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Effect of Compound Training Based on Variable Resistance on Lower-Limb Explosive Power in Judo Athletes

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Abstract

This study compared the effects of variable-resistance compound training versus constant-resistance compound training on lower-limb explosive power in judo athletes, aiming to identify an effective and safe training method. Methods: Sixteen judo athletes were randomized into VRT (n = 8) or RT (n = 8) groups for a 6-week, twice-weekly intervention. Outcomes included rate of force development (RFD), counter movement jump (CMJ), squat jump (SJ), eccentric utilization ratio (EUR), reactive strength index (RSI), squat 1RM, muscle architecture, and Special Judo Fitness Test (SJFT). After 6 weeks of training intervention, the time × group interaction effects were significant between the variable-resistance compound training group and the constant-resistance compound training group in the following parameters: CMJ ($p < 0.01$, $\eta^2 = 0.605$), SJ ($p < 0.01$, $\eta^2 = 0.391$), EUR ($p < 0.01$, $\eta^2 = 0.308$), RSI ($p < 0.01$, $\eta^2 = 0.306$), RFD ($p < 0.01$, $\eta^2 = 0.401$), squat 1RM ($p < 0.01$, $\eta^2 = 0.328$), SJFT index ($p < 0.01$, $\eta^2 = 0.537$), femoral rectus feather angle ($p < 0.05$, $\eta^2 = 0.380$), femoral rectus thickness ($p < 0.05$, $\eta^2 = 0.288$), femoral rectus cross-sectional area ($p < 0.01$, $\eta^2 = 0.868$), gastrocnemius feather angle ($p < 0.05$, $\eta^2 = 0.274$), and gastrocnemius thickness ($p < 0.05$, $\eta^2 = 0.390$). No significant group effects were observed for any of the parameters ($p > 0.05$). Conclusion: Both variable-resistance training (VRT) and constant-resistance training (CRT) are effective in enhancing lower-body power in judo athletes; both training methods can be regarded as effective options for developing lower-body power in judo athletes, although VRT may offer a slight advantage in specific performance domains.

Keywords: variable-resistance training; constant-resistance training; Judo:Ippon-Seoi-Nage; compound training; lower-body explosiveness

Academic Editor: Claudio Belvedere

Received: 7 April 2026
Revised: 1 June 2026
Accepted: 3 June 2026
Published: 25 June 2026

1. Introduction

As an Olympic combat sport featuring direct confrontation, judo imposes exceptionally high demands on athletes' lower-limb explosive power. During matches, athletes frequently perform explosive movements such as pushing, pulling, and spinning to rapidly disrupt their opponents' balance. The ability to apply maximal force instantly is crucial for the successful execution of techniques and tactics. Strength fitness serves as the foundation for enhancing athletic skills and directly impacts judo athletes' competitive performance and skill development. As a key component of strength fitness, explosive power represents a quintessential manifestation of rapid strength [1]. Effective lower-limb explosive power helps reduce the risk of injuries to athletes' lower-limb joints, muscles, and ligaments [2].

Therefore, exploring efficient and scientific training methods for lower-limb explosive power is of paramount importance for improving judo athletes' competitive level.

The unique characteristics of judo determine its specific physical training requirements. Studies indicate that judo competitions rely primarily on anaerobic energy supply, demanding athletes to execute high-intensity explosive movements repeatedly within short timeframes [1]. Ippon-seoi-nage (shoulder throw), a critical scoring technique in judo, follows a sequential kinetic chain: knee flexion and entry → lower-limb extension → trunk rotation → upper-limb pulling. The ground reaction force generated during the lower-limb extension phase serves as the primary driving force for initiating the opponent's center-of-gravity shift. From a physiological perspective, lower-limb explosive power consists of three interrelated dimensions—the rate of force development (RFD), elastic potential energy utilization efficiency, and maximum power output—all highly correlated with competitive performance in judo [3]. For instance, the reaction strength index (RSI) assesses an athlete's rapid eccentric–concentric transition capability, corresponding to the technical rhythm of "diving-up" movements in judo, whereas the RFD directly correlates with high-intensity repetitive exertion capacity during matches [4]. Research by Almeida et al. [5] demonstrates that an 8.8% increase in peak speed during the counter movement jump (CMJ) yields significant improvements in technical execution time for elite judo athletes. Therefore, developing efficient lower-limb explosive power training methods tailored to judo's specific demands holds substantial practical value.

With the continuous advancement of sports science research and the evolution of physical training methodologies, an increasing number of scientifically validated training techniques are being employed to enhance athletes' explosive performance. Compound training is a method that involves resistance training followed by rapid stretching–compression exercises with similar biomechanical characteristics within a single session, aiming to simultaneously improve muscle strength and explosive power [6]. The theoretical basis of this approach lies in the post-activation potentiation effect (PAP), whereby high-load resistance training increases motor unit excitability and enhances myosin light chain phosphorylation, thereby providing an acute improvement in subsequent explosive movements. However, the resistance component in current compound training typically employs constant resistance provided by traditional barbells. Since the force generated by the human body varies across different joint angles, applying constant resistance at the weakest joint angle (i.e., the "viscous zone") forces the body to decelerate to overcome the external load. This not only limits the effective output of explosive power but also increases the risk of injury due to excessive local loading [7].

To address the aforementioned issues, variable-resistance training has garnered widespread attention in recent years. This training method typically combines resistance bands or chains with traditional constant resistance. Since the load increases linearly with the range of motion, it better aligns with joint biomechanical characteristics, hence the name "variable-resistance training." Compared to traditional constant-resistance training, this approach involves progressively increasing resistance during band stretching or chain lifting. This allows for initiating exercise with lower loads at the "viscous point" and applying higher loads at biomechanically advantageous positions, thereby significantly enhancing muscle recruitment and elasticity, overcoming the "viscous zone" during movement, triggering the stretch reflex, mobilizing more motor units, and improving explosive power output [8].

Systematic reviews and meta-analyses in recent years have provided high-quality evidence supporting the efficacy of variable-resistance training. The systematic review and meta-analysis by Shi et al. (2022) [9] incorporated 12 randomized controlled trials, demonstrating that variable-resistance training significantly improved maximal strength performance compared to constant-resistance training (SMD = 0.25; 95% CI: 0.05–0.45; $p < 0.05$). Subgroup analyses further revealed superior outcomes with intervention durations shorter than 7 weeks and the use of chains as variable-resistance equipment. In terms of explosive power, variable-resistance training also showed a trend toward better performance than constant-resistance training (SMD = 0.26; 95% CI: −0.03–0.55; $p = 0.08$), particularly when using intensity-controlled protocols and resistance bands as the variable-resistance device [9]. The meta-analysis by Jiang et al. (2025) [10], covering 14 studies, indicated that 6–12 weeks of variable-resistance training more effectively enhanced athletes' maximal lower-limb strength (SMD = 5.93), standing long jump performance (SMD = 0.03), and counter-movement jump scores (SMD = 3.58), with optimal variable-resistance loads ranging from 20% to 30% of 1RM. A new systematic review and meta-analysis (published in 2026) [11] included 15 studies involving a total of 442 subjects. The results demonstrated that variable-resistance training significantly improved jumping performance (SMD = 0.81, $p < 0.001$), sprint performance (SMD = −1.13, $p < 0.001$), and directional agility (SMD = −1.66, $p < 0.001$). Subgroup analyses revealed particularly notable improvements in the CMJ (SMD = 1.01, $p < 0.001$) and SJ (SMD = 0.94, $p < 0.001$).

