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The enhancement of explosive power contributes to the development of anaerobic capacity: A comparison of autoregulatory progressive resistance exercise and velocity-based resistance training

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ABSTRACT

Objectives: Due to the character of the taekwondo, the adenosine triphosphate–phosphocreatine system provides the energy for each kick, the glycolytic system supports the repeated execution of kicks, and the aerobic system promotes recovery between these movements and the bout. Therefore, taekwondo athletes require high explosive power and anaerobic capacity in order to carry out sustained and powerful attacks. So, the purpose of this study is to compare the effects of APRE and VBRT on lower-limb explosive power and anaerobic capacity in college taekwondo players.
Methods: A total of 30 taekwondo players completed an 8-week training intervention with autoregulatory progressive resistance exercise (APRE; $n = 15$) and velocity-based resistance training (VBRT; $n = 15$). Testing included the one-repetition maximum squat, countermovement jump (CMJ), taekwondo anaerobic intermittent kick test (TAIKT), and 30-s Wingate anaerobic test (WAnT).
Results: (1) Intragroup comparisons revealed significant effects for one-repetition maximum squat, peak power of CMJ (CMJ_{PP}), relative peak power of CMJ (CMJ_{RPP}), and total number of TAIKT ($TAIKT_{TN}$) in both the APRE and VBRT groups. The VBRT group exhibited small effect sizes for time at peak power of WAnT ($WAnT_{PPT}$) and moderate effect sizes for peak power of WAnT ($WAnT_{PP}$), relative peak power of WAnT ($WAnT_{RPP}$), and fatigue index of TAIKT ($TAIKT_{FI}$), whereas the APRE group exhibited small effect sizes for $TAIKT_{FI}$. (2) Intergroup comparisons revealed no significant effects in any of the results. However, VBRT demonstrated a moderate advantage in $WAnT_{PP}$ and $WAnT_{RPP}$, whereas APRE had a small advantage in CMJ_{PP} and CMJ_{RPP}.
Conclusions: These findings suggest that APRE improved explosive power (CMJ_{PP} and CMJ_{RPP}) more, whereas VBRT improved anaerobic power output ($WAnT_{PP}$ and $WAnT_{RPP}$) more. Both methods were found to have similar effects in improving the anaerobic endurance ($WAnT_{PPT}$ and $TAIKT_{TN}$) and fatigue index (power drop of WAnT and $TAIKT_{FI}$).

1. Introduction

In the context of physical activity, the human body relies on three distinct energy systems to provide energy for various types of activity: the adenosine triphosphate–phosphocreatine (ATP–PCr), glycolytic, and oxidative systems. The activation of these systems is responsible for the rate of energy release, which ultimately determines the intensity and duration of effort required.[1] In taekwondo competitions, the power and power output generated during short-distance movements, such as rapid kicking, punching, and footwork, are crucial to a player's performance.[2–4] Competitions typically consist of three 2-min rounds with 1-min rest intervals between rounds,[5] during which players perform

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high-intensity actions lasting 1–6 s, such as scoring or defensive techniques, interspersed with low-intensity periods consisting of stepping actions or referee's breaks. Fighting to non-fighting ratios can range from 1:2 to 1:7.[4–6] The ATP–PCr system may provide energy during high-intensity actions, the glycolytic system supports repeated high-intensity actions, and the oxidative system is crucial for promoting these actions and facilitating recovery between competition rounds.[2,5,7] Taekwondo players, particularly in their lower limbs, require high peak anaerobic power to perform numerous sequences of fast and powerful attacks and counterattacks,[8] often with short, incomplete recovery periods.[5] Therefore, effective management of metabolic demands during competition requires high anaerobic and aerobic capacities.

Currently, research on anaerobic capacity has primarily focused on non-strength training methods, such as high-intensity interval training[9,10] and repeated sprint training.[11,12] The dearth of studies on the effects of resistance training (RT) on anaerobic capacity may be due to the perception that RT is not the optimal method for improving anaerobic capacity. However, RT has been suggested to increase muscle strength and mass while also enhancing muscle anaerobic capacity.[13] For example, Drapsin et al.[14] conducted an 8-week self-control study on RT and found that RT could improve peak power and relative peak power in the Wingate anaerobic test (WAnT). Similarly, in a study by Rønnestad et al.,[15] 16 elite cyclists underwent 25 weeks of endurance and percentage-based resistance training (PBRT, which relied on different percentages of one-repetition maximum (1RM) to determine the intensity and volume of training loads.[16]) or endurance training only. The results indicated that endurance and percentage-based PBRT training had a moderate effect on relative peak power in the WAnT (effect size (ES) = 0.76). However, a study[17] investigating the effect of adding strength training to the daily endurance training of long-distance runners on their anaerobic capacity found that after 8 weeks of intervention, neither the strength training group nor the control group (which only underwent endurance training) exhibited a significant improvement in anaerobic capacity. Despite these findings suggesting that RT may have a positive effect on anaerobic capacity, the existing research results are inconsistent, and the underlying mechanisms remain uncertain.

In the context of the continuous development of competitive sports, a new RT method, called autoregulatory resistance training (ART), has been proposed and implemented.[18,19] This method primarily helps coaches to adjust the training load in time, including training volume and intensity, through the monitoring of the training state of athletes. This enables players to acquire an appropriate training load, resulting in enhanced maximal strength gains and reduced fatigue.[20] Autoregulatory progressive resistance exercise (APRE) and velocity-based resistance training (VBRT) are two commonly used forms of ART.[21] APRE can be defined as a form of autoregulatory resistance training that adjusts training on the basis of an individual's daily training status, similar to nonlinear periodization resistance training.[22] While, VBRT is an emerging and popular method of monitoring and designing training prescription that uses advanced speed measurement devices during strength training to track the speed of moving loads and provide feedback.[23,24] Previous research has demonstrated the positive effects of both APRE[25,26] and VBRT[27] on anaerobic capacity. However, the research is still not established, and there is currently no study directly comparing the effects of these two RT methods on anaerobic capacity. Therefore, the purpose of this study is to compare the effects of APRE and VBRT on lower-limb explosive power and anaerobic capacity in college taekwondo players. On the basis of the research progress of APRE and VBRT, we hypothesize that both methods will cause similar strength gains regarding explosive power, but VBRT will be superior to APRE regarding anaerobic capacity.

