)	4.15±0.12	3.90±0.11	-0.25 (-0.30, -0.20)#	<0.001	1.250
	Control group (No pressure applied)	4.12±0.16	4.01±0.11	-0.11 (-0.20, -0.02)	0.015	0.303
Standing long jump (cm)	Pressurized group (50%APO)	251.20±8.96	263.12±7.25	11.92 (8.68, 15.16)##	<0.001	1.433
	Control group (No pressure applied)	252.11±10.15	259.14±8.99	7.03 (3.02, 11.04)	0.001	0.505
FSKT10s	Pressurized group (50%APO)	11.36±2.05	14.26±2.12	2.90(1.95, 3.85)#	0.001	1.504
	Control group (No pressure applied)	11.85±2.05	13.58±2.98	1.73(1.05, 4.51)	0.019	0.270

Note: # indicates a difference in between-group comparison (p<0.05); ### indicates a highly significant difference between groups (p<0.001)

6. Discussion on experiment II

In this study, the effects of pressurized resistance training on body composition, muscle strength, were investigated in depth by subjecting outstanding taekwondo athletes to an 8-week period of pressurized resistance training. The results of the study showed that the pressurized training significantly improved the body composition of the athletes, as evidenced by a significant decrease in body fat mass and body fat percentage, as well as a significant increase in muscle mass and skeletal muscle mass (Laurentino et al., 2008; Manimmanakorn et al., 2013). In addition, the pressurized group outperformed the control group in maximal strength of upper and lower extremities, core muscle strength and knee isometric strength tests, especially in the important strength indexes such as deep squat, bench press and hard pull. These changes not only reflected the enhancement effect of pressurization training on muscle strength and endurance, but also showed the effectiveness of this training in improving the athletes' lower limb explosive power and reaction power (Michel et al., 2004; Sougiannis & Wallace, 2012). These findings not only provide a scientific basis for athletes' training programs, but also provide an important reference for coaches to develop individualized training plans. Overall, the significance of this study is to reveal the multiple benefits of pressurized resistance training on the physical quality improvement of excellent taekwondo athletes, which provides empirical support for optimizing athletes' training methods and promoting athletic performance(Fleck, 2011; Kraemer & Ratamess, 2005).

(1) Changes in body composition before and after intervention

By restricting blood flow to the limb, pressurized resistance training increases metabolic accumulation within the muscle, thereby increasing the release of muscle growth hormone and accelerating muscle growth and repair. The results of this study support the fact that pressurized training can effectively enhance muscle mass and skeletal muscle mass while reducing body fat, which is important for enhancing athletes' competitive performance and physical adaptations. In particular, in terms of the increase in muscle mass and reduction in body fat percentage, the present study found that the changes in the pressurized group were significantly better than those in the control group, a result that is consistent with the study of Loenneke et al. who found that low-intensity blood flow restriction (BFR) training significantly increased muscle volume and strength (Patterson & Ferguson, 2010; Reeves et al., 2006).

Blood flow restriction (BFR) training, as a unique form of resistance training, creates a hypoxic environment by partially restricting blood flow to the limb, prompting the muscles to achieve the effect of high workload training at a lower workload. The physiological mechanisms of this training method are complex, involving multiple biochemical processes and molecular pathways (Harber et al., 2009; Sforzo & Touey, 1996). By restricting blood flow and reducing oxygen supply, pressurized training causes muscle cells to work under hypoxic conditions and rapidly accumulate metabolic waste products such as lactic acid. In addition, lactate acts as a signaling molecule involved in the regulation of signal transduction pathways within muscle cells, such as mTOR (mammalian target of rapamycin), which promotes muscle protein synthesis (De Renty et al., 2023; Yang et al., 2024). The hypoxic training environment enhances oxidative stress within muscle cells, which is reflected by enhanced cellular adaptation through the activation of antioxidant enzyme systems such as superoxide dismutase (SOD) and glutathione peroxidase (GPx) (Loenneke et al., 2015; Martinez-Rodriguez et al., 2023). This increase in oxidative stress promotes the development of cellular antioxidant defense mechanisms and contributes to cellular resistance to future stress (Tian et al., 2022). Stress training may also induce a shift in muscle fibers from IIx to IIa, a shift that results in higher endurance and metabolic activity. IIa fibers have greater fatigue resistance and higher oxidative capacity than IIx fibers and are adapted to longer periods of muscle activity (Cook et al., 2014; Hjortshoej et al., 2023). In addition, by increasing the proportion of IIa fibers in the muscle, BFR training improves overall muscle function and metabolic efficiency. Therefore, BFRT is more effective than traditional resistance training in improving body composition in athletes. Compared to other studies, the results of the present study show that pressurized resistance training is particularly effective in reducing body fat. For example, Abe et al. found in their 2010 study that pressurized training resulted in a significant reduction in adipose tissue without increasing heart rate (Ikezoe et al., 2020; Sinclair et al., 2022). The significant decrease in body fat mass and body fat percentage in the present study may be related to the increased oxidative utilization of fat by muscles after exercise.

