Original Article

Effects of 4-week circuit strength combined with blood flow restriction training on muscle status and performance in Taekwondo athletes

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ABSTRACT

This study explored the effects of a 4-week circuit strength training with blood flow restriction on Taekwondo athletes. Six male athletes (age 20.6 ± 1.85, height 184.3 ± 7.63 cm, training duration 7.5 ± 2.07 years) were assessed for explosive strength, muscle recruitment, and sport-specific skills. The regimen encompassed evaluations of lower limb power, Isokinetic strength, force via electronic kicks, and Tensiomyography (TMG) measurements pre-and post-training. Outcomes revealed enhanced jumping abilities, improved knee muscles, and superior kicking skills. There was a notable increase in muscle fibre recruitment and a shift towards type II muscle fibres. Medial thigh muscle displacement showed a positive correlation with jump duration, while lateral thigh muscles indicated a connection with kick numbers. The regimen notably improved explosive power, muscle fibre distribution, and reduced muscle contraction times. Yet, no significant changes in lower limb bilateral symmetry or the link between TMG parameters and athletic prowess were observed.

Keywords: Performance analysis, Blood flow restriction training, Circuit strength, Taekwondo, Tensiomyography, Sports performance.

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INTRODUCTION

Taekwondo (TKD), as an official Olympic sport, has garnered global attention. It is a competitive sport where athletes, under equal weight conditions, primarily rely on lower limb attacking techniques to score. To excel in such competitions, athletes need outstanding explosive leg power, agile footwork, and effective kicking striking abilities (Jin & Liu, 2012). The prevalent method for athletes to enhance strength currently is through high-intensity training (≥70% 1RM) resistance training, which effectively promotes muscle hypertrophy and strength gain (Pescatello et al., 2009). However, such high-intensity training has its drawbacks. For instance, without proper athletic supervision and good training modalities, long-term high-intensity load training may increase the risk of sports injuries (Wei et al., 2019). Additionally, muscle hypertrophy from intense training may result in weight gain in athletes, reducing their competitive advantage within the same weight category (Li, 2022). Consequently, finding safe and effective ways to enhance athletic muscle strength and performance has become a pressing issue.

In recent years, Blood Flow Restriction Training (BFRT) has been garnering increased attention. It refers to a novel training approach where pressure devices are worn during exercise to achieve resistance. The principle behind BFRT is to restrict blood flow to the working muscles using pressure bands, stimulating the muscles to produce a series of responses, ultimately leading to increased muscle volume and strength (Spranger et al., 2015). A significant advantage of BFRT is that it promotes protein synthesis, stimulates muscle growth, and improves muscular fitness at relatively low exercise intensities. Preliminary studies have shown that resistance training under pressure offers better rehabilitation outcomes for injured athletes compared to low-intensity resistance training (Loenneke et al., 2013). Additionally, it has been found to effectively enhance explosive power, muscle strength, and anaerobic metabolic capacities in athletes across various sports, including handball, martial arts, soccer, and rugby (Luebbers et al., 2014; Wang et al., 2019; Liu et al., 2020; Sun et al., 2023). It also has positive effects on hormone secretion, vascular compliance, and bone health (Takarada et al., 2000; Karabulut, McCarron, et al., 2011; Karabulut, Bemben, et al., 2011). Owing to its versatile exercise modalities, high training efficiency, ease of operation, and relative safety, BFRT holds promising applications across various domains (Abe et al., 2006, 2010; Godawa et al., 2012; Cook et al., 2014).

Strength training in Taekwondo primarily emphasizes explosive power, rapid force, and foundational physical fitness. This training approach not only considers the growth of an athlete's muscular strength and endurance but also contemplates how to enhance their strength while simultaneously reducing body fat and weight during the training process. The objective is to provide athletes with a competitive advantage in their respective categories by maintaining a lower weight relative to their height (Li, 2022). The application of circuit strength training aptly meets the demands of this sport. It incorporates resistance training while also serving as an aerobic exercise. It can effectively increase lean body mass without altering bone density, reduce body fat, and elevate an athlete's base metabolism (Wang et al., 2011). This form of training subsequently enhances an athlete's muscular strength, endurance, and overall performance (Paoli et al., 2010; Rosety et al., 2015). Research indicates that circuit training significantly improves muscle strength, agility, metabolic capacity, and cardiorespiratory endurance in athletes from disciplines like soccer and tennis (Sumaryanti & Yudhistira, 2021; Belli et al., 2022; Francis & Lohar, 2022).