2. Materials and methods

2.1. Study design

The present study was a randomized controlled trial. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee(approval number 2022LCLL-28). The players volunteered to participate in the study from October 2022 to December 2022. Each player provided signed written informed consent after being informed of the risks and benefits associated with the study. No physical limitations, health problems, or musculoskeletal injuries that could affect training were found after a medical examination.The study was registered at www.chictr.org.cn (NO. ChiCTR2300070266)

Randomization was performed after the baseline test. The players were randomized to APRE or VBRT using random numbers for SPSS. The taekwondo coaches informed the players that they could not participate in any additional resistance training during the study.

2.2. Participants

A total of 35 players, all with 3 or more years of taekwondo, originally volunteered to take part in the research study. However, because of injury ($n = 5$), only 30 taekwondo players (male = 14, female = 16) were recruited and completed the training intervention (age, 19.8 ± 1.3 years; height, 173.3 ± 8.7 cm; weight, 61.3 ± 10.2 kg). The players were randomly distributed into two groups: VBRT ($n = 15$) and APRE ($n = 15$), randomization was performed with the use of stratified randomization, with boys and girls randomly assigned separately. There was no statistically significant difference between the two groups as regards baseline ($p > 0.05$) (Table 1).

2.3. Experimental design

Based on the progressive linear periodization structure (from 70% to 90% 1RM),[28] the RT program (Table 3) was used to compare the effects of APRE and VBRT on explosive power and anaerobic capacity of the lower limb. From October 2022 to December 2022, each player completed resistance training sessions for 8 weeks (3 sessions/week on Mondays, Wednesdays, and Fridays), and each interval between each resistance training session was at least 48 h (Fig. 1). Between the two groups, the training goals, targeted relative loads, number of sets, and intervals were equal, but absolute loads (lifted weight is the weight lifted by the individual during each training session) and repetitions were different.

One week before the baseline test, the participants started to become familiar with the test procedures, intervention, and rating of perceived exertion (RPE) scale.[29] After familiarizing, the players were randomly assigned into two groups using the SPSS random number generator: VBRT ($n = 15$) and APRE ($n = 15$). Four performance tests, including maximal strength, explosive power, and anaerobic capacity (Table 2), were conducted over 2 days based on the testing content and the need for physical recovery. All tests were conducted at least 48 h before/after the most recent training session, with a minimum 48-h interval between each testing day.

Table 1
Information of the players.

Players	APRE	VBRT
Age (year)	19.8 ± 1.2	19.7 ± 1.5
Height (cm)	172.9 ± 9.2	173.7 ± 8.5
Body weight (kg)	59.8 ± 9.5	62.7 ± 11.0
Squat 1RM (kg)	87.67 ± 28.4	96 ± 30.31

Note: APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training; 1RM, one-repetition maximum.

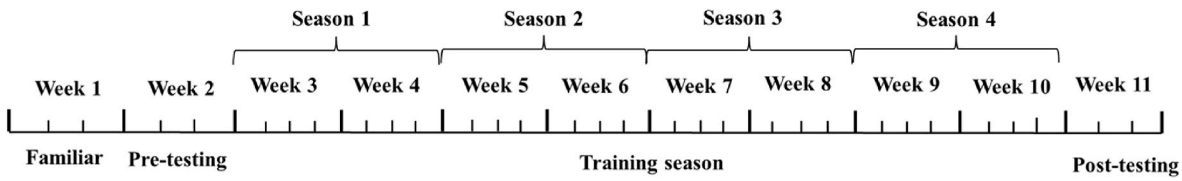

Fig. 1. Timeline of the study.

Table 2
Testing procedures and index.

Performance	Procedures	Index	Equipment
Maximum strength	Squat 1RM	Weight (kg)	Barbell, barbell rack
Explosive power	CMJ	Height (cm), PP (W), RPP (W/kg)	ForceDecks force platform
Anaerobic capacity	WAnT	PP (W), RPP (W/kg), PPT (ms), FI (%)	Monark 894E Peak Bike
	TAIKT	FI (%), total (number)	Daedo Electronic Protectors

Note: CMJ, countermovement jump; TAIKT, taekwondo anaerobic intermittent kick test; WAnT, 30-s Wingate anaerobic test; PP, peak power; RPP, relative peak power; PPT, time at peak power; PD, power drop; FI, fatigue index; 1RM, one-repetition maximum.

2.4. Resistance training program

Velocity-based resistance training: The VBRT training program is based on Signore's scientific classification of training loads and speed zones,[30–32] using primarily 70%, 80%, and 90% of 1RM and their corresponding speed zones to develop players' muscle strength. In each training session, players perform four sets of squats. The program is designed to help the players improve their strength by focusing on specific training loads and speed zones (Table 3). In addition, previous studies[33] have suggested that if the mean concentric velocity (MCV) in a set was ±0.06 m/s outside of the sessional target velocity, the lifted weight was then adjusted by ±5% 1RM for the subsequent set between the sessions for back squat. In addition, the maximum number of squat repetitions for each training intensity was also determined to allow for adjustments in training intensity over time.

Autoregulatory progressive resistance exercise: The APRE training program follows established rules,[22,25,26] whereby players perform a set number of repetitions at a percentage of their 10RM, 6RM, or 3RM (Table 3). With the use of 6RM as an example, the first set consists of 10 squats at 50% of the 6RM, and the second set consists of six squats at 75% of the 6RM. In the third set, players are required to perform squats with 100% of their 6RM load until failure, and then the weight for the fourth set is determined based on the load-adjustment table (Table 4). During the fourth set, players are instructed to perform as many repetitions as possible until failure, and the number of repetitions achieved is used to adjust the starting load for the next training session after 48 h.