For practical applications, the results of the present study suggest that blood flow restriction training through appropriate intensities of pressurization (AOP%) can be effective in improving body composition and muscle strength in athletes, especially for competitive athletes who need to control or reduce their weight class. Athletic training programs should take into account the specific needs of the individual and adjust the pressurization intensity and training frequency to achieve optimal training results. In summary, 8 weeks of pressurized resistance training significantly improved the body composition of taekwondo athletes, especially in terms of increasing muscle mass and decreasing body fat. These changes not only improved athletes' physical performance, but may also be beneficial to their health and long-term athletic development(Aslam et al., 2013; Cohen et al., 2021).

(2) Changes in body circumference before and after intervention

In this study, we investigated the effect of blood flow restriction (BFR) training on the circumference of various body parts. By comparing the changes between the pressurized group and the control group before and after the training, we found that especially on the left thigh circumference, BFR training showed a significant growth effect. This result not only provides empirical support for the effectiveness of BFR training, but also provides important application value for the field of athletic training, rehabilitation and sports science (Patterson et al., 2019).

Blood flow restriction training triggers a number of physiological responses by reducing the oxygen supply to the muscles. First, the hypoxic environment exacerbates metabolic stress in the muscle, inducing an accumulation of lactate and hydrogen ions within the muscle. This environment contributes to the enhancement of anaerobic metabolic processes in muscle cells, which in turn triggers an increase in the release of growth hormone and promotes muscle protein synthesis (Bielitzki et al., 2021). In addition, BFR training may also promote muscle growth and repair by activating the mTOR signaling pathway and increasing protein synthesis in muscle cells (Patterson & Brandner, 2018). Compared with other studies, our results showed a more pronounced effect of muscle circumference increase. For example, the study by Laurentino et al. also reported that BFR training significantly increased muscle circumference, but the magnitude of the change was relatively small. This may be related to the intensity of pressurization (AOP%) used in this study, and our design of pressurization intensity may be better suited to promote rapid muscle growth (Ikezoe et al., 2020). AOP%, the percentage of arterial occlusion pressure, is a key variable in BFR training. Past studies have shown that different AOP% have significantly different effects on training effectiveness. For example, Abe et al. found in their study that using a higher AOP% (e.g., 70%-80%) resulted in a significant increase in muscle circumference over a shorter period of time. The AOP% settings used in this study were within this range, which may be an important reason for the larger circumference increases observed (Loenneke, Wilson, et al., 2011).

(3) Changes in muscle strength before and after intervention

This study investigated the effects of 8 weeks of pressurized resistance training on excellent taekwondo athletes in terms of muscle strength. The results of the study showed that the pressurized group showed significant improvement in upper and lower extremity maximal strength, core muscle strength and lower extremity explosive strength. These findings not only provide a scientific basis for pressurized training in terms of athletic performance enhancement, but also lay the foundation for future training method optimization.