Tensiomyography (TMG) is a non-invasive testing method designed to study the contractile properties of muscles (Peng et al., 2017). It is specifically employed to analyse the ratio between Type I and Type II muscle fibres in a given superficial muscle and assess the fatigue or tension state of the tested muscle. TMG evaluates muscular function, as well as temporal and morphological symmetry. Clinically, it's also used for rapid diagnostics during the onset of muscle injury and for continuous monitoring throughout rehabilitation (Dahmane et al., 2006). Several studies have described TMG as an effective tool for detecting muscle fatigue, fibre type composition, lateral symmetry, and muscle stiffness, and it has broad applications across numerous fields (Rey et al., 2012; Rodríguez-Ruiz et al., 2012). Its primary indicators are Contraction Time (Tc) and Maximal Displacement (Dm). Tc refers to the time the muscle takes to move from 10% to 90% of its maximum displacement, reflecting the contraction speed of the targeted muscle (Krizaj et al., 2008). Dm denotes the radial displacement of the muscle belly after electrical stimulation. A decreased Dm value suggests increased muscle stiffness or a more developed muscle, whereas a larger Dm indicates reduced muscle stiffness or fatigue (Valencic & Knez, 1997). Thus, some studies propose using this parameter as an indirect measurement method for muscle stiffness (Watsford et al., 2010).

While combined pressure strength training can achieve neuromuscular adaptation effects similar to high-intensity resistance training at relatively lower exercise loads (Ma, 2021), circuit strength training and blood flow restriction training have different mechanisms when it comes to improving muscle strength, endurance, and athletic performance. As a result, their impacts on muscle strength and related metrics vary. Although both training methods have been researched, there is a scarcity of studies that combine them for Taekwondo athletes. Therefore, this study selected six -68kg athletes from the Shaanxi Province Taekwondo Team to explore the impact of a 4-week blood flow restriction combined with circuit strength training on their muscle condition and athletic performance. Additionally, we analysed the changes in muscle structure before and after the experiment, along with the potential association between Taekwondo athletes' TMG parameters (Dm and Tc) and jumping, muscular strength, and specialized skills. This study aims to provide new perspectives and strategies for Taekwondo training and hopes to offer valuable insights for the training methods of other competitive sports.

METHODS AND MATERIALS

Participants

This study was approved by the Ethics Committee of Xi'an Physical Education University. From June 2021 to March 2022, six athletes (age 20.6 ± 1.85 years, height 184.3 ± 7.63 cm, training duration 7.5 ± 2.07 years) from the Shaanxi Province Taekwondo Team in the -68kg category were recruited (see Table 1). Among them, one was a national-level elite athlete, and five were first-level national athletes. This study adhered to the principles of the Helsinki Declaration and obtained informed consents signed by all participants. All participants were in good health, with no injuries or illnesses, and did not undergo high-intensity training three days prior to the experiment.

Table 1. Basic information of the participants.

Participants	Gender	Age	Height (cm)	Weight (kg)	Training Duration (Y)
6	Male	20.6 ± 1.85	184.3 ± 7.63	68.0 ± 2.45	7.5 ± 2.07

Primary experimental equipment

Fully Automatic Pressure Training Device and Pressure Bands (KAATSU Master, Made in Japan),3D Force Plate (Kistler, Made in Switzerland),Isokinetic Dynamometer (ISOMED2000, Made in Germany),Electronic Protective Gear (DAEDO, Made in Spain),Muscle Condition Analyzer (TMG S1, Made in Slovenia).

Training protocol

Under the condition of lower limb blood flow restriction, the participants completed circuit strength training for the lower limbs in the following sequence: barbell squats, barbell lunge squats, bodyweight squat jumps, bodyweight alternating lunge jumps, deadlifts, and kettlebell swings. Specifically, athletes used 30% of their 1RM intensity for barbell squats, barbell lunge squats, and deadlifts, and employed a 16kg kettlebell for the kettlebell swing exercises.

For each of the exercises (squats, deadlifts, weighted lunges, bodyweight squat jumps, bodyweight alternating lunge jumps, and kettlebell swings), the participants performed 4 sets. The first set consisted of 30 repetitions, and the number of repetitions decreased with each subsequent set due to muscle fatigue. However, by the fourth set, the repetitions should not be fewer than 20. The rest interval between sets was 60 seconds. Before training, athletes wore pressure bands that were 5 cm in width, secured around the upper third of the thigh, perpendicular to the longitudinal axis of the thigh. They used a fully automatic pressure training device for inflation, with a dressing pressure of 40 mmHg and a training pressure of 200 mmHg.