2.5. Testing procedures

Testing consisted of maximum strength, explosive power, and anaerobic capacity tests. The players completed all tests in 2 days. Day 1 comprised squat 1RM and taekwondo anaerobic intermittent kick test (TAIKT). Day 2 comprised countermovement jump (CMJ) and 30-s WAnT. All tests were performed at least 48 h before/after the most recent training session and at least 48 h between each test day. Before all testing and training sessions, the players were supervised during a standardized warm-up, consisting of a 5-min myofascial release and 10-min dynamic stretching (Fig. 2). All testing and training sessions took place at the same venue under the direct supervision of the lead investigator.

2.6. Outcome measures

Countermovement jump: During the testing procedure, the players were first required to stand upright and steady on the force platform while keeping their torsos stable. They then needed to raise their hands over their heads and swiftly swing them downward while simultaneously performing a continuous and rapid squat jump to reach the highest possible height while keeping their torsos upright during the flight phase.[34] The CMJ test used the ForceDecks force platform to measure vertical jump height. Each player was allowed three attempts to perform the test, with the best value being retained. The intraclass correlation coefficient (ICC), 95% confidence interval (95% CI), and coefficient of variation (CV) were observed at baseline. The test–retest reliability was observed during baseline for all players in CMJ (ICC = 0.99, 95%CI: 0.98–1, CV = 0%).

Table 4
Adjustment table for APRE.

10RM		6RM		3RM	
Repetitions	Adjusted intensity	Repetitions	Adjusted intensity	Repetitions	Adjusted intensity
4–6	−5–10 kg	0–2	−2.5–5 kg	1–2	−5–10 kg
7–8	−0–5 kg	3–4	−0–2.5 kg	3–4	Keep
9–11	Keep	5–7	Keep	5–6	+5–10 kg
12–16	+5–10 kg	8–12	+2.5–5 kg	7+	+10–15 kg
17+	+10–15 kg	13+	+5–10 kg		

Note: APRE, autoregulatory progressive resistance exercise.

Table 3
APRE and VBRT protocols.

Weeks	APRE					VBRT	
	Intensity	Repetitions				Intensity	Repetitions
		Set 1	Set 2	Set 3	Set 4		
1–2	10RM	50% × 12	75% × 10	100% × Max	Adjusted weight × Max	70% 1RM	0.5–0.75 m/s, 12
3–4	6RM	50% × 10	75% × 6			80% 1RM	0.4–0.6 m/s, 8
5–6	3RM	50% × 6	75% × 3			90% 1RM	0.2–0.3 m/s, 4
7–8	6RM	50% × 10	75% × 6			80% 1RM	0.4–0.6 m/s, 8

Note: APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training; In actual monitoring, the velocity at 70%1RM was maintained at 0.48–0.72 m/s. The velocity at 90%1RM was maintained at 0.32–0.48 m/s.

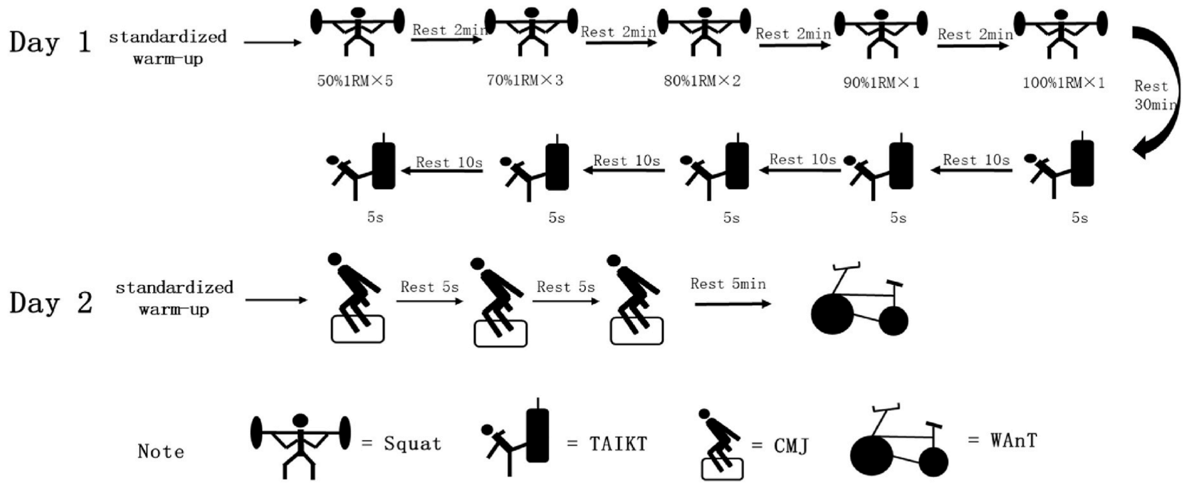

Fig. 2. Flowchart of the testing procedure. Note: TAIKT, taekwondo anaerobic intermittent kick test; CMJ, countermovement jump; WAnT, Wingate anaerobic test.

One-repetition maximum squat: The players completed 1RM testing in the free-weight back squat using the methods modified previously. Briefly, the players performed a standardized warm-up followed by five repetitions at ~50% 1RM, three repetitions at ~70% 1RM, and two repetitions at ~80% 1RM. Thereafter, players performed 1RM attempts with progressively increased loads.[34] The players were required to achieve a parallel squat depth (thigh parallel to the floor), which was monitored by a member of the research team. A maximum of five attempts were permitted, and the last successful lift was taken as the 1RM.

