Journal of Human Kinetics volume xx/xxxx, x–x DOI: 10.5114/jhk/224327 x
Section III – Sports and Physical Activity

The Effects of Flywheel and Plyometric Training on Strength and Neuromuscular Performance of Wrestling and Judo Athletes

by
Zhiyong Zhang [1], Ziqing Qin [2], Wenfeng Zhang [3], Min Lu [3], Jian Sun [3], Peng Yuan [1,], Duanying Li [3,*]*

This study examined the effects of 4-week flywheel eccentric overload training (FEOT) versus plyometric training (PT) on back squat (BS) strength and neuromuscular performance in collegiate wrestlers and judo athletes. Nineteen participants (9 judo athletes and 10 wrestlers) were randomly assigned to either the FEOT group (n = 10) or the PT group (n = 9). The FEOT group performed BS exercises using a flywheel device, while the PT group completed four types of jump training. Both interventions were performed three times per week for four weeks. The countermovement jump (CMJ), the squat jump (SJ), the eccentric utilization ratio (EUR), the modified T-test (MT), the standing long jump (SLJ), and the BS 1-repetition maximum (1-RM) were assessed pre- and post-intervention. A two-way repeated-measures analysis of variance (ANOVA) was used to examine the main effects of the group and time and the group × time interaction. Effect sizes were calculated, and their magnitude was interpreted using magnitude-based inferences. The FEOT group demonstrated significant improvements in the BS 1-RM (p = 0.019; ES = 0.42, likely beneficial) and the EUR (p = 0.036; ES = 0.75, unclear), but not in the MT (p = 0.114; ES = 0.18, possibly beneficial). The PT group showed significant enhancements in the CMJ (p = 0.002; ES = 0.74, very likely beneficial), the SLJ (p = 0.004; ES = 0.52, very likely beneficial), and the MT (p = 0.003; ES = 0.76, very likely beneficial). These results suggest that 4-week FEOT led to within-group improvements in lower-limb strength (BS 1-RM), whereas PT led to within-group improvements in neuromuscular performance (CMJ, SLJ, and MT).

Keywords: *performance; strength; combat athletes; power training*

Introduction

Wrestling and judo are Olympic combat sports in which athletes employ explosive technical movements to score points while overcoming their opponents' resistance during high-intensity physical confrontations. Success in wrestling and judo depends on excellent physical attributes, particularly strength and neuromuscular performance (Franchini et al., 2011; Yoon, 2002). Studies have shown that high- and sub-elite wrestling and judo athletes differ significantly in lower-limb strength and neuromuscular performance (Fagerlund, 1991; García-Pallarés et al., 2011; Kuvačić et al., 2017). These qualities are commonly assessed using the back squat one-repetition maximum (BS 1-RM), vertical jump tests, the agility T-test, and the 10 × 5 m shuttle run.

Enhancing strength and neuromuscular performance is critical for success in wrestling and judo. Maximal strength is considered an important foundation for neuromuscular performance. In addition, neuromuscular performance declines across successive judo bouts, suggesting that it may serve as a sensitive indicator of competition-induced fatigue (Kons et al., 2026). These qualities can be improved through targeted interventions, such as weightlifting, plyometric training (PT), and eccentric overload training, which have been shown to enhance vertical jump height, sprint speed, and change-of-direction (COD)

[1] *School of Athletic Performance, Shanghai University of Sport, Shanghai, China.*
[2] *Physical Education Department, Guangzhou College of Technology and Business, Guangzhou, Guangdong, China.*
[3] *Sports Training Institute, Guangzhou Sport University, Guangzhou, Guangdong, China.*
* Correspondence: limid_yp@126.com (P.Y.); liduany@gzsport.edu.cn (D.L.)

CC BY

performance (Asadi et al., 2016; Douglas et al., 2017; O Brien et al., 2020). Neuromuscular performance tasks such as jumping, sprinting, and COD rely on a rapid transition from eccentric to concentric contractions, which helps conserve elastic energy and enhance force production. This physiological process is known as the stretch-shortening cycle (SSC) (Komi, 1986). Both PT and flywheel eccentric overload training (FEOT) utilize the SSC, which may provide a potential physiological mechanism for improving neuromuscular performance.