Experimental test metrics

Isokinetic strength metrics and explosive power test

Isokinetic Knee Joint Strength Test: The peak torque of knee flexion and extension was tested using the ISOMED 2000 isokinetic strength training and testing system from Germany at an angular velocity of 60°/s. The test participants were seated, secured in place to prevent compensatory movements, such as lifting the buttocks off the chair during the test.

Three-dimensional Force Platform CMJ and SJ Test: Participants stood on a three-dimensional testing platform with their hands hanging by their sides. Upon a verbal command, athletes performed a semi-squat jump (SJ) and a counter-movement jump (CMJ). The jump height (H) and flight time (T) were calculated. Each test was performed three times, and the highest value was taken as the analysed metric.

Muscle condition diagnostic test

TMG Test: The TMG (Tensiomyography) was utilized to measure the Tc and Dm parameters of the dominant and non-dominant legs of the participants. The participants were instructed to lie supine on a bed, with a supporting cushion placed under the leg being tested. Manual palpation was used to identify the thickest part of the Rectus Femoris , Biceps Femoris, Vastus Lateralis, and Vastus Medialis muscles. The TMG sensor was then placed perpendicular to the skin surface at the point of the muscle's greatest belly (Ditroilo et al., 2013). Two self-adhesive surface electrodes were positioned 5 cm apart, centred on the sensor, ensuring they did not cross the muscle boundary to avoid stimulating adjacent muscles. A constant voltage of 30V was applied, starting with an initial intensity of 30mA. The stimulation amplitude was progressively increased until the linear sensor detected the muscle's maximum contraction. The interval between stimulations was set at 10-15 seconds. The TMG software was used to select the Dm parameter (indicating the maximum radial displacement of the muscle) and the Tc parameter (representing the time required for Dm to increase from 10% to 90% of its peak). These data were then used for subsequent analysis (Wilson et al., 2019). Additionally, using the calculation formula as follows, we computed the change in the proportion of slow-twitch (Type I) to fast-twitch (Type II) muscle fibres before and after the test:

$$\text{Slow-Twitch Fibers} = 1.63 \times \text{Tc} - 8.85$$
$$\text{Fast-Twitch Fibers} = 100 - \text{Slow-Twitch Fibers}$$

Sport-specific skills test

After warming up, participants executed left and right horizontal kicks against an electronic protective gear for 10 seconds. The force, frequency, and accuracy of the kicks against the electronic protective gear were measured. This was tested three times with a 5-minute rest interval between tests, and the best result was selected for analysis.

Data analysis

All data were compiled and organized using Microsoft Excel software. Subsequent statistical analyses were conducted using SPSS Statistics 26.0. Data are presented as mean ± standard deviation (M ± SD).The Shapiro–Wilk test was employed to check for the normality of the data distribution. The internal consistency of the TMG parameters was computed using the Intraclass Correlation Coefficient (ICC). The paired sample T-test was applied to determine significant differences before and after the intervention. The Pearson correlation coefficient was used to examine the relationship levels between Tc and Dm of the dominant side Rectus Femoris (RF), Biceps Femoris (BF) , Vastus Lateralis (VL), and Vastus Medialis (VM) with isokinetic knee strength, electronic armour impact force, counter-movement jump (CMJ), and semi-squat jump (SJ) flight time and height. An independent samples T-test was utilized to examine the symmetry of the related muscles on both sides after the intervention. The above analytical approaches provide comprehensive insights into the effects of the intervention and any inherent relationships between the various muscular and athletic performance parameters studied.

RESULTS

After undergoing the Shapiro–Wilk test and the Intraclass Correlation Coefficient assessment, the data related to isokinetic strength, flight time, and flight height of both the counter-movement jump and the semi-squat jump, as well as the specific abilities, were found to be normally distributed ($W = 0.866$-0.978, $p > .05$). This allowed for the application of the Pearson correlation coefficient test. Based on the inquiry with the participants, the right leg was designated as the dominant side (Dom) and the left leg as the non-dominant side (Ndom). For the dominant side, the contraction time (Tc) ICC values for RF, BF, VL, and VM were 0.853, 0.901, 0.859, and 0.771, respectively. The maximum radial displacement (Dm) ICC values were 0.803, 0.748, 0.833, and 0.855, respectively. For the non-dominant side, the Tc ICC values for RF, BF, VL, and VM were 0.899, 0.867, 0.921, and 0.877, respectively, and the Dm ICC values were 0.854, 0.835, 0.886, and 0.789, respectively.