While the aforementioned systematic reviews provide robust evidence supporting the overall effectiveness of variable-resistance training, several aspects of existing research remain worthy of refinement. First, most studies included in these meta-analyses focused on general athletes or sports students, with relatively limited research specifically targeting combat sports athletes (particularly judo practitioners). Second, the combined application of compound training with variable-resistance training (i.e., variable-resistance compound training) has been scarcely explored in current studies. Although some researchers have investigated the impact of compound training on lower-limb strength in judo athletes, the resistance components still employed constant loads, failing to incorporate the advantages of variable resistance into compound training systems. Third, existing evaluations of training outcomes predominantly concentrate on macroscopic functional metrics (e.g., vertical jump height, 1RM), with insufficient observation of microscopic muscular structural adaptations (e.g., changes in pinnate angle, cross-sectional area, and thickness). For judo athletes, who must develop specialized strength while maintaining low body fat percentages, alterations in muscle microstructure are crucial for understanding the underlying mechanisms of training adaptation.

In view of this, this study aims to conduct experimental research by combining variable-resistance training with compound training and compare the effects of variable-resistance compound training versus constant-resistance compound training on the lower-limb explosive power of judo athletes. The study seeks to explore efficient and scientifically sound training methods to provide more targeted theoretical foundations and practical references for lower-limb explosive power training in judo athletes.

2. Materials and Methods

2.1. Study Design

This study aimed to investigate differences in lower-body explosive power between judo athletes undergoing variable-resistance compound training and constant-resistance compound training. In the variable-resistance compound training group, participants performed squats with resistance bands attached to both ends of the barbell, followed by plyometric exercises including counter-movement jumps and lunge jumps. All exercises in the constant-resistance compound training group were identical to those in the variable-resistance group, except that resistance bands were not used. According to the NSCA Resistance Training Guidelines, the load for compound exercises should be maintained between 65% and 85% of 1RM, with training intensity following a 6-week progressive overload protocol, 80% of 1RM for the first 3 weeks and 85% of 1RM for the latter 3 weeks, with the experimental group incorporating 20–30% variable-resistance load. Fatigue during all resistance training sets is monitored using the 20% velocity loss threshold to accommodate differences in fatigue levels, strength levels, and training conditions among athletes under the same load. If an athlete shows significant fatigue before reaching the threshold, the set may be terminated early; if the athlete is in good condition, they may complete more repetitions. The number of repetitions for lower-body rapid stretch–compression exercises is typically calculated based on foot contact frequency or distance per training session. Once optimal resistance is achieved within a single exercise set, the repetition range for rapid stretch–compression training is 5 to 15 repetitions. See Table 1 for the detailed training plan.

Table 1. Interventional content in the experimental group and control group. VRT: variable-resistance training; CRT: constant-resistance training; VRS: variable-resistance squat; CRS: constant-resistance squat; VLT: velocity loss threshold; CMJ: counter-moment jump; LJ: lunge jump.

Phase	Weeks	Group	Resistance Type	Load & Reps	Sets	Inter-Set Rest	Plyo-Exercise	Sets × Reps	Rest Between Sets
Phase 1	1–3	VRT	VRS	80%1RM/20%VLT	4	2 min	CMJ/LJ	4 × 8	4 min
		CRT	CRS	80%1RM/20%VLT	4	2 min	CMJ/LJ	4 × 8	4 min
Phase 2	4–6	VRT	VRS	85%1RM/20%VLT	4	2 min	CMJ/LJ	4 × 8	4 min
		CRT	CRS	85%1RM/20%VLT	4	2 min	CMJ/LJ	4 × 8	4 min

All participants completed two training sessions per week for six consecutive weeks, resulting in a total of twelve training sessions per participant. Each session consisted of two components: resistance training (squat exercise) followed by plyometric training. For the resistance training component, participants performed 4 sets of 8 repetitions per exercise. The total weekly resistance training volume was calculated as sets (4) × repetitions (8) × sessions per week (2) × exercises per session (1) = 64 repetitions per week, with the load progressing from 80% 1RM (weeks 1–3) to 85% 1RM (weeks 4–6). For the plyometric training component, participants performed 4 sets of 8 repetitions of either continuous rebound jumps or forward stride jumps per session, resulting in 64 plyometric repetitions per week. The training time per session (resistance + plyometric) was approximately 40–50 min, excluding warm-up and cool-down periods.

Determination of Elastic Band Load

The resistance provided by resistance bands is influenced by their overall stiffness and elongation rate. According to Hooke's Law, the tension generated by a resistance band equals its stiffness (k) multiplied by deformation (d) [12]. To evaluate the resistance provided by resistance bands during squat training interventions, it is necessary to calculate the average load between the highest and lowest points of the movement. Since subject height may affect resistance band performance, measurements were conducted using participants from the experimental group whose height was closest to the average. Subjects performed weighted squats on a squat bench with four different resistance band models (Performbetter Super Training Band, West Warwick, RI, USA) suspended from barbells. For specific data, see Table 2. One end of the band was anchored to the ground with dumbbells, while the other end connected to the barbell. Tensometers (Tensometric, Shanghai, China) were used to measure tension across the four band models from the lowest point of weighted squats to the highest standing position, with the average value between the highest and lowest points calculated as the average resistance band tension [13]. Stretch lengths and resistance levels of different band models are shown in Table 2. Band load selection primarily followed Joy et al.'s research [14], who recruited 14 athletes into a variable-resistance training group and a control group. The variable-resistance group received 20–35% 1RM as the band load. Post-intervention results demonstrated significant improvements in half-squat 1RM, bench press 1RM, leg press 1RM, and vertical jump height in the variable-resistance group, with particularly notable gains in bench press 1RM and vertical jump height. Therefore, the experimental group in this study selected band loads equivalent to 20–30% of the total barbell load.

Table 2. Stretch length and resistance of elastic bands for different models.