PT consists of jump-based movements that utilize the SSC. During the eccentric phase, elastic energy is stored and subsequently released during the concentric phase, thereby facilitating rapid force production. PT is widely applied in combat sports such as wrestling, judo, karate, and boxing to enhance strength and neuromuscular performance. However, the findings are inconsistent. For example, an 8-week PT program conducted three times per week did not lead to improvements in maximal power output during the Wingate test in wrestlers (Şahin, 2023). This lack of improvement might be partly explained by the use of the Wingate test, which may be less sensitive to the short-duration explosive qualities targeted by PT. In contrast, Moreno-Azze et al. (2023) reported that a six-week unilateral PT program performed once per week improved countermovement jump (CMJ) performance in karate athletes (effect size = 0.39–0.59). Another study involving karate athletes implemented PT with high-intensity intervals as part of the training regimen. After six weeks, participants demonstrated moderate to large improvements in the 5-m sprint (−12.1%), the 10-m sprint (−11.7%), and the Illinois Agility Test (−11.6%) (Ojeda-Aravena et al., 2020). Overall, available studies suggest that PT may improve physical performance in karate athletes. In addition to improving neuromuscular performance, PT can also enhance strength. Soyler et al. (2025) demonstrated that PT may also improve bench press 1-RM performance in boxers. Recently, a meta-analysis by Yuan et al. (2025) further examined the effects of PT on strength and power in martial arts athletes. The results showed that PT significantly improved strength (e.g., BS 1-RM, leg extension, handgrip strength) and power (vertical jump performance) in this population. These findings further support the role of PT in enhancing strength among combat sport athletes. However, it remains unclear how the strength gains from PT compare with those from FEOT in combat sport athletes, particularly because evidence in wrestling and judo remains limited.

FEOT is a novel eccentric resistance training method used to improve muscle strength and neuromuscular performance using flywheel devices. During the concentric phase, the athlete applies force to unwind the flywheel strap, generating kinetic energy. This energy then rewinds the strap during the eccentric phase, producing a downward resistive force. The athlete resists this force during the eccentric phase, and the concentric phase begins immediately afterward. During this transition, the eccentric phase typically involves a greater load than the concentric phase, resulting in eccentric overloading (Maroto-Izquierdo et al., 2017a). FEOT has been shown to effectively improve strength (Maroto-Izquierdo et al., 2017b), jump performance (Cabanillas et al., 2020; Coratella et al., 2019; O Brien et al., 2020; Shimizu et al., 2025), sprint performance over 10–30 m (Cabanillas et al., 2020; O Brien et al., 2020), agility (assessed by the T-test) (Coratella et al., 2019; Maroto-Izquierdo et al., 2017b), and COD performance (Madruga-Parera et al., 2025; Vazquez Romero et al., 2024) among team-sport athletes. Recently, another study reported partially inconsistent findings, showing that FEOT improved CMJ performance, but had no significant effects on sprint performance or COD ability (Galiano et al., 2024). In addition, Hu et al. (2024) reported that FEOT could improve strength and neuromuscular performance in college sprinters, with the exception of the eccentric utilization ratio (EUR). Although the results are not entirely consistent across studies, they collectively suggest that FEOT has beneficial effects on strength and neuromuscular performance. However, all participants in those studies were athletes from non-combat sports. Since judo and wrestling athletes differ considerably in terms of physical demands and performance characteristics, these findings may not be directly transferable to these sports. The lack of research on the effects of FEOT on lower-limb strength and athletic performance in wrestling and judo limits the availability of evidence-based guidance for coaches seeking to

implement this training method.

Therefore, this study aimed to directly compare the effects of FEOT and traditional PT on lower-body strength and neuromuscular performance in collegiate judo and wrestling athletes. Nineteen collegiate wrestlers and judokas from a Chinese university participated in a 4-week intervention involving either FEOT or PT. Based on the training characteristics of each method, where FEOT emphasizes slower eccentric muscle actions and PT focuses on faster concentric-eccentric transitions, we hypothesized that FEOT would lead to greater improvements in maximal strength, eccentric capacity, and COD performance. In contrast, PT would result in greater improvements in jumping performance, including both vertical and horizontal directions. Specifically, we anticipated that FEOT would produce greater improvements in the BS 1-RM, the EUR, and the modified agility T-test (MT), whereas PT would be more effective in enhancing CMJ, squat jump (SJ), and standing long jump (SLJ) performance.