As an emerging training method, Blood Flow Restriction Training (BFR) can effectively stimulate muscle growth and strength gains by applying a certain intensity of compression under low load conditions. Studies have shown that even at lower loads, BFR training induces physiological mechanisms similar to those of high-intensity training, including the promotion of muscle protein synthesis and the enhancement of neuromuscular activation (Manini & Clark, 2009). By systematically evaluating the effects of pressurized resistance training on taekwondo athletes, this study demonstrated the effectiveness of this training method in improving athletes' competitive performance and body composition, which has important practical applications.

In this study, the significant improvement in the indexes of deep squat, bench press and hard pull demonstrated that pressurized training was effective in enhancing the maximal strength of the upper and lower limbs.BFR training activated signaling pathways related to muscle growth, such as the mTOR (Mammalian Target of

Rapamycin Protein Complex 1) pathway by limiting the blood flow, increasing the metabolic stress and lactic acid accumulation in the muscle, thus promoting muscle protein synthesis(Kubota et al., 2008). Compared with traditional high-load training, BFR training was also effective in stimulating these physiological responses at lower loads, indicating its broad applicability in strength training. The significant improvement of the core muscles in the pressurized group in tests such as flexion and extension and lateral flexion further validated the effectiveness of BFR training in enhancing stability and strength. The core musculature not only plays a supporting and stabilizing role during exercise, but also serves as the basis for athletic execution and explosive power(Hakkinen & Alen, 1989; Ratamess et al., 2009).By enhancing the strength of the core muscles, athletes are able to better control their bodies and improve their athletic performance when performing other technical maneuvers. The results of the study showed that pressurization training had a significant effect on the enhancement of lower limb explosive power, especially in the standing long jump and 30-meter sprint tests. This improvement may be related to the stimulation of fast muscle fibers by BFR training. Fast-twitch muscle fibers are key to explosive force production, and BFR training promotes the recruitment and activation of fast-twitch muscle fibers by increasing metabolic stress within the muscle (chan-Mo, 2008).In addition, BFR training enhances neural adaptations and improves the efficiency of neuromuscular connectivity in athletes, which in turn enhances the explosive power of exercise(Spreuwenberg et al., 2006).

The results of the present study complement the existing literature and support the effectiveness of BFR training in different domains. The study by Loenneke et al. showed that BFR training was effective in enhancing muscle strength and function in older adults under low load conditions, further confirming the generalizability and effectiveness of BFR training in different populations(Kraemer et al., 1990; Kubota et al., 2008). In addition, a study by Abe et al. also found that BFR training can significantly improve strength and muscle volume in young exercisers in a short period of time, which is consistent with the findings of the present study on taekwondo athletes(Yamada et al., 2004). However, the results in this study showed a more significant increase for core muscle strength gains, which may be due to the fact that we paid more attention to core stability training during training. In comparison to F. Javier's study, which focused on the effects of traditional strength training on the core muscle groups, the present study integrated the unique characteristics of BFR training and emphasized its multifaceted effects on muscle growth and strength gains(Yost et al., 2005).

During blood flow restriction (BFR) training, muscles can achieve a physiological state of stress similar to that of high-load training at lower mechanical stresses due to the use of lower external loads. Studies have shown that BFR training can significantly increase serum growth hormone levels with effects comparable to traditional high-intensity training(Brunner et al., 2007). Specifically, the localized hypoxic state during BFR training enhances metabolic stress, leading to the accumulation of lactic acid in muscle cells. Lactate, an important metabolite, has been shown to act as a hormonal signal that directly promotes the release of growth hormone(Kraemer & Ratamess, 2005; Shinohara et al., 1998).

7. Research Limitations and Prospects Concerning Experiment II

The present study aimed to investigate the effects of pressurized resistance training on body composition, muscle strength, by administering it to outstanding taekwondo athletes for a period of 8 weeks. However, the results of the study may lack generalizability due to the limited sample size and did not adequately consider individual differences in training intensity, length of intervention, psychological factors, and a comprehensive assessment . Therefore, future studies should expand the sample size, explore individualized training protocols, conduct longitudinal follow-up, and incorporate modern technological tools and psychological assessment tools to obtain more comprehensive data support and insight into the long-term effects of stress training and its applicability to different sports.