Taekwondo anaerobic intermittent kick test: As previously described by Tayech et al.,[35] the TAIKT protocol required the player to undertake the maximal number of stationary roundhouse kicks (named *bandal-tchagui*) after the sound signal, alternating right and left legs, during six sets of 5 s, interspersed with 10-s active recovery (i.e., bouncing movements) between each set. The total time for kick execution during the TAIKT was 30 s. The kicks were executed on an electronic body protector (TK-Strike Protector, Daedo, Barcelona, Spain) placed around a hanging punching bag, which was stabilized by one of the researchers. The number of kicks was automatically displayed on the computer screen after each kicking set. The two indices of anaerobic performance are fatigue index (FI) and the total number of 30-s kicks (TN).

$$\text{FI}\ (\%) = \frac{\text{highest 5 sec number} - \text{lowest 5 sec number}}{\text{highest 5 sec number}} \times 100.$$

30-s Wingate anaerobic test: A standard 30-s WAnT was conducted on a friction belt cycle ergometer (Monark 894E Peak Bike, Vansbro, Sweden; software version 2.2) for each player to evaluate the power output. Before the WAnT, all players completed a warm-up period consisting of 5 min of cycling on the cycle ergometer and stretching exercises. The WAnT consisted of lower limb cycling with the highest possible number of revolutions per 30 s. The load for each player was considered as 7.5% of the body mass.[36,37] The WAnT began from a rolling start against minimal resistance and was performed against the aforementioned constant resistance.[37] All players were strongly and consistently encouraged throughout the test to keep the number of revolutions as high as possible. In addition, they were instructed to maintain a seated posture to avoid the effect of postural changes and to pedal at the maximal effort. The six indices of anaerobic performance are peak power (PP), relative peak power (RPP), time at peak power (PPT), and power drop (PD).

2.7. Statistical analysis

Data analysis was completed using Statistical Product and Service Solutions (SPSS19.0) and JASP14.1, both of which are software used for statistical analysis, data mining, predictive analytics, and decision support tasks. The mean and standard deviation values were calculated using standard statistical methods. The normality of all variables was tested using the Shapiro–Wilk test procedure. Levene's test was used to determine the homogeneity of variance. Repeated measures analysis of variance was performed to compare the differences in pretesting, pretraining, and post-training change and differences in change between the two groups. Independent samples *T* test was used to analyze the differences in training load, repetitions, and RPE between the two groups. The Bonferroni adjustment was performed to determine the *p* value of the comparisons. $P < 0.05$ was considered statistically significant, and $p < 0.01$ was considered very statistically significant.

The effect size (Hedge's g, ES) of the within-group differences was calculated for each outcome. To estimate the paired effect sizes between groups, the intragroup were interpreted as trivial (ES $\leq$ 0.2), small (0.20 $<$ ES $\leq$ 0.60), moderate (0.60 $<$ ES $\leq$ 1.20), large (1.20 $<$ ES $\leq$ 2.00), or very large (ES $\geq$ 2.0).[38] The intergroup ES was interpreted as trivial (ES $<$ 0.2), small (0.20 $\leq$ ES $<$ 0.50), moderate (0.50 $\leq$ ES $<$ 0.8), and large (ES $\geq$ 0.8).[39] The partial squares eta (η_p^2) is a measure of ES for intergroup differences in intervention effects that were calculated and considered small ($0.01 < \eta_p^2 \leq 0.06$), moderate ($0.06 < \eta_p^2 \leq 0.14$), or large ($\eta_p^2 > 0.14$).[40]

3. Result

3.1. Pretesting

All body descriptive variables had no differences intergroup, which included age (APRE, 19.8 ± 1.2 years; VBRT, 19.7 ± 1.5 years), height (APRE, 172.9 ± 9.2 cm; VBRT, 173.7 ± 8.5 cm), and weight (APRE, 59.8 ± 9.5 kg; VBRT, 62.7 ± 11.0 kg), all with $p > 0.05$ (Table 1).

No significant differences between the APRE and VBRT groups were reported before training for any variables analyzed ($p > 0.05$) (Table 6).

3.2. Training load prescription

There was no significant difference ($p > 0.05$) in the repetitions (APRE, 35.93 ± 5.28; VBRT, 39.17 ± 4.98) between the APRE and VBRT groups, whereas there were significant differences ($p < 0.05$) in training load (APRE, 2191.96 ± 879.93 kg; VBRT, 3015.49 ± 983.24 kg), intensity (APRE, 246.39 ± 71.35 kg; VBRT, 308.06 ± 87.37 kg), and RPE (APRE, 13.88 ± 1.34; VBRT, 12.97 ± 0.85) (Fig. 3).

After the analysis of the training load, repetitions, intensity, and RPE of APRE and VBRT across all weeks (Table 5, Fig. 3), the training load between APRE and VBRT exhibited significant differences ($p < 0.05$) at

80%–90% 1RM, with highly significant differences ($p < 0.01$) observed in weeks 3, 6, and 8. Repetitions of APRE were higher than those of VBRT at 70% 1RM with significant differences ($p < 0.05$); however, starting from 80% 1RM, the repetitions of VBRT gradually exceeded those of APRE, with highly significant differences observed from week 4 onward. The intensity only exhibited significant differences ($p < 0.05$) in weeks 3 and 7. RPE exhibited highly significant differences ($p < 0.01$) at 90% 1RM and significant differences ($p < 0.05$) at $\geq$80% 1RM (weeks 7 and 8).

3.3. Anaerobic performance

Intragroup comparisons revealed highly significant time effects ($p < 0.01$) for 1RM squat (APRE, 28.33 kg; VBRT, 27.33 kg), CMJ$_{PP}$ (APRE, 328.33 W; VBRT, 241.41 W), and CMJ$_{RPP}$ (APRE, 5.04 W/kg; VBRT, 3.39 W/kg) in both the APRE and VBRT groups and significant time effects ($p < 0.05$) for TAIKT$_{TN}$. However, WAnT$_{PP}$, WAnT$_{RPP}$, WAnT$_{PPT}$, WAnT$_{PD}$, and TAIKT$_{FI}$ did not exhibit significant time effects ($p > 0.05$), but VBRT exhibited small ES for WAnT$_{PPT}$ ($g = 0.34$) and moderate ES for WAnT$_{PP}$ ($g = 0.94$), WAnT$_{RPP}$ ($g = 0.66$), and TAIKT$_{FI}$ ($g = 0.69$), whereas APRE exhibited small ES for TAIKT$_{FI}$ ($g = 0.32$).