Methods

Experimental Design

The experiment was conducted over a 4-week intervention period. Baseline testing was conducted during the week before the intervention, and post-intervention testing was conducted during the week after the final training session. Following baseline testing, participants were randomly assigned to one of the two groups. A minimum interval of 48 h was maintained between consecutive training sessions. All training sessions were supervised by certified strength and conditioning coaches.

Participants

The sample size was determined using G*Power software based on an F test for repeated-measures ANOVA with a within-between interaction, an expected effect size of f = 0.40, α = 0.05, statistical power = 0.80, two groups, and two measurements. The analysis indicated that a minimum of 16 participants was required. To account for the potential dropout, 20 collegiate athletes were initially recruited, including ten judo athletes and ten wrestling athletes from a Chinese university. Randomization was performed using SPSS software to generate random numbers. Participants were randomly assigned to one of the two experimental groups, with an equal distribution of males and females in each group. After one female participant in the PT group withdrew because of an injury sustained during training, 19 participants were included in the final analysis, with six male and four female athletes in the FEOT group and six male and three female athletes in the PT group. The inclusion criteria for the participants were as follows: (1) age between 19 and 23 years; (2) BS 1-RM of at least 1.5 times body mass; (3) no sports-related injuries within the past month; and (4) participation in provincial- or national-level competitions and attainment of at least the Chinese National Second-Class Athlete level. All participants completed a questionnaire to collect basic demographic and training information. Individuals who did not meet the inclusion criteria were excluded from the study.

All participants had engaged in specialized training three times per week since entering university, in addition to their regular physical education classes. The final analysis included 10 participants in the FEOT group (age: 20.92 ± 1.08 years; body height: 168.75 ± 7.65 cm; body mass: 72.42 ± 8.25 kg; training experience: 5.20 ± 2.44 years) and 9 participants in the PT group (age: 21.50 ± 1.24 years; body height: 167.08 ± 10.40 cm; body mass: 73.92 ± 8.52 kg; training experience: 4.44 ± 2.65 years). The FEOT group consisted of 4 judo and 6 wrestling athletes, while the PT group included 5 judo and 4 wrestling athletes.

This study was approved by the Ethics Committee of the Guangzhou Sport University, Guangzhou, Guangdong, China (protocol code: 2023LcLL-72; approval date: 26 December 2023) and conducted in accordance with the Declaration of Helsinki. All participants voluntarily agreed to take part in the experiment and signed informed consent forms. They were instructed to maintain their usual lifestyle and diet throughout the intervention period.

Procedures

All participants completed pre- and post-intervention assessments over two testing days, separated by 48 h. On the first day of testing, participants completed the CMJ, SJ, MT, and SLJ tests in the same order. The BS 1-RM test was conducted on the second day. Before each testing session, participants performed a standardized warm-up consisting of a 5-min jog followed by a

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

10-min dynamic stretching routine. The order of the tests and the personnel administering them remained consistent between the pre- and post-intervention assessments. A flowchart outlining the experimental procedure is presented in Figure 1.

Modified T-Test

The MT was used to assess COD performance. In this test, four markers were placed at positions A, B, C, and D, forming a "T" shape as shown in Figure 2. To better reflect the movement patterns typical of wrestling and judo, the standard T-test was adjusted. Specifically, the distance between points A and B was set at 5 m, while the distances between B and both C and D were set at 2.5 m. Participants began the test at point A. Upon the start signal, they followed the movement sequence indicated in Figure 2, ultimately returning to point A, which marked the completion of the trial (Sassi et al., 2009). Each participant performed two trials, and the best time was recorded. The test was initiated with a whistle, and time was recorded manually using a stopwatch by the same experienced tester under identical pre- and post-intervention testing conditions.