Going forward, research should focus on developing training protocols for different individual characteristics (e.g., age, gender, and sport), as well as comparing the effects of training across different sport types. By combining modern methods such as biomechanical analysis and imaging techniques, as well as introducing the consideration of psychological factors, the accuracy and reliability of the training data can be effectively enhanced, further promoting the application of pressurized resistance training in competitive sports and helping athletes achieve excellent performance in their professional fields.

CHAPTER 5
DISCUSSION AND CONCLUSION

This study investigated the effects of Blood Flow Restriction Training (BFR) on lower limb strength and explosive power in outstanding taekwondo athletes. Through an 8-week training intervention, we found that the pressurized resistance training significantly increased the athletes' lower limb muscle strength, muscle mass, explosive power .

First, in terms of body composition, body fat mass and body fat percentage were significantly reduced in the pressurized group, while muscle mass and skeletal muscle mass were significantly increased. This indicates that BFR training effectively reduced body fat and improved the body composition of the athletes while improving muscle mass. Secondly, in terms of muscle strength performance, the pressurized group showed significant improvement in tests such as deep squat, bench press and hard pull, especially in the deep squat program, where the strength gain reached 10.94 kg, reflecting the effectiveness of BFR training in enhancing lower limb strength. In addition, the strength gains in the core muscles further validated the advantages of BFR training in improving the overall strength of the athletes. In the lower extremity explosive strength test, the pressurized group showed significant improvement in the standing long jump, CMJ, SJ and 30-m sprint. This result suggests that BFR training not only has a direct effect on muscle strength, but is also more effective in improving athletes' performance, especially in sports that require instantaneous explosions. This finding is consistent with the existing literature and further supports the potential application of BFR training in athletic training.

The present study also extends the understanding of different training modes by examining the different effects of interval pressurization versus continuous pressurization training in terms of strength and explosive power gains. This result provides a new direction for future research on how to design optimal training programs to improve athletes' competitive performance under different training modes.

The results of this study provide important practical guidance for coaches and athletes. In terms of training design, BFR training can be used as an effective method to realize the effect of high-intensity training with a lower load. For taekwondo athletes who need to control their body weight, appropriate blood flow restriction training can effectively improve muscle strength and explosive power, helping athletes gain a competitive advantage in competition. In addition, the results of the study emphasize the importance of individualized training. Different athletes may have differences in muscle activation, strength, and fatigue perception, so individualized training design for athletes' specific needs and physiological status will help maximize the training effect. At the same time, coaches should pay attention to athletes' psychological state and fatigue management in order to avoid the risk of overtraining during high-intensity training.

Future studies should consider the application of larger sample sizes to improve the external validity of the study and the generalizability of the results. In addition, it is recommended to explore the response of athletes of different genders, ages and training levels to BFR training to further validate its effectiveness. In terms of training program design, future studies should delve into the effects of variables such as training intensity, frequency and recovery time on the effectiveness of BFR training. These factors are not only related to the effectiveness of training, but may also affect the long-term health and performance of athletes. In addition, modern technology, such as biomechanical analysis and imaging techniques, can be combined to more comprehensively assess the effects of BFR training on the physiological status of athletes' muscles. Meanwhile, future research should also focus on the influence of athletes' psychological state on training effects, and explore how psychological interventions can enhance the effectiveness of training and athletes' adaptive capacity. In summary, this study provides empirical evidence for the application of BFR training in the enhancement of lower limb strength and explosive power in taekwondo athletes, emphasizing its multiple benefits in training. Future research should continue to explore the potential of BFR training to help athletes achieve better performance in the competitive arena.

Conclusion

(1) Effects of different blood restriction pressures and intervals on the degree of activation of thigh and calf muscle groups

The present study showed that under the condition of intermittent compression training, blood pressure had a significant effect on the activation level of thigh muscles, especially in the medial femoral and lateral femoral muscles, and the activation level of the muscles increased significantly with the increase of blood pressure. Compared with continuous pressure training, interval training can promote muscle activation more effectively, suggesting that the training mode of intermittent pressure should be given priority in the training program to optimize the effect of muscle activation.

(2) Immediate effects of pressurized weighted squat exercise on electromyographic activity and fatigue of lower limb muscles.