Width	Tensile Elongation	Resistance Poundage
1.3 cm wide, 2 m (circular length), 0.5 cm thick	120 cm 180 cm 240 cm 300 cm	20 pounds 25 pounds 40 pounds 50 pounds
2.5 cm wide, 2 m (circular length), 0.5 cm thick	120 cm 180 cm 240 cm 300 cm	30 pounds 50 pounds 75 pounds 100 pounds
4.5 cm wide, 2 m (circular length), 0.5 cm thick	120 cm 180 cm 240 cm 300 cm	60 pounds 90 pounds 130 pounds 180 pounds
6.4 cm wide, 2 m (circular length), 0.5 cm thick	120 cm 180 cm 240 cm 300 cm	90 pounds 130 pounds 190 pounds 270 pounds

2.2. Participants

The study subjects were 16 male athletes from the Beijing Judo Team who maintained optimal training status. The sample size was determined using G*power software (Windows 3.1.9.7) with the following parameters: α err prob = 0.05, effect size = 0.5, power (1-β err prob) = 0.95. The minimum sample size was 14 participants, with an initial recruitment of 20 subjects. However, the study was not powered to detect small or moderate reverse effect sizes ($d < 0.5$). Furthermore, given the number of dependent variables analyzed, the effective statistical power for each individual comparison is lower than the nominal value. Readers should interpret non-significant results with caution, as they may reflect Type II rather than true null effects. Basic characteristics are summarized in Table 3. Inclusion criteria included: (a) no history of surgery or orthopedic trauma within the past 6 months and no cardiovascular diseases; (b) proficiency in deep squat resistance training and rapid plyometric compound training techniques, with lower-limb barbell squats and deadlifts not less than 1.5 times body weight; (c) no acute or chronic conditions affecting strength training, all meals consumed at the athlete cafeteria, and no supplementation of additional sports supplements or intake of substances affecting strength training efficacy such as alcohol, caffeine, etc.; and (d) no contraindications to exercise. Two subjects were ultimately excluded due to joint injuries (n = 2) and scheduling conflicts with competitions (n = 2). The final sample consisted of 16 subjects who were randomly assigned to either the variable-resistance compound training group (n = 8) or the constant-resistance compound training group (n = 8). Before the experiment, all subjects independently signed informed consent forms and were briefed on the standardized procedures. This study was conducted in accordance with the Declaration of Helsinki and approved by the Scientific Experiment Ethics Committee of the Beijing Institute of Sports Science (Ethical Review Number: TKSLL202519).

Table 3. Basic information of subjects.

Basic Information	Experimental Group (Mean ± Standard Deviation)	Control Group (Mean ± Standard Deviation)
Age (years)	16.75 ± 1.28	16.63 ± 1.06
Height (cm)	176.4 ± 4.69	179.6 ± 7.23
Weight (kg)	76.4 ± 9.84	79.1 ± 7.39
Training Duration	5.25 ± 1.16	4.88 ± 0.83

To minimize potential biases during the research process, the following control measures were implemented: 1. Blinded evaluation of results: All data collection and processing for testing indicators were conducted by two independent researchers who neither participated in the training intervention nor knew the participants' group assignments. Testers recorded data solely based on participant IDs without access to group information (experimental or control groups). After data entry and preliminary organization, a third researcher verified the records, and statistical analysts uniformly decoded group assignments during the analysis phase. This blinded design aimed to prevent measurement bias or recording bias caused by testers' knowledge of group assignments. 2. External training load control: Throughout the six-week experimental intervention, all participants (both experimental and control groups) underwent standardized specialized technical training according to the Beijing Judo Team's schedule (five sessions per week, each lasting approximately 120 min, including throwing drills, newaza, and sparring practice). No additional strength training, explosive power training, or rapid stretching–compression compound training was permitted. To ensure compliance, the research team provided detailed training load guidelines to all participants and coaches prior to study initiation, with participants signing informed consent and cooperation agreements. 3. Participant adherence control: (1) Training completion monitoring: Researchers monitored and recorded in real-time whether participants completed training sessions at specified intensity levels, repetitions, sets, and rest intervals. For individuals who failed to complete the required training sessions, verbal reminders were issued; if they failed twice consecutively, communication with the coaching staff was initiated to adjust the workload or consider excluding them from participation. (2) Speed loss threshold monitoring: The Gymaware strength testing system continuously monitors the concentric speed of each squat set. When speed loss exceeds 20%, the system automatically terminates that set to ensure consistent training intensity. All training data is recorded in the system log for subsequent compliance verification.

2.3. Outcome Measurements

- Counter-movement jump and squat jump (CMJ&SJ)

This study employed the Smart Jump system (Fusion Sport, Brisbane, Australia) for counter-movement jump tests and squat jump tests. CMJ Test: Subjects stood on the mat with hands on hips. Upon activation of the green indicator light, they rapidly completed a squat jump while maintaining hands on the waist throughout the movement. During mid-air execution, they maintained upright posture without hip or knee flexion, landing both feet simultaneously on the mat with knee flexion for cushioning and stabilization. Vertical jump height (cm) was recorded. SJ Test: Subjects stood on the mat with hands on hips. After the green light activated, they performed a squat until achieving a 90° knee angle. Upon receiving a 2–3 s signal, they executed a single continuous takeoff without secondary squats, keeping hands on the waist and maintaining upright posture without hip/knee flexion. Both feet landed simultaneously on the mat with knee flexion for cushioning and stabilization. Vertical jump height (cm) was recorded. Each participant completed two trials, with the best performance recorded. Data was rounded to two decimal places.

- Reaction strength index (RSI)

The RSI is a test metric that reflects the rate of lower-limb force generation. The Output (Output Sports, Dublin, Ireland) sensor is attached above the instep. Athletes are instructed to perform a counter-movement jump, followed immediately by a series of 10 bilateral jumps. The final RSI score is calculated by averaging the top 5 RSI values obtained during the exercise.

- Eccentric utilization ratio (EUR)

The EUR is an indicator reflecting the utilization capacity of the stretch–shorten cycle (SSC), which can be calculated using an internationally recognized formula: CMJ/SJ. In this study, the eccentric utilization ratio was calculated as the ratio of the best performance in counter-movement jumps to that in squat jumps.

- Rate of force development (RFD)

The isometric mid-thigh pull-up (IMTP) enables reliable and accurate assessment of the RFD at various time intervals within a short period. The testing procedure involves the following steps: The athlete stands on a force plate (BTS PODIUM 3D Angle Force Analysis System, Milan, Italy), holds a horizontal bar fixed at the midpoint of the strength training rack and positioned along the mid-upper thigh with both hands, adjusts body posture to maintain knee angles between 120 and 145° and hip angles between 140 and 150°, and maintains trunk tension. Upon hearing the verbal command "3, 2, 1, start," the athlete rapidly applies downward force while simultaneously lifting the bar upward and holds the position for 5 s.