CMJ and SJ Testing

The CMJ was performed with the hands placed on the hips. Participants stood on a vertical jump mat (SmartJump, Fusion Sport, Australia), quickly performed a downward movement (eccentric phase), and then jumped vertically as high as possible. During the flight phase, participants were required to keep their body upright, without flexing the hips or knees, and then land within the mat area. Each participant completed three trials, and the highest jump height was recorded for subsequent analysis. The SJ was also performed with the hands on the hips. Participants began by assuming the lowest squat position used in the CMJ, held this position for 2–3 s to eliminate any countermovement, and then performed a maximal vertical jump. Three attempts were allowed, and the highest jump was recorded. The EUR was calculated as the ratio of CMJ height to SJ height: EUR = CMJ / SJ (McGuigan et al., 2006).

Standing Long Jump

In the SLJ, participants performed a rapid countermovement and jumped forward from a fixed starting line, aiming to achieve maximum horizontal distance. Participants were required to land on both feet. The horizontal distance from the starting line to the rearmost heel was measured. Each participant completed three trials, and the best performance was recorded with accuracy of 1 cm.

BS 1-RM

During the BS 1-RM test, each participant was closely supervised by a certified strength and conditioning coach to ensure safety throughout the session. The load was progressively increased by 2.5 kg to 20 kg, depending on the participant's strength level. Larger weight increments were used in the initial sets, while smaller ones were applied as the participant approached their maximal load. Each participant completed up to five sets to determine the one-repetition maximum. During the squat, participants maintained a stance approximately shoulder- or hip-width apart, with the feet externally rotated at an angle of about 30°. Proper alignment of the knees with the toes was required throughout the movement. A repetition was considered valid when the thighs reached at least parallel to the floor.

Training Protocol

The intervention lasted four weeks, with a training frequency of three sessions per week. Participants in the FEOT group (Figure 3) performed the BS using a flywheel device (Exxentric AB, Sweden). They completed four sets per session, with 8 repetitions per set in week 1, 10 repetitions per set in weeks 2 and 3, and 12 repetitions per set in week 4. Rest intervals between sets were maintained at 2–3 min. The flywheel device was equipped with three inertial disks of different sizes to provide varying inertial loads. To tailor the training load to individual power output levels, each participant underwent a progressive loading test in the laboratory prior to the intervention. During this test, participants performed four repetitions of the BS with each inertial load, with at least 3 min of rest between different load conditions. A real-time display attached to the device showed the power output for each load. The inertial load that produced the highest peak power output was selected as the participant's individualized training load.

Following a standardized warm-up,

participants in the PT group performed a series of exercises while wearing sandbags. These exercises included two-footed box jumps, drop jumps, hurdle jumps, and standing long jumps. The specific exercises, along with their descriptions, sets, and repetitions, are listed in Table 1. During the first two weeks, participants completed three sets of each exercise, which increased to four sets in the final two weeks. The intensity of PT was determined by the height of the equipment used. Training intensity was progressed in the third week by increasing the height of the boxes and hurdles. Because male and female participants differed in body height, body mass, and athletic ability, PT sessions were conducted separately by sex, and training equipment was adjusted accordingly.

The training volumes for the FEOT (Younes-Egana et al., 2023) and PT (Stojanović et al., 2017) groups were selected based on ranges commonly reported in previous reviews of flywheel and plyometric training, respectively. Throughout the intervention, all FEOT and PT sessions were supervised by two certified coaches. The coaches ensured that participants performed each exercise with maximal effort and correct technique. A stopwatch was used to monitor rest intervals between sets. If any movement did not meet the required technical standards, the coaches provided immediate feedback and correction to maintain training quality.

Statistical Analysis

Data are presented as means ± standard deviations (SD). The normality of the data distribution was assessed using the Shapiro-Wilk test. A two-way repeated-measures analysis of variance (ANOVA) was conducted to examine the main effects of the group and time and the group × time interaction. When significant main effects or interactions were detected, Bonferroni-adjusted pairwise comparisons were performed to identify within-group pre- to post-intervention changes and between-group differences. Effect sizes were calculated and interpreted using magnitude-based inferences. The effect size (ES) was determined by dividing the within-group mean difference by the baseline standard deviation. For variables where lower values indicated better performance, ES values were directionally adjusted so that positive values represented beneficial changes. The magnitude of the ES was interpreted using the following criteria: <0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; >1.2, large (Hopkins et al., 2009).