Intergroup comparisons revealed no significant group-by-time interactions in any of the results. However, based on ES and η_p^2, VBRT demonstrated a moderate advantage in WAnT$_{PP}$ ($g = 0.66$, $\eta_p^2 = 0.10$) and WAnT$_{RPP}$ ($g = 0.57$, $\eta_p^2 = 0.08$), whereas APRE had a small advantage in CMJ$_{PP}$ ($g = 0.45$, $\eta_p^2 = 0.05$) and CMJ$_{RPP}$ ($g = 0.49$, $\eta_p^2 = 0.06$) (Table 6, Fig. 4).

4. Discussion

The objective of this study was to compare the effects of APRE and VBRT on lower-limb explosive power and anaerobic capacity in university taekwondo players during an 8-week RT program. The findings revealed that after 8 weeks of APRE or VBRT training, college taekwondo players demonstrated improvements in maximal strength, power output, and anaerobic tolerance. However, some differences were observed between the two intervention methods. VBRT exhibited small-to-medium advantages in improving WAnT$_{PP}$ and WAnT$_{RPP}$, whereas APRE exhibited slight advantages in improving CMJ$_{RPP}$ and CMJ$_{PP}$. VBRT training exhibited higher training intensity and load, as well as lower RPE. This indicates that real-time monitoring of players' squatting speed through VBRT can accurately control their real-time status, enabling players to maintain higher training intensity and load without experiencing excessive fatigue. Consequently, this approach reduces mechanical stress while improving power output. By contrast, APRE involves two sets of exhaustive training, resulting in higher fatigue accumulation. Although it may better improve muscle strength, it may also more easily induce a higher level of perceived fatigue in players.

4.1. Explosive power

The study evaluated the impact of two RT methods, APRE and VBRT, on explosive power output using CMJ$_{PP}$, CMJ$_{RPP}$, WAnT$_{PP}$, and WAnT$_{RPP}$ as a direct variable. After an 8-week intervention, the results indicated that both APRE and VBRT improved CMJ$_{PP}$ and CMJ$_{RPP}$, with APRE being slightly more effective than VBRT. This finding is supported by previous research, including Orange et al.,[33] who compared the effects of 7 weeks of VBRT and percentage-based resistance training (PBRT) on strength and jump performance in rugby league players and found that both groups had the potential to improve their CMJ height, although there was no significant difference between the two groups. Dorrell et al.[32] also found similar results in their study comparing the effects of 6 weeks of VBRT and PBRT on strength and jump performance in trained men. They found that training resulted in a significant increase in CMJ performance for the VBRT group (5%) but not the PBRT group (1%). A systematic review[41] also supports the use of velocity-based thresholds as monitoring tools in strength training, as they can improve CMJ height and peak power to varying degrees. Although there was no previous research supporting the effect of APRE on CMJ performance, the improvement of CMJ in adult players largely depends on the increase in individual muscle strength. The training

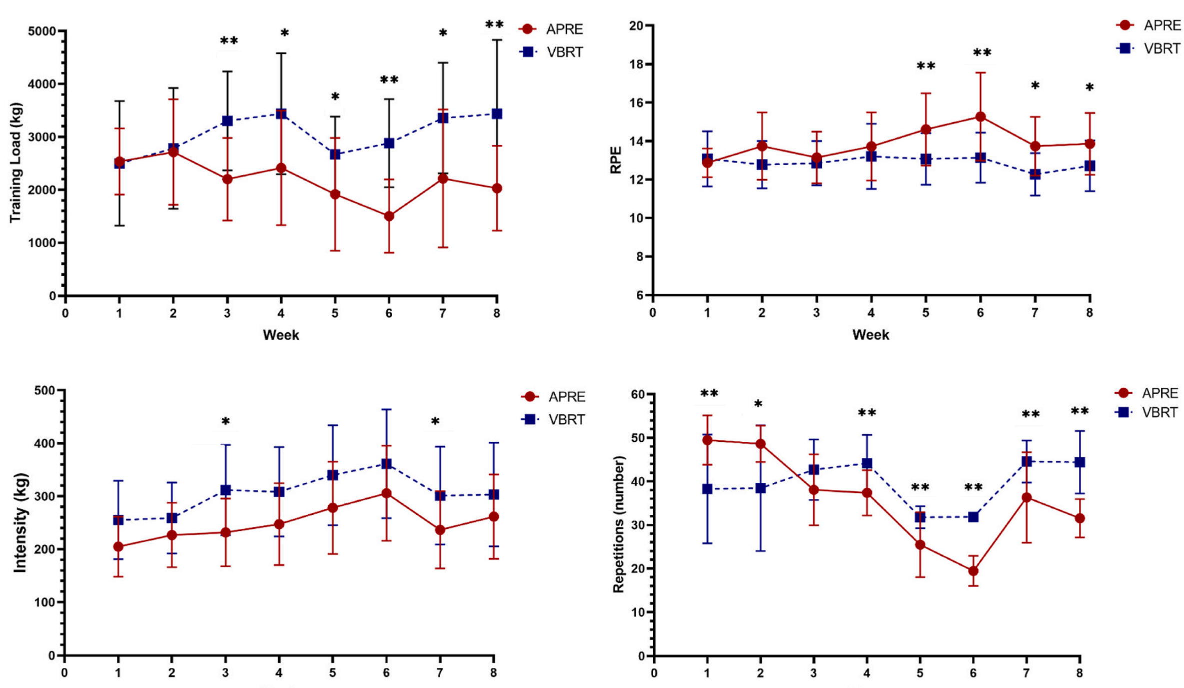

Fig. 3. Training load, repetitions, intensity, and RPE for APRE and VBRT
Note: *Denotes statistically significant difference (p < 0.05). **Denotes statistically highly significant difference (p < 0.01).
RPE, rating of perceived exertion; APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training.