- Squat one repetition maximum (1RM)

The Gymaware strength testing system (Kinetic Performance, Canberra, Australia) was employed to measure corresponding speeds under progressively increasing loads, thereby determining the force–velocity relationship curve and systematically estimating the athlete's 1RM based on this relationship. The basic procedure was as follows: Specialized warm-up included 3 sets of squats with progressively increased weights until the concentric phase speed reached 1.0–1.2 m/s (0.85–1.1 m/s for upper limbs) (approximately 40% 1RM). The formal testing then commenced with the following details: Data collection was performed using the four-point method. The first set involved light weights below 50% 1RM, with concentric phase speeds exceeding 1 m/s for 3 repetitions. The second and third sets consisted of 2 repetitions each, performed with 60% and 75% 1RM weights for standard squats. The fourth set utilized loads exceeding approximately 85% 1RM, requiring concentric phase speeds below 0.5 m/s. Additionally, the speed difference between the fourth set and the first set must exceed 0.5 m/s to meet the requirements.

- Special Judo Fitness Test (SJFT)

Developed by Sterkowicz [15], this test is closely related to judo-specific training. All participants were divided into groups of three based on their body weight (±5 kg), with each participant serving as both the subject and an assistant. The subjects stood between two assistants, maintaining a distance of 3 m from each. Upon initiation, the subject ran to the first assistant to complete one single-handed throw, then quickly moved to the second assistant to perform another single-handed throw. The objective was to maximize the number of single-handed throws completed within the allotted time before returning to the center for final evaluation. Participants then rested for 2–3 min before role reversal. The SJFT consists of three phases (15 s, 30 s, 30 s), with 10 s recovery periods between each phase. Performance was determined by the total number of completed single-handed throws. Heart rate was measured using a Polar heart rate monitor (First Beat, Finland), with immediate post-test HR and 1 min post-test HR recorded. The following metric was calculated, which decreased with improved performance:

$$\text{Index} = (HRpost + HRpost1\ \text{min})/\text{number of throws}. \quad (1)$$

- Musculoskeletal ultrasound

Musculoskeletal ultrasound is used to evaluate muscle morphology and function. It typically employs high-frequency linear array probes with a frequency range of 5–12 MHz to qualitatively and quantitatively assess changes in muscles and surrounding soft tissues, making it suitable for evaluating muscle activity, exploring mechanical mechanisms, and assessing training outcomes. Musculoskeletal ultrasound testing is performed using real-time B-mode ultrasound imaging systems (Huasheng Ultrasound, Shenzhen, China). (1) Before the formal testing begins, the tester must explain the testing procedure and requirements to the subject, then have the subject change into shorts, remove their shoes, and lie supine or prone on the testing table. (2) Using a tape measure, mark the measurement points and connecting lines for RF (quadriceps femoris) at 50% of the distance from the center of the patella to the anterior superior iliac spine, and for LG (gastrocnemius) at two-thirds of the distance between the lateral femoral condyle and the lateral malleolus. (3) The probe orientation is longitudinal (aligned with the femur), with measurement points matching the midpoint of the probe. Slight tilting movements are used to ensure clear, standardized images, which are then utilized to measure PA (feather angle), MT (thickness), and cross-sectional area (CSA).

2.4. Statistical Analyses

Data before and after experimental intervention were processed using SPSS 26.0 (IBM SPSS Statistics 26, New York, NY, USA). Data were expressed as means ± standard deviations. The Shapiro–Wilk test was used to assess normal distribution, and the Levene test was employed to test homogeneity of variances. If the data followed a normal distribution, an independent samples t-test was performed to compare baseline differences between the experimental group and control group. A sphericity test was conducted; if the assumption was violated, the Greenhouse–Geisser correction coefficient was used to adjust degrees of freedom. If the sphericity test was passed, repeated measures ANOVA was used to test the main effects of group and time as well as group × time interaction effects. If the group × time interaction effect was significant, post hoc comparisons and simple effect analysis were performed with a 95% confidence interval. If the data did not follow a normal distribution, the Friedman nonparametric test was used. The effect size was expressed as partial Eta-squared (η^2). Small effect: $0.01 \leq \eta^2 < 0.06$; moderate effect: $0.06 \leq \eta^2 < 0.14$; large effect: $\eta^2 \geq 0.14$.

3. Results

All indicators followed a normal distribution. Prior to intervention, no significant differences were observed between the two groups in the following parameters: force generation rate ($p = 0.787$), counter-movement jump ($p = 0.133$), static squat jump ($p = 0.498$), eccentric utilization ratio ($p = 0.777$), reactive strength index ($p = 0.755$), squat 1RM ($p = 0.834$), rectus femoris feather angle ($p = 0.104$), rectus femoris thickness ($p = 0.306$), rectus femoris cross-sectional area ($p = 0.534$), gastrocnemius feather angle ($p = 0.207$), gastrocnemius thickness ($p = 0.102$), and Special Judo Fitness Test Single ($p = 0.359$). After six weeks of training, significant time × group interaction effects were observed between the VRT and CRT groups for the following parameters: CMJ ($p < 0.01$, $\eta^2 = 0.605$), SJ ($p < 0.01$, $\eta^2 = 0.391$), EUR ($p < 0.01$, $\eta^2 = 0.308$), RSI ($p < 0.01$, $\eta^2 = 0.306$), RFD ($p < 0.01$, $\eta^2 = 0.401$), squat 1RM ($p < 0.01$, $\eta^2 = 0.328$), SJFT index ($p < 0.01$, $\eta^2 = 0.537$), rectus femoris feather angle ($p < 0.05$, $\eta^2 = 0.380$), rectus femoris thickness ($p < 0.05$, $\eta^2 = 0.288$), rectus femoris cross-sectional area ($p < 0.01$, $\eta^2 = 0.868$), gastrocnemius feather angle ($p < 0.05$, $\eta^2 = 0.274$), and gastrocnemius thickness ($p < 0.05$, $\eta^2 = 0.390$). No significant group differences were observed for any of the indicators ($p > 0.05$). The results of the analysis of variance are presented in Tables 4 and 5. Comparative analyses are shown in Figures 1 and 2.