To make practical inferences about the true value of the effect in the studied population, the effect was expressed as the probability of harm or benefit associated with the smallest important effect of 0.2 standardized units. The following scale was used to characterize the probability size: 25–75%, possibly; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely (Hopkins et al., 2009). Uncertainty in effect sizes for magnitude-based inferences was represented using 90% confidence intervals (CI). Magnitude-based inferences were calculated using publicly available spreadsheets. Effects were classified according to their magnitude, qualitative probability, and the spreadsheet-derived practical inference as beneficial, trivial, harmful, or unclear. The effect of each variable was described as "possibly trivial", "likely trivial", "very likely trivial", "most likely trivial", "possibly beneficial", "likely beneficial", "very likely beneficial", "most likely beneficial", "possibly harmful", "likely harmful", "very likely harmful", "most likely harmful" or "unclear". Effects classified as unclear were interpreted cautiously, regardless of statistical significance.

Results

The effect sizes, their descriptions, and the estimated likelihood of beneficial effects are presented in Table 2. Before the intervention, there were no significant differences between the FEOT and PT groups in any of the measured variables. No significant group × time interactions were observed for the CMJ, the SJ, the EUR, the SLJ, the MT, or the BS 1-RM (all $p > 0.05$). No significant main effects for the group were observed for any measured variable. Significant main effects for time were observed in the following variables: the CMJ ($F = 13.431$, $p = 0.002$), the BS 1-RM ($F = 6.608$, $p = 0.020$), the EUR ($F = 7.886$, $p = 0.012$), the SLJ ($F = 11.087$, $p = 0.004$), and the MT ($F = 13.502$, $p = 0.002$).

After the 4-week intervention, the FEOT group showed significant improvements in the BS 1-RM ($p = 0.019$; ES = 0.42, small; 90% CI = 0.15 to 0.69; likely beneficial). Although the improvement in the MT was not statistically significant ($p = 0.114$; ES = 0.18, trivial; 90% CI = –0.01 to 0.37), the effect was considered possibly beneficial. Additionally,

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

the FEOT group showed significant improvements in the EUR (ES = 0.75, moderate; 90% CI = 0.19 to 1.3; p = 0.036), although this effect was considered unclear.

In the PT group, significant improvements were observed in the CMJ (p = 0.002; ES = 0.74, moderate; 90% CI = 0.43 to 1.00; very likely beneficial), the SLJ (p = 0.004; ES = 0.52, small; 90% CI = 0.28 to 0.76; very likely beneficial), and the MT (p = 0.003; ES = 0.76, moderate; 90% CI = 0.42 to 1.10; very likely beneficial).

No significant between-group differences were found in any measured variable after the intervention.

Table 1. Plyometric training programme.

Name	Description	Sets	Repetitions
Two-footed box jumps	Jump onto the box with both feet simultaneously, then jump off and land on both feet. After landing, perform a squat motion to cushion the impact.	3–4	5
Drop jumps	Start from the jump box: land on both feet and immediately jump vertically as high and fast as possible after touchdown.	3–4	5
Standing long jump	Explosively jump forward for maximum distance, using the arm swing for momentum, and land on both feet simultaneously.	3–4	5
Hurdle jump	Jump over the hurdle with legs together, keeping knees and feet facing straight forward. Maintain an upright torso and minimize ground contact time after landing.	3–4	10

Table 2. Comparison of test results before and after the intervention.