The comparisons of isokinetic strength, CMJ and SJ flight time and height, and the force, frequency, and accuracy of kicks against the electronic protective gear before and after the experimental intervention are shown in Table 2. After the intervention, there was a significant increase in the peak torque of left and right knee flexion, flight time and height of CMJ and SJ, and the force and accuracy of kicks against the electronic protective gear ($p < .05$). However, there was no significant improvement in the frequency of kicks after the intervention ($p > .05$).

As shown in Table 3, after the intervention, there was a notable decrease ($p < .05$) in the Tc and Dm for both the dominant and non-dominant sides across the following muscles: RF, BF, VL, and VM. Moreover, the difference for the RF of the non-dominant side post-intervention was significant ($p = .00$, $p < .01$). As depicted in Figures 1 and 2, there was no significant difference in the symmetry between the two sides after the intervention.

Table 4 indicates that the ratio of fast-twitch muscle fibres in RF, BF, VL, and VM increased significantly on both sides compared to before the experiment, while the ratio of slow-twitch muscle fibres decreased.

Table 2. Changes in isometric muscle strength, lower limb explosive strength, and specific abilities.

Variable	**Pre-test**	**Post-test**	***p*-value**
60°Flexion Ndom	76.00 ± 10.73	94.17 ± 11.10	.04*
60°Flexion Dom	72.83 ± 13.77	97.17 ± 17.75	.00**
60°Extension Ndom	116.00 ± 18.07	149.33 ± 24.56	.00**
60°Extension Dom	134.00 ± 26.69	148.17 ± 17.86	.04*
CMJ Flight Time (s)	0.21 ± 0.01	0.23 ± 0.12	.00**
CMJ Flight Height (cm)	23.21 ± 3.52	25.92 ± 2.98	.01*
SJ Flight Time (s)	0.21 ± 0.14	0.22 ± 0.14	.00**
SJ Flight Height (cm)	22.05 ± 2.58	25.98 ± 4.26	.00**
Kick Force （bls）	46.20 ± 2.39	50.88 ± 2.75	.00**
Effective Hits	21.16 ± 0.82	23.50 ± 0.54	.01*
Number of Kicks	22.67 ± 0.82	23.17 ± 0.75	.08

*Note: * indicates p < .05, ** indicates p < .01, indicating statistical significance; Dom: Dominant side; Ndom: Non-dominant side; CMJ: counter-movement jump; SJ: semi-squat jump.*

Table 3. Changes in Dm and TC indicators.

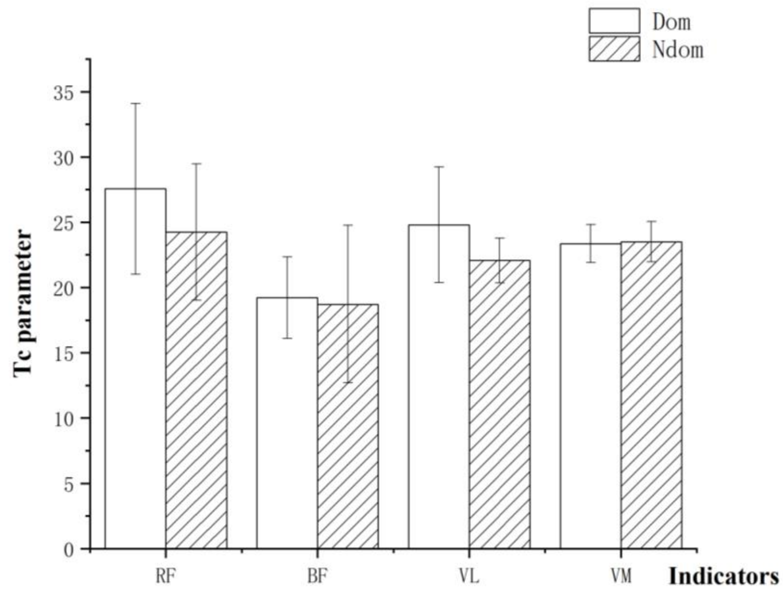
Indicators		**Pre-test**		**Post-test**	
		Dom	Ndom	Dom	Ndom
RF	Tc	31.65 ± 6.76	31.95 ± 7.62	27.56 ± 6.55*	24.25 ± 5.23**
	Dm	8.04 ± 4.43	8.01 ± 2.22	4.47 ± 3.63*	3.65 ± 2.51**
BF	Tc	29.15 ± 7.41	29.26 ± 10.43	19.23 ± 3.12*	18.72 ± 6.04*
	Dm	3.58 ± 1.16	4.26 ± 1.64	1.58 ± 0.62*	1.56 ± 1.22**
VL	Tc	26.50 ± 3.26	27.41 ± 4.67	24.81 ± 4.44*	22.07 ± 1.72*
	Dm	6.15 ± 1.52	5.93 ± 1.89	4.91 ± 1.71**	4.59 ± 1.38*
VM	Tc	25.06 ± 1.29	25.00 ± 1.89	23.36 ± 1.46*	23.50 ± 1.55*
	Dm	8.12 ± 2.61	8.58 ± 2.14	5.28 ± 2.15*	6.68 ± 1.87*