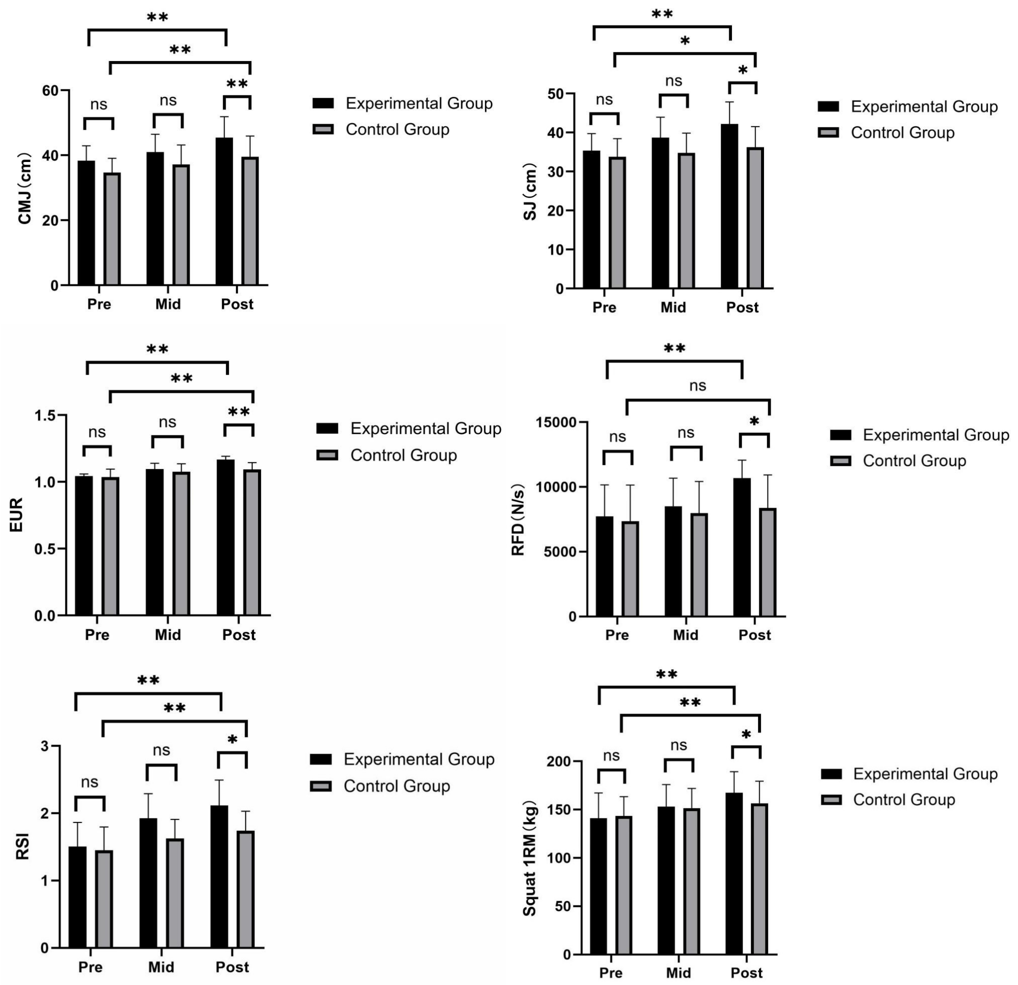

Figure 1. Post hoc analysis of counter-movement jump, squat jump, eccentric utilization ratio, rate of force development, reactive strength index, and squat 1RM differences. * $p < 0.05$, ** $p < 0.01$, ns indicates no significant difference.

Table 4. Changes in three time-related indicators between the experimental group and the control group. VRT: variable-resistance training; CRT: constant-resistance training.

Outcome	VRT			CRT			Time × Group Effect
	Pre	Mid	Post	Pre	Mid	Post	η^2
CMJ (cm)	38.30 ± 4.64	40.96 ± 5.53	48.03 ± 5.27	34.70 ± 4.38	37.19 ± 5.99	38.52 ± 5.56	0.605
SJ (cm)	35.34 ± 4.38	38.67 ± 5.27	42.17 ± 5.70	33.76 ± 4.68	34.77 ± 5.07	39.20 ± 6.14	0.391
EUR	1.04 ± 0.02	1.10 ± 0.04	1.17 ± 0.03	1.04 ± 0.06	1.08 ± 0.06	1.09 ± 0.05	0.308
RSI	1.51 ± 0.36	1.92 ± 0.37	2.12 ± 0.38	1.45 ± 0.35	1.62 ± 0.28	1.74 ± 0.29	0.306
RFD (N/s)	7717.15 ± 2437.68	8508.10 ± 2174.18	10,676.31 ± 1398.55	7356.24 ± 2789.37	7967.34 ± 2452.08	8370.84 ± 2565.38	0.401
Squat 1RM (kg)	140.88 ± 26.31	153.13 ± 22.87	167.38 ± 21.87	143.38 ± 20.10	151.63 ± 20.27	156.63 ± 22.80	0.328

https://doi.org/10.3390/app16136377

Table 5. Changes in two time-related indicators between the experimental group and the control group. VRT: variable-resistance training; CRT: constant-resistance training.

Outcome	VRT		CRT		Time × Group Effect
	Pre	Post	Pre	Post	η^2
SJFT index	12.85 ± 1.56	11.20 ± 1.51	13.51 ± 1.25	12.80 ± 1.38	0.537
Rectus femoris feather angle (°)	16.09 ± 1.17	17.77 ± 0.86	15.57 ± 1.18	16.62 ± 0.75	0.380
Rectus femoris muscle thickness (cm)	2.42 ± 0.27	2.77 ± 0.16	2.31 ± 0.16	2.53 ± 0.16	0.288
Cross-sectional area of rectus femoris muscle (cm^2)	14.63 ± 3.21	17.74 ± 3.37	15.49 ± 2.08	17.35 ± 2.10	0.868
Gastrocnemius feather angle (°)	12.93 ± 2.22	23.11 ± 5.07	13.40 ± 2.37	19.20 ± 1.43	0.274
Gastrocnemius muscle thickness (cm)	1.70 ± 0.17	2.27 ± 0.06	1.77 ± 0.29	2.07 ± 0.21	0.390