Variable	Group	Pre-test	Post-test	Magnitude-based inferences					
				Effect size	90% CI	Likelihood effect is beneficial (%)	Likelihood effect is trivial (%)	Likelihood effect is harmful (%)	Effect description
BS 1-RM (kg)	FEOT	124.50 ± 33.204	138.50 ± 31.802*	0.42	0.15 to 0.69	91.5%	8.4%	0.1%	likely beneficial
	PT	115.56 ± 28.66	121.67 ± 31.72	0.21	−0.14 to 0.56	52.1%	44.9%	3.1%	unclear
CMJ (cm)	FEOT	38.10 ± 9.23	39.44 ± 9.96	0.15	−0.05 to 0.35	32.6%	67.0%	0.5%	possibly beneficial
	PT	37.31 ± 5.36	41.25 ± 3.84*	0.74	0.43 to 1.00	99.4%	0.5%	0.0%	very likely beneficial
SJ (cm)	FEOT	36.64 ± 8.36	36.76 ± 8.68	0.01	−0.08 to 0.10	0.2%	99.6%	0.1%	most likely trivial
	PT	36.69 ± 5.41	39.45 ± 3.09	0.51	0.04 to 0.98	87.2%	11.6%	1.2%	unclear
EUR (ratio)	FEOT	1.04 ± 0.04	1.07 ± 0.06*	0.75	0.19 to 1.3	94.8%	4.6%	0.6%	unclear
	PT	1.02 ± 0.04	1.05 ± 0.04	0.75	−0.01 to 1.5	89.2%	8.3%	2.4%	unclear
SLJ (cm)	FEOT	228.5 ± 34.89	232.40 ± 36.27	0.11	−0.03 to 0.25	14.1%	85.7%	0.2%	likely trivial
	PT	230.56 ± 19.41	240.67 ± 18.70*	0.52	0.28 to 0.76	98.0%	2.0%	0.0%	very likely beneficial
MT (s)	FEOT	6.88 ± 0.87	6.72 ± 0.92	0.18	−0.01 to 0.37	42.5%	57.2%	0.2%	possibly beneficial
	PT	6.86 ± 0.46	6.51 ± 0.34*	0.76	0.42 to 1.10	99.3 %	0.7%	0.0%	very likely beneficial

*90% CI = 90% confidence interval; BS 1-RM = back squat 1-RM; CMJ = countermovement jump; SJ = squat jump; EUR = eccentric utilization ratio; SLJ = standing long jump; MT = modified T-test. * Significant difference compared with the pre-test, p < 0.05*

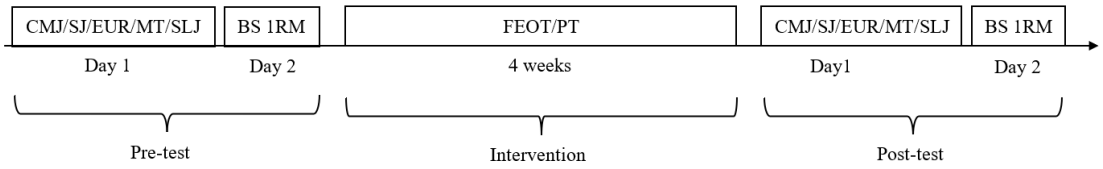


Figure 1. Flowchart of the experiment.
CMJ, countermovement jump; SJ, squat jump; EUR, eccentric utilization ratio; MT, modified T-test; SLJ, standing long jump; BS 1-RM, back squat one-repetition maximum; FEOT, flywheel eccentric overload training; PT, plyometric training

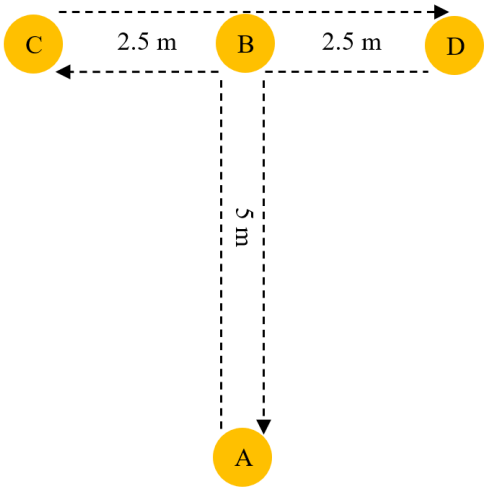


Figure 2. Modified T-test.



Figure 3. Schematic diagram of the training movements for the FEOT group.

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Discussion

The purpose of this study was to investigate the effects of FEOT and PT on lower-limb strength and neuromuscular performance. The results showed that, after four weeks of training, the FEOT group demonstrated a significant within-group improvement in the BS 1-RM (ES = 0.42), with a likely beneficial effect. This finding partially supports our hypothesis. The improvement in eccentric capacity, assessed using the EUR, was partly consistent with our hypothesis. However, the unclear practical inference indicates that the effect of FEOT on the EUR remains uncertain. A trivial improvement in the MT was observed in the FEOT group (ES = 0.18), with a possibly beneficial effect. In the PT group, significant within-group improvements were observed in the CMJ (ES = 0.74), the SLJ (ES = 0.52), and the MT (ES = 0.76), with effects classified as very likely beneficial. These findings partially support our hypothesis, as PT improved CMJ and SLJ performance, but did not significantly improve SJ performance. Contrary to our hypothesis, PT also improved MT performance.