*Note: * indicates p < .05, ** indicates p < .01, indicating statistical significance; RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Dom: dominant side; Ndom: nondominant side; Tc: time of contraction; Dm: maximum radial direction of contraction.*

Table 4. Changes in the proportion of fast-twitch and slow-twitch muscle fibres.

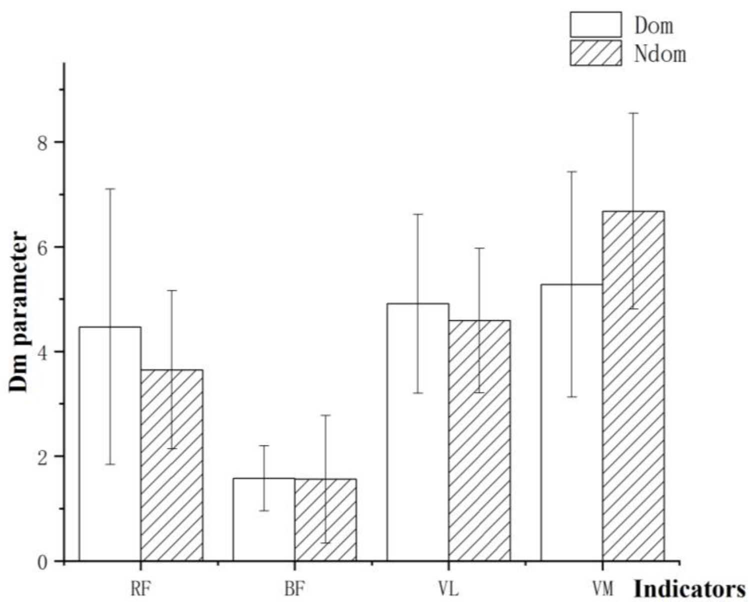
Indicators		**Pre-test**		**Post-test**	
		Dom	Ndom	Dom	Ndom
RF	ST	43.55 ± 9.52	43.23 ± 12.42	36.08 ± 10.68*	30.69 ± 8.52**
	FT	56.45 ± 9.52	56.77 ± 12.42	63.92 ± 10.68*	69.31 ± 8.52**
BF	ST	38.66 ± 12.07	38.74 ± 16.82	22.49 ± 5.08*	21.67 ± 9.85*
	FT	61.34 ± 12.07	61.26 ± 16.82	77.51 ± 5.08*	78.33 ± 9.85*
VL	ST	72.87 ± 2.80	35.83 ± 7.60	34.34 ± 5.31**	31.58 ± 7.24*
	FT	27.13 ± 2.80	64.17 ± 7.60	30.05 ± 2.46*	68.42 ± 7.24*
VM	ST	32.03 ± 2.11	31.89 ± 3.08	29.18 ± 2.29**	29.46 ± 2.52*
	FT	67.96 ± 2.11	70.54 ± 3.23	68.10 ± 3.07**	70.82 ± 2.29*

*Note: * indicates p < .05, ** indicates p < .01, indicating statistical significance; RF: rectus femoris; BF: biceps femoris; VL:vastus latissimus; VM: vastus medialis; Dom: dominant side; Ndom: nondominant side; ST: slow-twitch muscle fibres; FT: fast-twitch muscle fibres.*



Note: RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Dom: dominant side; Ndom: nondominant side; Tc: time of contraction.

Figure 1. Changes in Tc parameter.



Note: RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Dom: dominant side; Ndom: nondominant side; Dm: maximum radial direction of contraction.

Figure 2. Changes in Dm parameter.

As indicated in Tables 5, 6, and 7, several relationships emerged between the tensiomyography (TMG) parameters and athletic performance metrics for the Taekwondo athletes. The Dm of the VM on the dominant side demonstrated a significant positive correlation with the CMJ flight time (r = 0.844, *p* = .035). Conversely, it exhibited a significant negative correlation with the knee extensor strength (r = -0.844, *p* = .034).The Dm of the VL presented a significant negative relationship with the SJ flight time (r = -0.899, *p* = .015) and a significant positive relationship with the number of leg kicks (r = 0.821, *p* = .045).The Dm of the BF showed a significant positive correlation with the kick force (r = 0.917, *p* = .010).