The pressurized weighted squat exercise significantly affected the $_{RMSMVC}$ values of the lower limb muscle groups under different pressurization modes, especially the muscle fatigue induced by continuous pressurization training was significantly increased. The results of the study suggest that although continuous pressurized training can effectively enhance muscle strength, it is also accompanied by higher fatigue, so in practical application, the training intensity and recovery time should be reasonably arranged to avoid excessive fatigue.

(3) Effects of pressurized training on body composition and strength

An 8-week period of pressurized training significantly improved the body composition of outstanding taekwondo athletes, including increased muscle mass and skeletal muscle mass, while significantly reducing body fat. In strength tests, the deep squat, bench press, and hard pull were significantly improved in the pressurized group, suggesting that blood flow restriction training is effective in enhancing lower extremity strength and providing a stronger training base for taekwondo athletes.

(4) Using 50% AOP and intermittent pressure training significantly improved the athlete's lower limb explosive power, including the performance of standing long jump, counting exercise high jump, and 30-meter sprint. The pressurized group outperformed the control group in these tests, further validating the effectiveness of blood flow restriction training in enhancing athletes' lower extremity explosive strength.

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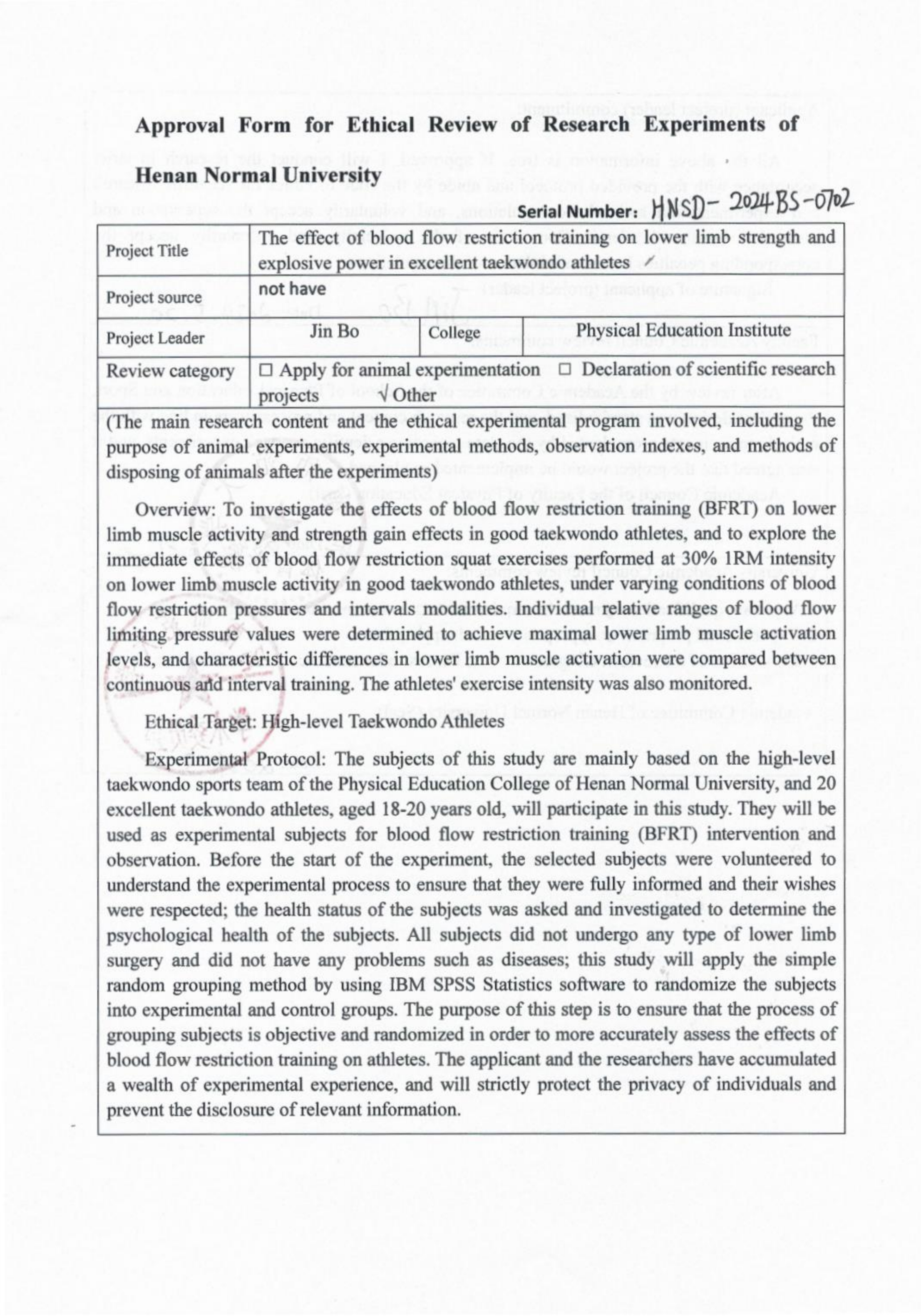
APPENDIX