Lower-Limb Strength

In terms of enhancing lower-limb strength, the 4-week FEOT program significantly improved the BS 1-RM within the group, whereas the same duration of PT did not produce a significant within-group improvement in this variable. To our knowledge, no previous study has directly compared FEOT and PT in wrestling or judo athletes. However, consistently with our findings, previous research has shown that FEOT improves the leg press 1-RM in handball players (Maroto-Izquierdo et al., 2017b) and the BS 1-RM in basketball players (O Brien et al., 2020). Our intervention consisted of a 4-week training program with three sessions per week. In contrast, a 6-week training program comprising 15 sessions had been implemented in previous FEOT research (Maroto-Izquierdo et al., 2017b), while another study used a 4-week intervention with two sessions per week (O Brien et al., 2020). Those studies indicate that FEOT interventions lasting 4 to 6 weeks, comprising 8 to 15 sessions in total, can enhance lower-limb strength.

A meta-analysis also reported that FEOT significantly improved maximal strength (ES = 1.33) (Petré et al., 2018). FEOT has been shown to promote both neurological and muscular adaptations, thereby enhancing force production (Gabriel et al., 2006; Higbie et al., 1996; Moritani and deVries, 1979). Furthermore, previous research reported increases in muscle size and electromyographic activity following resistance training, suggesting that neural and morphological adaptations may contribute to strength gains (Tesch et al., 1989).

In contrast, a study by Uzun and Karakoc (2017) reported that a 10-week PT program, performed three times per week, did not significantly improve lower-limb strength in judo athletes. Those findings are consistent with the results of the present study. A previous meta-analysis (Ramírez-delaCruz et al., 2022) found that PT significantly improved strength in both elite athletes and untrained individuals. However, three studies included in the analysis showed substantial improvements, while others reported no significant or only modest gains. Notably, the studies with greater improvements involved participants with minimal or no prior physical activity, despite training duration of up to 10 weeks (20 sessions in total). This suggests that PT can induce neural and muscular adaptations (Grgic et al., 2021; Markovic and Mikulic, 2010) which contribute to strength gains. However, these larger improvements may partly be explained by the participants' lower training status. Therefore, the absence of significant strength gains after the 4-week PT program may be related to the participants' prior resistance-training experience and the relatively short intervention duration.

Neuromuscular Performance

The 4-week PT program significantly improved CMJ (ES = 0.74), SLJ (ES = 0.52), and MT (ES = 0.76) performance within the group. However, no significant improvement was observed in the SJ (ES = 0.51). In combat sports, several studies have reported results consistent with our findings. For instance, one study reported that a 6-week plyometric-based high-intensity interval training protocol, which included 30-s CMJ exercises, improved CMJ (ES = 0.28), SJ (ES = 0.30), and Illinois Agility Test performance (ES = −1.20) in karate athletes (Ojeda-Aravena et al., 2020). However, their small sample size, with only three participants per group, may have increased the influence of individual variability on the

results. In contrast, another randomized trial of 20 karate athletes reported that a 6-week PT program performed once per week significantly improved CMJ, SLJ, and karate-specific COD performance (Moreno-Azze et al., 2023). Although their intervention focused on unilateral exercises, it included the CMJ, the DJ, and the SLJ—movements that are functionally similar to those used in our study.

Based on the limited available evidence, PT appears to improve CMJ, SLJ, and COD performance in karate athletes. As the performance of the CMJ and the SLJ depends on an efficient SSC to enhance athletic output (McGuigan et al., 2006; Walshe et al., 1996), PT is commonly used to improve SSC function and thereby enhance performance in both movements (Markovic, 2007). Moreover, the jump-based exercises used in the PT program may have enhanced intermuscular coordination (Bobbert and Van Soest, 1994; Leirdal et al., 2008; Zhao et al., 2026) and were biomechanically similar to the CMJ and SLJ tests, which may have facilitated performance improvements. This may partly explain the improvements observed in CMJ and SLJ performance. Regarding the SJ, which excludes the eccentric phase and requires participants to rely solely on concentric muscle contractions (McGuigan et al., 2006), the training movements applied in both the FEOT and PT groups involved the full SSC. No specific training targeting purely concentric contractions was included. This may explain the lack of significant improvements in SJ performance in either group, where the effect was classified as most likely trivial in the FEOT group and unclear in the PT group. Moreover, a previous study has shown that PT can enhance speed and COD performance (Chaabene et al., 2021), which supports the observed improvement in the MT.