Table 5. Correlation analysis of lower limb explosive power and TMG indicators.

Indicators	**CMJ Flight Time**		**CMJ Flight Height**		**SJ Flight Time**		**SJ Flight Height**	
	r	*p*	r	*p*	r	*p*	r	*p*
RF Dm	-0.445	.376	-0.504	.308	-0.372	.121	-0.469	.280
RF Tc	-0.135	.798	0.022	.966*	0.700	.468	0.530	.348
BF Dm	-0.414	.414	-0.487	.328	-0.470	.347	-0.557	.251
BF Tc	-0.474	.342	-0.342	.506	0.680	.137	0.391	.443
VL Dm	-0.060	.910	0.041	.939	0.514	.297	0.325	.529
VL Tc	-0.648	.164	-0.683	.135	-0.745	.089	-0.899*	.015
VM Dm	0.796	.058	0.844*	.035	0.463	.320	0.535	.274
VM Tc	-0.015	.977	0.095	.857	0.493	.356	0.524	.286

*Note: * indicates p < .05, indicating statistical significance; CMJ: counter-movement jump; SJ: semi-squat jump; RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Tc: time of contraction; Dm: maximum radial direction of contraction.*

Table 6. Correlation analysis of isokinetic muscle strength and TMG indicators.

Indicators	**60°Flexion**		**60°Extension**	
	r	*p*	r	*p*
RF Dm	-0.163	.757	0.286	.582
RF Tc	-0.111	.834	-0.057	.915
BF Dm	-0.028	.959	0.266	.611
BF Tc	-0.140	.792	-0.024	.964
VL Tc	0.431	.393	0.596	.212
VL Dm	0.201	.703	-0.355	.490
VM Dm	-0.506	.306	-0.844*	.034
VM Tc	-0.137	.796	0.283	.587

*Note: * indicates p < .05, indicating statistical significance; RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Tc: time of contraction; Dm: maximum radial direction of contraction*.

Table 7. Correlation analysis of specific abilities and TMG indicators.

Indicators	**Number of Kicks**		**Effective Hits**		**Kick Force**	
	r	*p*	r	*p*	r	*p*
RF Dm	-0.345	.503	0.288	.580	0.117	.825
RF Tc	0.417	.411	-0.519	.292	0.734	.097
BF Dm	-0.318	.539	0.395	.439	0.917*	.010
BF Tc	0.492	.322	-0.521	.289	0.047	.929
VL Tc	-0.248	.635	0.483	.332	0.201	.702
VL Dm	0.821*	.045	-0.207	.694	0.546	.263
VM Dm	0.458	.361	0.343	.506	0.003	.995
VM Tc	-0.148	.780	-0.765	.076	0.227	.666

*Note: * indicates p < .05, indicating statistical significance; RF: rectus femoris; BF: biceps femoris; VM: vastus medialis; VL: vastus latissimus; Tc: time of contraction; Dm: maximum radial direction of contraction.*

DISCUSSION

The findings from this study reveal that after a 4-week circuit training regimen combined with blood flow restriction, participants exhibited improvements in knee joint flexor and extensor muscle groups, lower limb explosive power, and specific kicking capabilities. There was a significant enhancement in muscle fibre contraction and recruitment capacities compared to before the intervention. TMG data highlighted that after the intervention, the proportion of slow-twitch muscle fibres decreased, while that of fast-twitch muscle fibres noticeably increased. This implies that the training intervention had modified the muscle fibre composition in favour of those fibres typically associated with power and speed. The shift towards a higher percentage of fast-twitch fibres suggests that the athletes' lower limb strength, explosiveness, and overall muscle composition have been enhanced, all of which are beneficial for optimizing athletic performance.

Lower limb explosive strength

The experimental results suggest that circuit strength training combined with blood flow restriction has a positive impact on the lower limb explosiveness of Taekwondo athletes. Prior studies corroborate our findings. Cook et al. (2014) observed a 1.8% ± 0.7% improvement in jumping capability in rugby players after employing medium-load (70% 1RM) combined with BFR training for three weeks. Similarly, Wang et al. (2019) reported that after eight weeks of medium-load (70% 1RM) BFR training on handball players, the improvements in lower limb explosiveness matched those achieved through traditional high-intensity strength training.