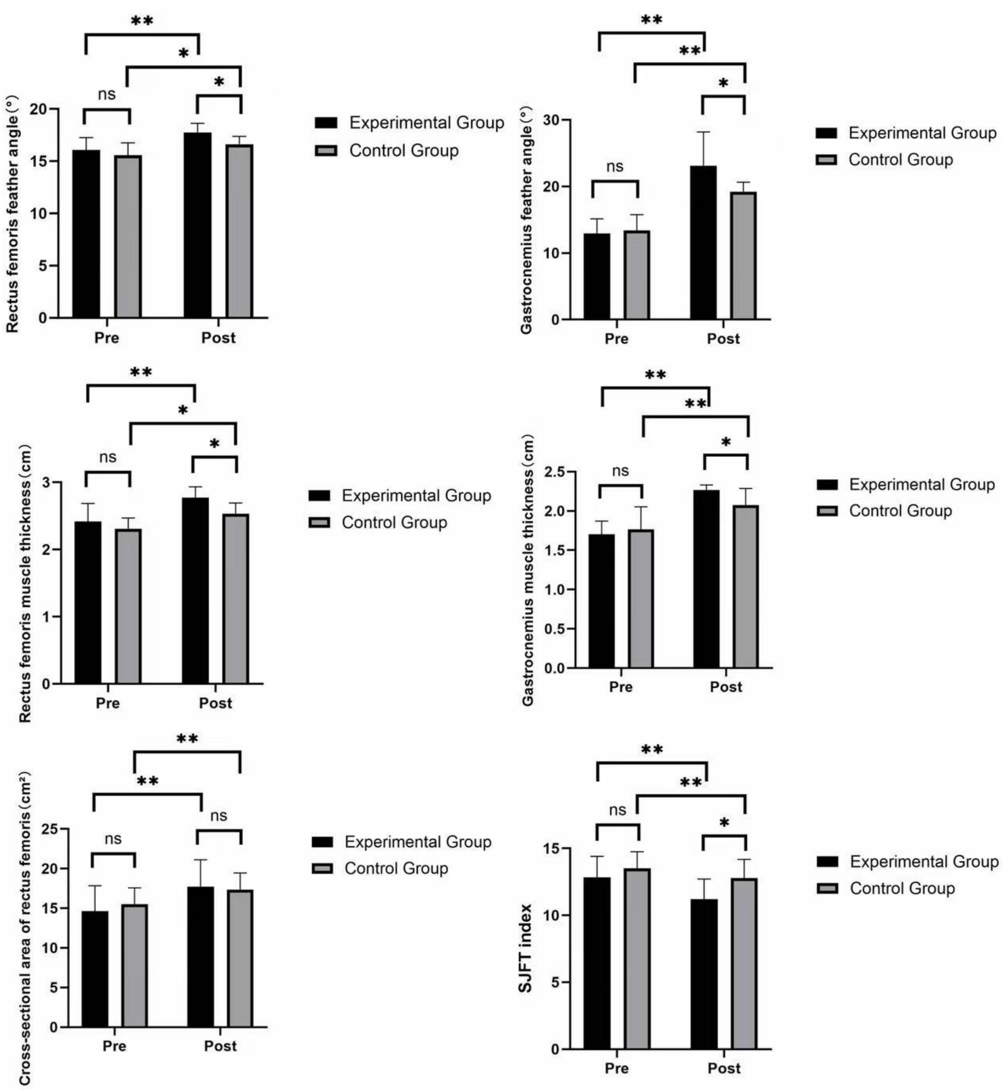

Figure 2. Post hoc analysis of differences in rectus femoris feather angle, thickness of rectus femoris, cross-sectional area of rectus femoris, gastrocnemius feather angle, thickness of gastrocnemius, and SJFT index. * $p < 0.05$, ** $p < 0.01$, ns indicates no significant difference.

The pairwise comparison results of all indicators are presented in Table 6 with a 95% confidence interval.

Table 6. Results of paired time comparison. VRT: variable-resistance training; CRT: constant-resistance training.

Outcome	Group	Time (I)	Time (J)	Mean Error (I-J)	(SD)	(p)	CI, 95%	
							Lower	Upper
CMJ	VRT	pre-test	mid-test post-test	−2.652 −9.725	0.876 0.756	0.027 0.000	−5.026 −11.774	−0.279 −7.676
	CRT	pre-test	mid-test post-test	−2.490 −3.818	0.876 0.756	0.039 0.001	−4.863 −5.866	−0.117 −1.769
SJ	VRT	pre-test	mid-test post-test	−3.335 −6.830	0.819 0.920	0.003 0.000	−5.553 −9.322	−1.117 −4.338
	CRT	pre-test	mid-test post-test	−1.005 −2.466	0.819 0.920	0.561 0.053	−3.223 −4.959	1.213 0.026
EUR	VRT	pre-test	mid-test post-test	−0.052 −0.124	0.016 0.016	0.014 0.000	−0.095 −0.166	−0.010 −0.082
	CRT	pre-test	mid-test post-test	−0.039 −0.056	0.016 0.016	0.078 0.008	−0.081 −0.098	0.004 −0.014
RSI	VRT	pre-test	mid-test post-test	−0.419 −0.610	0.079 0.074	0.000 0.000	−0.632 −0.811	−0.205 −0.409
	CRT	pre-test	mid-test post-test	−0.175 −0.291	0.079 0.074	0.124 0.004	−0.388 −0.492	0.038 −0.091
RFD	VRT	pre-test	mid-test post-test	−790.950 −2959.163	321.794 388.913	0.081 0.000	−1662.617 −4012.759	80.816 −1905.566
	CRT	pre-test	mid-test post-test	−611.100 −1014.600	321.794 388.913	0.217 0.061	−1482.866 −2068.196	260.666 38.966
Squat 1RM	VRT	pre-test	mid-test post-test	−12.250 −26.500	2.701 3.061	0.001 0.000	−19.567 −34.793	−4.933 −18.207
	CRT	pre-test	mid-test post-test	−8.250 −13.250	2.701 3.061	0.025 0.002	−15.567 −21.543	−0.933 −4.957
SJFT index	VRT	pre-test	post-test	1.641	0.162	0.000	1.293	1.990
	CRT	pre-test	post-test	0.716	0.162	0.001	0.368	1.065
Rectus femoris feather angle	VRT	pre-test	post-test	−1.671	0.251	0.000	−2.209	−1.133
	CRT	pre-test	post-test	−1.050	0.251	0.001	−1.588	−0.512
Rectus femoris muscle thickness	VRT	pre-test	post-test	−0.354	0.050	0.000	−0.461	−0.246
	CRT	pre-test	post-test	−0.226	0.050	0.000	−0.334	−0.119
Cross-sectional area of rectus femoris muscle	VRT	pre-test	post-test	−3.113	0.092	0.000	−3.310	−2.915
	CRT	pre-test	post-test	−1.863	0.092	0.000	−2.060	−1.665
Gastrocnemius feather angle	VRT	pre-test	post-test	−10.179	1.345	0.000	−13.064	−7.924
	CRT	pre-test	post-test	−5.806	1.345	0.001	−8.691	−2.921
Gastrocnemius muscle thickness	VRT	pre-test	post-test	−0.562	0.060	0.000	−0.692	−0.433
	CRT	pre-test	post-test	0.562	0.060	0.000	−0.437	−0.178

4. Discussion

After a 6-week intervention, this study found that both the variable-resistance compound training group and the constant-resistance compound training group exhibited significant time × group effects in indicators such as CMJ, SJ, EUR, RSI, RFD, squat 1RM, femoral rectus feather angle, femoral rectus thickness, femoral rectus cross-sectional area, gastrocnemius feather angle, gastrocnemius thickness, and SJFT ($p < 0.05$). This indicates that both training methods effectively improved the lower-limb explosive power and related physiological adaptations in judo athletes. Further simple effect analysis revealed that in the post-test, the experimental group significantly outperformed the control group in improvements of CMJ, SJ, EUR, RSI, RFD, squat 1RM, femoral rectus feather angle, femoral rectus thickness, gastrocnemius feather angle, gastrocnemius thickness, and SJFT ($p < 0.05$), demonstrating that the intervention effect of variable-resistance compound training was overall superior to that of constant-resistance compound training.