Approval Form for Ethical Review of Research Experiments of Henan Normal University

Serial Number: HNSD-2024BS-0702

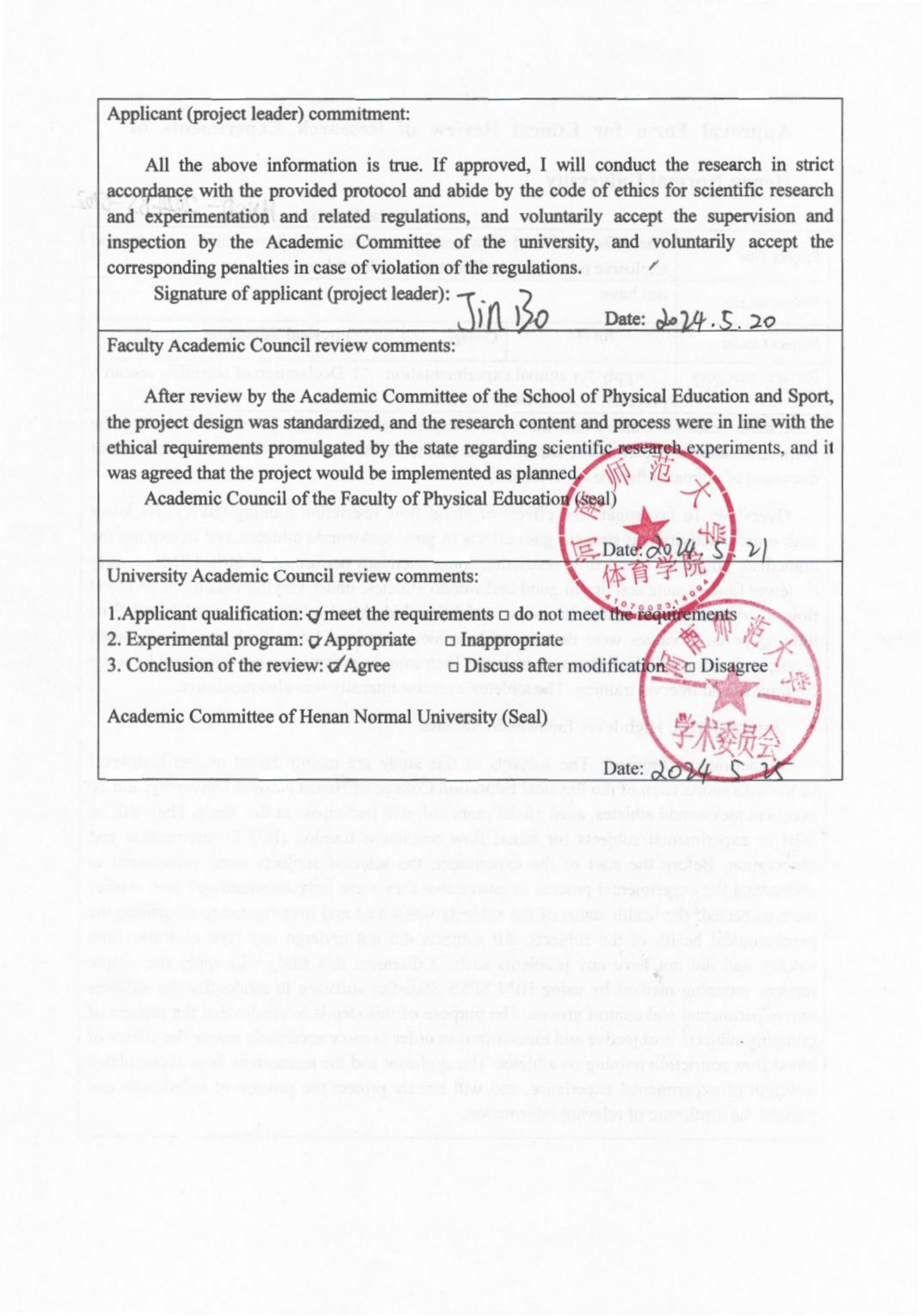
Project Title	The effect of blood flow restriction training on lower limb strength and explosive power in excellent taekwondo athletes		
Project source	not have		
Project Leader	Jin Bo	College	Physical Education Institute
Review category	☐ Apply for animal experimentation ☐ Declaration of scientific research projects √ Other		