A distinguishing feature of our study was the attainment of comparable results with a lower exercise load compared to medium loads. This suggests that the combination of circuit strength and blood flow restriction training not only enhances athletic performance but may also be safer than other training modalities. The aforementioned results can be elucidated through TMG data. Prior research posits that stronger forces and increased strength training are associated with lower Tc and Dm values, with Dm directly correlated to power and force capabilities (Loturco et al., 2015; Šimunic et al., 2018). A decreased Dm value implies heightened muscle stiffness, reflecting superior performance in activities involving stretch-shortening cycles. Zubac & Šimunič (2017) identified a correlation between the reduction in lower limb muscle Dm and increased jump height following an 8-week resistance training program. Therefore, after 4 weeks of BFR combined with circuit training, our participants displayed increased muscle stiffness and improved muscle function, which, in turn, bolstered their lower limb explosiveness.

Muscle fibre recruitment

The research results indicate that after a 4-week intervention, there was a significant increase in the peak torque of knee flexion and extension for both legs. Notably, the growth rate for the knee extensor muscles in both legs was larger than for the flexors, with increments of 39.17 ± 4.53 and 34.16 ± 10.11, respectively. This aligns with the findings of prior studies. Takarada et al. (2004) subjected 18 male athletes to an 8-week knee extension exercise regimen (totalling 16 sessions) at a load intensity of 20% 1RM. The results showed that after undergoing the 20% 1RM pressurized training, the experimental group experienced an increase of 9.2 ± 2.2 % in knee extensor muscle strength. Similarly, Sakuraba & Ishikawa (2009) performed an 8-session, 4-week knee flexion and extension exercise regimen on 21 athletes with thigh pressure set at 200mmHg. The results revealed a 13.6% increase in knee extensor muscle strength.

However, a distinct difference between our study and prior research is that according to the TMG and isokinetic strength data, the increase in the strength of the knee flexor and extensor muscles for the left leg was more pronounced compared to the right. This can be attributed to Taekwondo being a predominantly unilateral sport. For many athletes, the right leg serves as the primary attacking leg, hence its flexor and extensor muscles are inherently stronger. Conversely, the left leg, primarily used for support and subjected to fewer flexion movements, tends to be weaker. This results in an imbalance in strength between the two legs. Yet, after the 4-week pressurized training, there was a significant improvement in the left leg, thereby reducing the asymmetry between the two legs and enhancing their balanced muscular strength.

Sport-specific skills

After the experimental intervention, participants showed a significant improvement in kick force and effective hits on the electronic protective gear. However, the number of kicks remained relatively consistent pre and post-intervention. A possible explanation for this outcome is that the circuit strength training, when combined with blood flow restriction, effectively enhanced the muscular strength and recruitment capability of the lower limbs. This increase in turn bolstered the athletes' explosive power in their legs (Gao & Yu, 2023). Consequently, athletes could deliver higher effective kick forces on the electronic protective gear, leading to a rise in the count of effective hits. This development can address the issue faced by Taekwondo athletes, where they might land a hit during competition but fail to score due to inadequate force (Li, 2022).

Our research data revealed only a minimal correlation between the specific ability parameters (number of kicks, effective hit counts, and kick force) and the TMG metrics following the combined pressure training. This might be attributed to the fact that the electronic protective gear, integral to taekwondo competitions, can be influenced by a myriad of factors such as lower limb strength, coordination, and core power (Guo, 2021). As our study primarily centred on the enhancement of lower limb power and explosiveness, it might have resulted in the observed lack of correlation between the two aspects.

Muscle status

The results of the study indicate that post-intervention, there was a significant decline in both the dominant and non-dominant sides' Tc and Dm for the RF, BF, VL, and VM. Concurrently, the data reveals a pronounced increase in the fast-twitch muscle fibre ratio for the left and right legs in these muscles post-intervention, with a notable decrease in the slow-twitch fibre ratio. This suggests that, after blood flow restriction training, the contraction speed of RF, VM, VL, and BF muscles increased, muscle fibre recruitment capability intensified, and the number of muscle fibres recruited also grew. However, this was accompanied by a concurrent increase in muscle tension and rigidity. The findings from this study align with these past research endeavours, suggesting that a period of strength training consistently results in a decrease in Tc and Dm of the relevant muscle groups. Existing research indicates that athletes with a higher level of strength training show TMG characteristics of shorter Tc and smaller Dm (Loturco et al., 2015; Šimunic et al., 2018). A study conducted by de Paula Simola et al (2015) on 14 male athletes, encompassing a range of lower limb strength exercises over 5 weeks, discovered that various leg training types could reduce respective muscle's Dm and Tc. García-García et al (2016) found that, following 10 weeks of speed and power training, there was a significant decrease in Tc, Dm, and Td of the knee extensor muscles.