After 6 weeks of intervention, both groups exhibited significant time main effects in CMJ, SJ, and RSI ($p < 0.001$), which is consistent with previous research findings [16]. Studies indicate that judo athletes require excellent reactive strength, dynamic maximal strength, and explosive power [17]. The stretch–shortening cycle (SSC) is a functional pattern where muscles undergo eccentric elongation prior to active contraction, storing elastic energy during the eccentric phase and releasing it during the concentric phase to enhance movement efficiency [18]. Therefore, reactive strength refers to the muscle's ability to rapidly transition from eccentric to concentric contraction [19]. Counter-movement jumps (CMJ) and squat jumps (SJ) are used as indicators to assess power and strength generation capabilities in judo [20], while the reactive strength index (RSI) serves as a critical measure for evaluating athletes' SSC utilization during the concentric phase of jumps [21]. Athletes generating equivalent force within shorter landing durations can achieve faster body movement and produce more powerful strikes [22]. Explosive power denotes rapid SSC activation [23] in judo, observable in high-speed force-generating movements such as shoulder throws [24]. During shoulder throws, athletes mobilize more motor neurons to activate additional muscle fibers, generating greater force within shorter timeframes to complete the throw [25]. Consequently, the rate of force development (RFD) is crucial for explosive movements in judo athletes [26]. Elite judo athletes exhibit higher maximum relative velocity of the center of gravity in the anteroposterior direction when executing shoulder throw techniques. Consequently, they must perform these techniques at high speed to render opponents less responsive and exert greater force during execution. This results in judo athletes developing exceptionally high levels of maximal strength and muscular power.

The VRT group effectively utilized the stretch–shortening cycle (SSC), storing elastic energy during the eccentric phase and releasing it during the concentric phase [27]. This approach more effectively leveraged the muscle stretch reflex mechanism, enhancing muscle recruitment capacity, movement speed, and power output [28]. The greater changes observed in experimental group jumping performance indicators (e.g., CMJ, SJ, RSI) may be attributed to increased demands placed on the neuromuscular system by variable-resistance training. Since skeletal muscles generate maximum force near their resting length [29], and the "viscous point" typically occurs at the farthest point from resting length, variable-resistance training employs linearly increasing resistance provided by resistance bands. This enables lower-load initiation at the movement bottom (viscous point), avoiding the deceleration required during this phase in traditional constant-resistance training. Consequently, Type II muscle fibers are recruited more efficiently [30], leading to stronger neuromuscular adaptation and ultimately higher power output. Studies have demonstrated that resistance training using resistance bands can achieve an optimal load at any point within the movement range, thereby prolonging neuromuscular adaptation across the entire range of motion [31]. The presence of elastic resistance also results in minimal deceleration of the barbell rod throughout the movement, facilitating increased power output rates during muscle contraction [32].

The EUR is defined as the ratio of CMJ to SJ. A higher EUR reflects the ability to effectively utilize elastic energy and the stretch–shortening cycle mechanism [22]. In this study, the EUR exhibited significant time main effects and time × group interaction effects, with the experimental group's post-test EUR (1.17 ± 0.03) significantly higher than that of the control group (1.09 ± 0.05). This result is attributed to the greater improvement in CMJ compared to SJ. CMJ demonstrates superior strength, power, and jumping height relative to SJ, primarily due to its ability to generate greater force before the propulsion phase [33].

https://doi.org/10.3390/app16136377

Additionally, studies have shown that a higher EUR does not always correlate with better performance [34], as superior CMJ performance or inferior SJ performance may lead to an increased EUR. Variable-resistance training, compared to constant-resistance training, allows dynamic adjustment of resistance based on movement angles, adding additional load during the eccentric phase to compensate for torque attenuation caused by joint angle changes. This forces the neuromuscular system to more efficiently control eccentric velocity, thereby enhancing the EUR.

Generating force within the first 0.3 s of a movement is particularly crucial for explosive movements [26]. The increase in concentric force produced by stretching–shortening cycles results from a combination of neural reflexes and the utilization of elastic energy stored in muscle–tendon units [4]. The primary benefit gained through enhanced stretching–shortening cycles is increased power output [35], which is closely related to the RFD (rate of force development) and movement speed. In this study, the RFD exhibited significant time main effects and time $\times$ group interaction effects. Previous research has found [4] that when performing squats with resistance bands, peak speed during the eccentric phase and the RFD during the concentric phase are significantly higher, while average and peak speeds during the concentric phase without resistance bands are greater, indicating that resistance bands actually impede concentric speed in squats. This may be attributed to the proportion of resistance band load and our choice of isometric mid-thigh pull (IMTP) for RFD measurement. The IMTP allows individuals to generate greater force compared to maximal concentric movements, enabling the exclusion of technical and coordination-related interference factors during dynamic movements and purely assessing neuromuscular explosive force output capacity. Compared to constant-resistance training, variable-resistance training imposes lower loads at the movement bottom phase, which is critical for achieving higher speeds during early concentric phases. Although increased resistance may hinder speed during the initial phase, greater strength improvements are observed at biomechanically advantageous positions (e.g., the latter half of the movement), ultimately leading to enhanced RFDs through the interaction of force and speed [4]. Additionally, studies have demonstrated that using resistance bands as variable resistance produces superior RFD effects compared to chains [36]. These findings collectively indicate that loading more load at biomechanically advantageous positions is a critical factor in enhancing the RFD.

Judo is a dynamic high-intensity intermittent sport, with elite judo athletes consistently demonstrating higher maximum strength compared to lower-level competitors [37]. The study revealed significant time effects and time $\times$ group interaction effects in squat 1RM, consistent with previous research findings. A meta-analysis by Lin et al. [38] demonstrated superior VRT efficacy when trained individuals trained with loads $\geq$ 80% of 1RM. Key mechanisms underlying VRT's impact on maximal strength improvement may involve alterations in movement speed and neuromuscular adaptation. Regarding movement speed, Rhea et al. [39] found maximal strength gains were most pronounced during slow-speed training, likely attributable to increased cross-sectional areas of type I and IIa skeletal muscle fibers due to slower concentric phase movements. Stevenson et al. [4] reported that VRT enhances eccentric phase velocity but may reduce concentric phase velocity, with eccentric phase acceleration potentially contributing to maximal strength gains [40]. Neuromuscular adaptations primarily include motor unit activation, intermuscular coordination, and changes in motor neuron firing frequency [41]. The greater maximal strength improvement observed in the variable-resistance training group in this study was primarily attributed to enhanced neuromuscular adaptability rather than simple muscle hypertrophy.