Table 5
The data of training load, repetitions, intensity, and RPE for APRE and VBRT.

	Training load		Repetitions		Intensity		RPE	
	APRE	VBRT	APRE	VBRT	APRE	VBRT	APRE	VBRT
Week 1 70% 1RM	2536.39 ± 625.55	2849.63 ± 1349.58	49.478 ± 5.64**	38.262 ± 12.483	205 ± 56.76	226.72 ± 60.80	12.89 ± 0.80	13.05 ± 1.43
Week 2 70% 1RM	2712.67 ± 998.67	2782.15 ± 1141.44	48.633 ± 4.208*	38.464 ± 14.461	255.85 ± 76.26	258.97 ± 67.15	13.67 ± 1.67	12.82 ± 1.18
Week 3 80% 1RM	2202.32 ± 780.36	3302.14 ± 933.54**	38.07 ± 8.13	42.68 ± 6.92	229.023 ± 70.18	304.72 ± 81.95*	13.06 ± 1.34	12.71 ± 1.27
Week 4 80% 1RM	2413.72 ± 1081.28	3436.89 ± 1143.49*	37.367 ± 5.221	44.17 ± 6.47**	247.42 ± 77.42	308.67 ± 84.55	13.73 ± 1.79	13.2 ± 1.69
Week 5 90% 1RM	1917.86 ± 1068.00	2671.53 ± 714.18*	25.4 8 ± 7.45	31.76 ± 2.50**	278.19 ± 87.48	340 ± 94.33	14.66 ± 1.87**	13 ± 1.31
Week 6 90% 1RM	1504.11 ± 693.12	2882.33 ± 834.20**	19.43 ± 3.47	31.87 ± 0.87**	305.77 ± 89.84	361.28 ± 102.68	15.21 ± 2.30**	13.11 ± 1.34
Week 7 80% 1RM	2212.06 ± 1304.89	3356.14 ± 1044.11*	36.33 ± 10.39	44.6 ± 4.83**	236.64 ± 73.23	301.06 ± 92.51*	13.61 ± 1.49*	12.29 ± 1.11
Week 8 80% 1RM	2079.95 ± 828.28	3296.06 ± 1199.42**	33.29 ± 4.68	42.44 ± 6.06**	253.56 ± 74.69	307.22 ± 91.51	13.75 ± 1.57*	12.64 ± 1.29

Note: *Denotes statistically significant difference ($p < 0.05$). **Denotes statistically highly significant difference ($p < 0.01$).
RPE, rating of perceived exertion; APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training.

Table 6
The data of intragroup and intergroup comparisons for APRE and VBRT.

	Intragroup										Intergroup			
	APRE					VBRT								
	Pre	Post	Δ	p_{bonf}	ES_d	Pre	Post	Δ	p_{bonf}	ES_d	$Δ_D$	p	η_p^2	ES_g
Squat 1RM (kg)	87.67 ± 28.4	116.00 ± 33.12	28.33	0.00**	1.68	96.00 ± 30.31	123.33 ± 34.73	27.33	0.00**	1.92	1.00	0.86	0.00	0.06
CMJ (cm)	38.31 ± 11.23	43.23 ± 11.53	4.92	0.00**	1.84	38.19 ± 10.60	41.50 ± 10.53	3.31	0.00**	0.88	1.61	0.19	0.06	0.48
CMJ_{PP} (W)	2981.07 ± 970.04	3309.40 ± 978.33	328.33	0.00**	1.92	3105.51 ± 985.72	3346.91 ± 931.05	241.41	0.00**	1.15	86.93	0.23	0.05	0.44
CMJ_{RPP} (W/kg)	48.98 ± 11.91	54.03 ± 11.33	5.04	0.00**	1.64	48.74 ± 10.19	52.13 ± 10.00	3.39	0.00**	0.91	−12.63	0.19	0.06	0.47
$WAnT_{PP}$ (W)	518.75 ± 229.6	515.26 ± 177.87	−3.49	1.00	−0.04	511.53 ± 148.88	559.49 ± 129.33	47.97	0.15	0.94	−51.45	0.08	0.10	0.66
$WAnT_{RPP}$ (W/kg)	8.50 ± 2.59	8.42 ± 2.02	−0.07	1.00	−0.06	8.28 ± 1.61	8.87 ± 1.19	0.60	0.36	0.66	−0.67	0.13	0.08	0.57
$WAnT_{PPT}$ (ms)	3869.73 ± 2542.56	4731.80 ± 4560.3	862.07	1.00	0.18	3469.93 ± 2058.34	4574.33 ± 3234.93	1104.4	1.00	0.34	−242.33	0.87	0.00	0.06
$WAnT_{PD}$ (%)	61.83 ± 20.94	56.52 ± 9.47	−5.31	1.00	0.20	66.51 ± 20.18	66.96 ± 13.18	0.43	1.00	−0.02	−5.74	0.53	0.01	0.23
$TAIKT_{TN}$ (%)	93.87 ± 10.76	104.53 ± 15.44	10.66	0.03*	0.63	94.07 ± 8.24	103.93 ± 7.88	9.86	0.04*	1.10	0.80	0.87	0.00	0.06
$TAIKT_{FI}$ (%)	32.67 ± 8.67	25.03 ± 19.90	−7.65	0.91	0.32	29.76 ± 12.31	19.38 ± 8.35	−10.37	0.33	0.69	2.73	0.71	0.01	0.14

Note: *Denotes statistically significant difference in APRE or VBRT ($p < 0.05$). **Denotes statistically highly significant difference in APRE or VBRT ($p < 0.01$).
CMJ, countermovement jump; TAIKT, taekwondo anaerobic intermittent kick test; WAnT, 30-s Wingate anaerobic test; PP, peak power; RPP, relative peak power; PPT, time at peak power; PD, power drop; FI, fatigue index; TN, total number; APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training.

mechanism of APRE is more conducive to inducing the development of maximum strength.[42] Therefore, the improvement in CMJ performance by APRE can be explained.