Upregulation of IGF-1 (insulin-like growth factor-1) expression is a primary physiological mechanism that promotes muscle strength and hypertrophy (Yoshida & Delafontaine, 2020). Some studies have illustrated that low-load occlusion strength training significantly elevates the concentration of insulin-like growth factors (Abe et al., 2005).Blood flow restriction training operates by restricting blood flow, leading to hypoxia and an acidic environment in the body, resulting in a substantial accumulation of lactic acid. This condition inhibits the contraction of slow-twitch fibres, thereby mobilizing a large number of additional fast-twitch fibres to maintain the body's movement needs (Yasuda et al., 2006). Recruiting and stimulating these additional rapid-contracting fibres during exercise may be one reason for the muscle hypertrophy and strength enhancement induced by occlusion training (Sumide et al., 2009). Consequently, after blood flow restriction training, there was a significant growth in the fast-twitch fibres of RF, VM, VL, and BF, while slow-twitch fibres saw a decline.

TMG parameters and sport-specific skills

This study's findings revealed: (1) There's a significant positive correlation between vastus medialis Dm and CMJ flight time, and a significant negative correlation with knee joint extensor muscles. The vastus lateralis Dm shows a significant negative correlation with SJ flight time and a notable positive correlation with the number of kicks. Additionally, biceps femoris Dm has a significant positive correlation with kick force. (2) There is no correlation between TC and any of the tests. (3) Post-experiment, an evaluation based on TMG parameters found no significant disparity in symmetry between the two sides.

Our study results differ from previous research. For instance, Loturco et al (2016) conducted a TMG test on football players and found a moderate negative correlation between the Dm of biceps femoris and rectus femoris with contraction time. There was also a moderate correlation between the Dm of the biceps femoris and the reaction intensity index. However, there was no connection between reactive jump height, jump height, sprinting ability, and TMG parameters, and there was no disparity in symmetry between the dominant and non-dominant legs. The reason for this discrepancy could be that, although TMG parameters reveal characteristics of muscle fibre excitation-contraction coupling and associated muscle contractions and mechanics, the TMG assessment is passively performed on isolated muscles. In contrast, all sports tasks are actively completed, involving multiple muscle groups and numerous dynamic variables, encompassing diverse contributing factors (Gil et al., 2015). This suggests that the conditions assessed in this current study are distinct from those in previous research, which might, to an extent, explain the lack of association between these variables.

Our study has several limitations that should be noted. Firstly, due to the objective circumstances and the limited number of athletes available for the study, the sample size was relatively small and somewhat homogeneous. Secondly, this research primarily focused on short-term effects, leaving mid-term and long-term training effects to be investigated in future studies. Lastly, the lack of a control group in this experiment might hinder an accurate assessment of the combined effects of blood flow restriction and circuit strength training.

Future research could further explore the efficacy of this training method for Taekwondo athletes of different ages, genders, and skill levels. It might also be worthwhile to extend the study to other sports disciplines, such as boxing or wrestling, to understand the generalizability and adaptability of this combined training approach across different athletic fields. Moreover, examining the long-term impacts of this training on athletes' muscle conditions, performance enhancements, and related biochemical indicators will be valuable directions for further research.

CONCLUSION

Our study indicates that combining blood flow restriction with circuit strength training has a positive effect on the lower limb explosive strength and specific kicking ability of Taekwondo athletes. Furthermore, this combination can shorten the contraction time of muscles relevant to Taekwondo athletes, alter muscle fibre ratios, and enhance muscle explosiveness. However, there was no observed correlation between TMG (Tensiomyography) and athletic performance. In addition, based on the TMG-related parameter evaluations, there was no significant asymmetry between the left and right lower limbs post-intervention, and the tensiomyographic parameters were unrelated to the athletic performance of the Taekwondo athletes.

AUTHOR CONTRIBUTIONS

LW and GZ designed the study, wrote the initial draft, and made revisions, managed data, conducted surveys, formulated methods, created visualizations, supervised, and managed the project. LY participated in software, data curation, formal analysis, visualization, and manuscript revision. WJ conducted formal analysis, supervision, validation and revision . All authors have contributed to the manuscript, approved the final version for submission, and consent to its publication in JHSE.

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DISCLOSURE STATEMENT

No potential conflict of interest were reported by the author.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material and further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving humans were approved by Ethics Committee of Xi'an Physical Education University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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