(The main research content and the ethical experimental program involved, including the purpose of animal experiments, experimental methods, observation indexes, and methods of disposing of animals after the experiments)

Overview: To investigate the effects of blood flow restriction training (BFRT) on lower limb muscle activity and strength gain effects in good taekwondo athletes, and to explore the immediate effects of blood flow restriction squat exercises performed at 30% 1RM intensity on lower limb muscle activity in good taekwondo athletes, under varying conditions of blood flow restriction pressures and intervals modalities. Individual relative ranges of blood flow limiting pressure values were determined to achieve maximal lower limb muscle activation levels, and characteristic differences in lower limb muscle activation were compared between continuous and interval training. The athletes' exercise intensity was also monitored.

Ethical Target: High-level Taekwondo Athletes

Experimental Protocol: The subjects of this study are mainly based on the high-level taekwondo sports team of the Physical Education College of Henan Normal University, and 20 excellent taekwondo athletes, aged 18-20 years old, will participate in this study. They will be used as experimental subjects for blood flow restriction training (BFRT) intervention and observation. Before the start of the experiment, the selected subjects were volunteered to understand the experimental process to ensure that they were fully informed and their wishes were respected; the health status of the subjects was asked and investigated to determine the psychological health of the subjects. All subjects did not undergo any type of lower limb surgery and did not have any problems such as diseases; this study will apply the simple random grouping method by using IBM SPSS Statistics software to randomize the subjects into experimental and control groups. The purpose of this step is to ensure that the process of grouping subjects is objective and randomized in order to more accurately assess the effects of blood flow restriction training on athletes. The applicant and the researchers have accumulated a wealth of experimental experience, and will strictly protect the privacy of individuals and prevent the disclosure of relevant information.



Applicant (project leader) commitment:

All the above information is true. If approved, I will conduct the research in strict accordance with the provided protocol and abide by the code of ethics for scientific research and experimentation and related regulations, and voluntarily accept the supervision and inspection by the Academic Committee of the university, and voluntarily accept the corresponding penalties in case of violation of the regulations.

Signature of applicant (project leader): Jin Bo
Date: 2024.5.20

Faculty Academic Council review comments:

After review by the Academic Committee of the School of Physical Education and Sport, the project design was standardized, and the research content and process were in line with the ethical requirements promulgated by the state regarding scientific research experiments, and it was agreed that the project would be implemented as planned.

Academic Council of the Faculty of Physical Education (seal)

Date: 2024.5.21

University Academic Council review comments:

1.Applicant qualification: ☑ meet the requirements ☐ do not meet the requirements
2. Experimental program: ☑ Appropriate ☐ Inappropriate
3. Conclusion of the review: ☑ Agree ☐ Discuss after modification ☐ Disagree

Academic Committee of Henan Normal University (Seal)

Date: 2024.5.25

VITA