RT can effectively increase a player's CMJ performance primarily because of an increase in thigh muscle strength.[43] APRE training involves self-adjusting weight loads on the basis of the player's response to achieve better-personalized training effects.[44] The advantage of APRE in CMJ may be attributed to its exhaustion training in the third and fourth sets during each training session, which is based on the basic principle of maximal recruitment of motor units.[45] In high-intensity RT, the squat-to-failure training method primarily recruits type IIb muscle fibers within type II muscle fibers. This type of training intensity and load quickly activates muscle fibers, causing muscle failure, and results in rapid improvements in muscle strength and muscle mass in a short period.[46] This type of training method usually focuses on improving muscle strength and explosiveness, thereby enhancing the player's ability to generate maximum power in a short period.[22] Therefore, APRE may be more suitable for improving CMJ_{PP} and CMJ_{RPP}, which is an indicator of the muscle's ability to generate maximum power in a short period.[47] By contrast, VBRT training usually adjusts training intensity by controlling the speed and acceleration of the movement to achieve better strength and muscle adaptation.[48] This type of training method usually focuses on improving muscle coordination and movement skills,[49] thereby enhancing the player's ability to maintain high power output for a longer time. Therefore, both APRE and VBRT can improve CMJ performance, but APRE is more advantageous in improving CMJ performance.

PP is mainly determined by the muscle mass involved and the maximal leg strength.[50] Therefore, the observed increase in PP after strength training intervention may be due to an increase in thigh muscle cross-sectional area (CSA) and leg strength. A high percentage of fast-twitch fibers is positively correlated with high anaerobic power

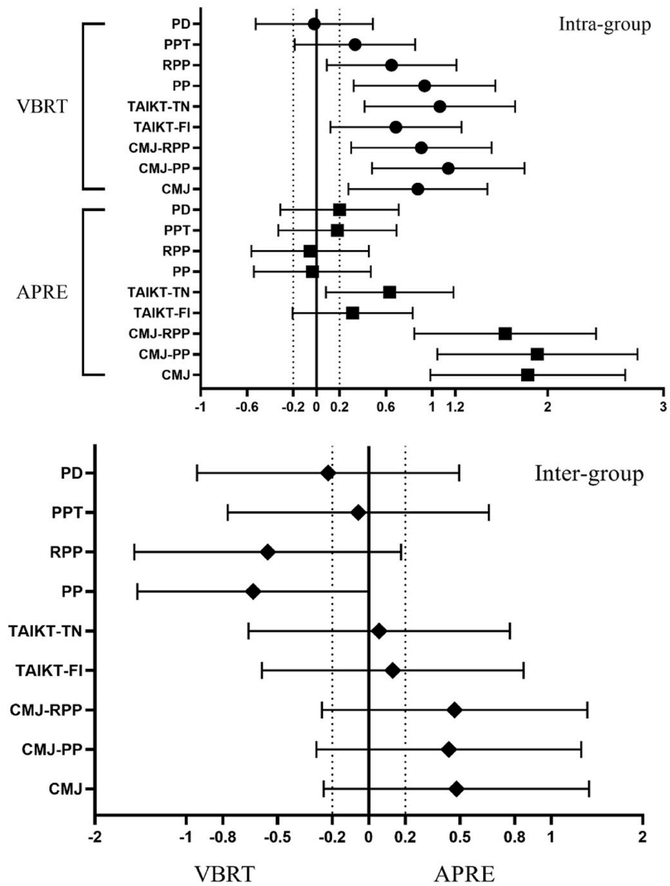

Fig. 4. The effect size of intragroup and intergroup comparisons for APRE and VBRT

Note: CMJ, countermovement jump; TAIKT, taekwondo anaerobic intermittent kick test; WAnT, 30-s Wingate anaerobic test; PP, peak power; RPP, relative peak power; MP, mean power; RMP, relative mean power; PPT, time at peak power; FI, fatigue index; TN, total number; APRE, autoregulatory progressive resistance exercise; VBRT, velocity-based resistance training.

output during contraction.[51] The advantages of fast-twitch fibers as regards maximal instantaneous power output and short-term anaerobic power have also been observed.[27] In sports that depend heavily on anaerobic metabolism, faster muscle fibers or larger cross-sectional areas can maintain maximal power output for a longer time.[52] However, in this study, although both APRE and VBRT significantly increased leg strength, only VBRT exhibited an improvement in PP.

In previous studies, Weber[25] compared the effects of 8 weeks of APRE and linear programming resistance training on anaerobic power in male college wrestlers. The results indicated that both RT methods significantly improved peak power and average power in the upper and lower limbs ($p < 0.05$), although the differences between the two groups were not statistically significant ($p > 0.05$). Ghobadi et al.[26] obtained similar results. However, these two studies mainly used a 6RM protocol for exercise intervention, and the intensity of 6RM (≈85% 1RM) is primarily used to develop explosive power in players.[53] Therefore, the previous results indicating improved anaerobic power output can be explained. Beneke et al.[54] indicated that the energy supply proportions of the oxidative systems, ATP–PCr system, and anaerobic glycolysis system in the Wingate test were 18.6%, 31.3%, and 50.3%, respectively. The ATP–PCr system lasts for 3–15 s during maximum effort, and the anaerobic glycolysis system can be sustained for the remainder of the all-out effort.[25] During a 30-s all-out sprint, the glycolytic anaerobic energy system is the main contributor to energy production, and because strength training has been found to have minimal impact on this system,[55] the result of APRE in this study is not surprising. However, the mechanism and effects of APRE on anaerobic power output still need further investigation.