The Specialized Judo Fitness Test (SJFT) is the most widely used assessment in judo research [3]. Studies have demonstrated that SJFT performance correlates with offensive attempts during actual competitions [42]. In this study, the SJFT exhibited significant time main effects and time × group main effects, which may be related to changes in body composition and strength [43]. Compared to constant-resistance training, variable-resistance training demonstrates advantages across multiple biomechanical parameters that collectively enhance specialized performance: increased force generation rate directly supports explosive movement execution; elevated reaction force index optimizes stretch–shortening cycle efficiency; improved eccentric utilization enhances energy efficiency; and maximal strength gains provide foundational support for explosive power. By dynamically adjusting resistance, variable-resistance training more effectively activates fast-twitch muscle fibers, improves neural–muscular coordination control, and its nonlinear load variations more closely simulate real combat scenarios, thereby increasing specialized strength conversion efficiency. The design featuring low load during eccentric phases and high load during concentric phases allows for reduced joint stress while prolonging muscle tension duration, accumulating greater metabolic stress to promote endurance adaptation.

Hakkinen et al. [44] found that the first 8 weeks of strength training primarily improve neural adaptability, while the subsequent 8 weeks increase muscle fiber size. Studies indicate that VRT-enhanced maximal strength is mainly associated with improvements in neuromuscular adaptability and muscle fiber morphology [32]. Therefore, in this study, significant time main effects were observed in the pectoral angle, thickness, and cross-sectional area of the rectus femoris muscle, as well as the pectoral angle and thickness of the gastrocnemius muscle. These findings may be related to protein phosphorylation via the mTOR pathway [45], which enhances protein synthesis and translation, ultimately promoting muscle growth. The rectus femoris and gastrocnemius muscles endure sustained mechanical stress during squats and jumping movements, leading to muscle fiber thickening and sarcoplasmic reticulum expansion. Compound training, which combines high-load resistance with explosive movements, prolongs muscle tension duration and intensifies metabolic stress during recovery, thereby achieving supercompensation growth. Notably, no significant differences in mechanical stress or anabolic responses were observed between the two groups, resulting in no significant group effects or time × group interactions. Variable-resistance training and constant-resistance training demonstrated nearly equivalent hypertrophic effects. These results further support the previous hypothesis: the improvement in maximal lower-limb strength and explosive power in judo athletes through variable-resistance training primarily stems from neuromuscular adaptability enhancement rather than increased muscle fiber size. The improvement in muscle fiber morphology may be related to trainee proficiency levels, warranting further investigation.

Furthermore, this study has certain limitations that warrant candid discussion. Although the minimum sample size of 14 participants was determined during the experimental design phase based on a G*Power a priori power analysis, and the final inclusion of 16 participants met this requirement, the small sample size of only 8 participants per group still potentially affected the statistical robustness and generalizability of the results. Firstly, the small sample size reduced the detection sensitivity for moderate-to-small effect sizes ($d < 0.5$), meaning that some statistically insignificant group differences may result from Type II errors (false negatives) due to insufficient sample size rather than genuine differences. Secondly, with only eight participants per group, individual extreme data points could disproportionately influence group means and statistical test results. Although this study minimized such risks through randomization, baseline homogeneity testing (all pretest p-values > 0.05), and reporting standard deviations, systematic outlier diagnosis and sensitivity analyses were not conducted, constituting another methodological limitation of the study. Finally, extensive repeated-measurement ANOVA and post hoc comparisons were conducted in this study. Multiple statistical tests somewhat increased the risk of Type

I errors (false positives), although these were controlled for with the Greenhouse–Geisser correction and simple effects analysis. However, findings with p-values at the critical significance level (e.g., gastrocnemius pectoralis angle $p = 0.045$, one-arm carry index $p = 0.045$) should be regarded as preliminary evidence rather than definitive conclusions. Therefore, future studies are recommended to employ designs with larger sample sizes and longer intervention durations to more reliably validate the long-term training effects of variable-resistance compound training on the lower-limb explosive power of judo athletes and its cross-sample stability.

5. Conclusions

Research indicates that both variable-resistance training (VRT) and constant-resistance training (CRT) are effective methods for improving lower-body power in judo athletes, as evidenced by significant improvements in most assessment parameters within each group before and after training. Although VRT demonstrated certain advantages over CRT for some variables (such as the counter-movement jump, squat jump, eccentric utilization, reactive strength index, rate of force development, judo-specific fitness test index, and several muscle structural parameters), these differences did not appear consistently across all assessment indicators, and no significant main effects between groups were found. Consequently, both training programs are considered viable and effective strategies for developing lower-body explosive power in judo athletes and can be reasonably recommended in practice.

6. Limitations

Several limitations of this study should be acknowledged. First, the sample size was relatively small (n = 16), with only eight participants per group, which may limit the statistical power to detect smaller between-group differences and reduce the generalizability of the findings. Second, the intervention duration was limited to six weeks. While this period was sufficient to observe short-term training adaptations, it remains unclear whether the observed advantages of variable-resistance training would persist, diminish, or amplify over longer-term training periods (e.g., 12 weeks or more). Third, the study sample consisted exclusively of male adolescent judo athletes from a single provincial team. Therefore, the findings may not be directly generalizable to other populations, including female athletes, judo athletes at different competitive levels (e.g., recreational or international elite), or athletes from other combat or power-oriented sports. Finally, this study examined 12 dependent variables, resulting in over 20 statistical comparisons. With a small sample size (N = 16), this multiplicity creates a substantial risk of effect estimate inflation. Future studies with larger sample sizes, longer intervention periods, diverse participant populations, and follow-up measurements are warranted to further elucidate the comparative efficacy of variable-resistance compound training.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, Y.Z.; writing—review and editing, visualization, supervision, M.R.; project administration, funding acquisition, C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Laboratory of Physical Fitness, Beijing Institute of Sports Science, Grant No.: 2025ZDSYS003.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Beijing Institute of Sports Science (Approval No.: TKSLL202519).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Acknowledgments: We would like to thank the Beijing Institute of Sports Science for providing the facilities and assistance during the experiment, and we thank all participants for their involvement and support.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

VRT	Variable-resistance training
CRT	Constant-resistance training
CMJ	Counter-movement jump
SJ	Squat jump
EUR	Centrifuge utilization rate
RFD	Rate of force development
RSI	Reactive strength index
SJFT	Special Judo Fitness Test

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