The results of Zhang et al.[27] were consistent with the intervention results of VBRT in this study. Their research found that 6 weeks of VBRT was superior to PBRT in improving basketball players' $WAnT_{PP}$ and CMJ_{RPP}, indicating that VBRT may primarily induce greater instantaneous explosive power to adapt to explosive movements. The higher-intensity prescription in the VBRT group observed in this study may explain the observed increases in $WAnT_{PP}$, and $WAnT_{RPP}$. These results also appear to be due to the visual feedback during RT, which motivates players to achieve higher concentric velocities in VBRT,[56] which helps improve lifting weights and perform faster and fewer repetitions. Muscle fiber subtypes can be converted relatively quickly from myofiber subtypes to more active type II subtypes during RT programs, and high-intensity exercise appears to help convert myofiber subtypes from type IIx to type IIa.[27] Therefore, our study suggests that VBRT induces faster and less fatigable muscle fibers to adapt better, which has a greater impact on PP.

4.2. Anaerobic capacity

This study utilized $WAnT_{PPT}$ and $TAIKT_{TN}$ to evaluate anaerobic endurance, and $WAnT_{PD}$ and $TAIKT_{FI}$ to evaluate the rate of power decline. After a period of intervention, only $TAIKT_{TN}$ exhibited a significant improvement both in APRE and VBRT. Although, $WAnT_{PPT}$, $WAnT_{PD}$, and $TAIKT_{FI}$ exhibited varying degrees of improvement, no significant differences were observed both within the groups and between the groups.

Currently, there is no research investigating the impact of APRE or VBRT on anaerobic endurance. However, previous studies[26,27] have demonstrated that both methods can improve muscular endurance. In RT greater than 70% 1RM intensity, the training method of squatting to exhaustion mainly recruits type IIb muscle fibers in type II muscle fibers. This training intensity and load can quickly activate muscle fibers, causing muscles to reach exhaustion and rapidly improve muscle strength and muscle mass in a short period.[46] Type IIb muscle fibers are high-intensity, high-speed muscle fibers that can quickly produce high-intensity muscle contractions, but the corresponding degree of fatigue is also high. As anaerobic endurance requires continuous muscle contractions, the role of type IIb muscle fibers in anaerobic endurance is relatively small.[50] Therefore, it can be inferred that the effect of APRE on anaerobic endurance and fatigue index in this study is mainly due to the increase in muscle strength and muscle hypertrophy, but the underlying mechanisms need further investigation. The effect of VBRT on anaerobic endurance and fatigue index may be due to the high intensity and high number of repetitions that increase muscle anaerobic endurance. In high-intensity and high-repetition training, because the training intensity is high, muscles need to continuously produce greater force, so type IIa muscle fibers will be recruited first.[46] This type of muscle fiber has high glycogen storage capacity and strong creatine kinase activity but low oxidative enzyme activity and is a typical anaerobic muscle fiber that is adapted to high-intensity anaerobic exercise.[57] In addition, research has indicated that high-intensity, high-repetition training can promote mitochondrial proliferation in muscles and improve muscle oxygen utilization, further enhancing muscle endurance and anti-fatigue ability.[58] Therefore, the improvement of anaerobic endurance and fatigue index by VBRT can be elucidated.

Our study results indicate that both APRE and VBRT can cause higher anaerobic endurance and lower fatigue index. This study has practical significance for athletic performance and neuromuscular adaptation, as it provides new insights into the differences between VBRT and APRE from the perspective of anaerobic capacity.

5. Limitations and innovations

This study has some limitations, including (a) the lack of a control group to compare the effectiveness of the current experimental design; (b) the absence of squat jump testing, which prevents further analysis of explosiveness capabilities such as eccentric utilization ratio and muscle concentric contraction; (c) the lack of mid-term testing to readjust external load; and (d) the external validity of this study may be limited to taekwondo players. However, this study also has some innovations, such as (a) the first direct comparison of APRE and VBRT in an experimental setting and (b) the inclusion of TAIKT as a test indicator to measure the special anaerobic capacity of taekwondo players. On the basis of the findings of this study and previous research, we recommend future research to focus on (a) comparing the differential effects of APRE and VBRT programs with different load targets; (b) comparing the differences in training load, repetition, subjective fatigue, and anaerobic capacity improvement among APRE, VBRT, and PBRT at different training intensities; and (c) the effectiveness of ART in players in different sports or at different levels of competition.

6. Conclusions

This study's results indicate that after 8 weeks of resistance training, there were differences between APRE and VBRT in improving physical parameters related to taekwondo performance. In particular, APRE was more favorable in improving the explosive power of the lower limbs, whereas VBRT was more favorable in improving the anaerobic power output of the lower limbs. Both methods exhibited similar effects in improving the rate of power decline and fatigue index. These findings suggest that APRE may be more effective in improving maximal strength and maximal power output, whereas VBRT may primarily induce adaptations for sustained power output. They could be implemented during different periods of the training calendar. It can be said that APRE is more suitable for use in the strength/explosive phase of the first transition period, which is used to develop the maximum strength and maximum explosive power of athletes. VBRT, however, is more suitable for use during the competition season and is used to induce sustained or multiple adaptations of explosive power output that are more suitable for taekwondo programs.

Authors' contributions

Zijing Huang: Methodology, Data curation, Statistical analysis, Intervention, Writing, and Editing.

Jiayong Chen: Data curation, Statistical analysis, Critical revision.

Lunxin Chen: Implementation of the intervention.

Mingyang Zhang: Statistical analysis.

Wenfeng Zhang: Critical revision.

Duanying Li: Topic Selection, Revising.

Jian Sun: Topic Selection, Revising.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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