Although both training methods involve the SSC, FEOT emphasizes the eccentric phase with higher loads, allowing athletes to better utilize their eccentric strength capacity. Moreover, eccentric training-induced strength gains may be influenced by training intensity and the match between training and testing velocity (Roig et al., 2009). Eccentric training has also been shown to improve SSC function (Douglas et al., 2017). In contrast, PT involves high-velocity jump-based actions. These high-velocity actions may enhance neuromuscular performance by improving SSC efficiency, intermuscular coordination, and rapid force production (Cormie et al., 2010). Consequently, FEOT and PT may induce different within-group adaptations, with FEOT mainly improving the BS 1-RM and PT mainly improving the CMJ, SLJ, and MT performance.

Limitations

Several limitations of this study should be acknowledged. First, participants were recruited from judo and wrestling because of practical constraints. Although these combat sports share similar physical demands, sport-specific differences in anthropometric characteristics, training background, and neuromuscular performance may have influenced the results. According to previous research (James et al., 2016), elite wrestling athletes tend to exhibit higher CMJ performance, a characteristic not consistently observed in judo athletes. Future studies should recruit athletes from a single combat sport or include larger samples to allow sport-specific analyses. Second, training load was not fully monitored or matched between the FEOT and PT groups. Although training intensity was individualized within each method, the mechanical stimulus differed substantially between flywheel squats and plyometric exercises, making it difficult to equate training volume and intensity. Future studies should use external monitoring tools to record variables such as power output, inertial load, jump height, and contact time to better quantify and standardize training load. Using power-loss thresholds in flywheel eccentric training is also a feasible approach to monitoring and regulating training load (Vicens-Bordas et al., 2026). Third, this study included only FEOT and PT groups and did not include a no-training control group. Therefore, it is difficult to determine whether the observed improvements were solely attributable to the interventions or were partly influenced by other factors. Additionally, the relatively small sample size and short intervention duration limit the generalizability of the findings. Fourth, the modified T-test was timed manually using a stopwatch rather than timing gates, which may have reduced the precision and reliability of the COD performance measurement. Future studies should use timing gates to improve measurement accuracy.

Practical Implications

FEOT primarily targets the enhancement of lower-limb strength, whereas PT is more focused on improving neuromuscular performance. Generally, the proportion of strength- and power-oriented training within a training program varies across different phases of the training cycle to help athletes prepare for competition. Based on our findings, FEOT may be considered during the early and mid-preparation phases when the training goal is to improve lower-limb strength. Conversely, PT may be emphasized during the late preparation and pre-competition phases when the goal is to improve jump and COD performance. This periodization strategy may be relevant for wrestling and judo athletes because these sports require high levels of neuromuscular performance, such as jump and COD performance, during competition. Although FEOT led to within-group improvements in the BS 1-RM, its effects on jump and COD performance were less evident in this study. Consequently, if FEOT is used as a primary method, coaches and athletes should combine FEOT with other modalities to improve broader aspects of athletic performance. The effectiveness of PT depends largely on the form and quality of the exercises. If the goal is to improve SSC-related performance, the exercises selected in this study may be appropriate. However, if the emphasis is on enhancing concentric force production, training methods that reduce the preceding countermovement, such as squat-jump variations, may be more appropriate. In addition, pre-loaded squat jumps may be beneficial for SJ performance. Although their long-term effects remain unverified, applying an external preload before SJ may represent a potential exercise for improving concentric jumping ability (Gu et al., 2026).

Conclusions

Four weeks of FEOT led to within-group improvements in the BS 1-RM in collegiate wrestling and judo athletes, while four weeks of PT led to within-group improvements in CMJ, SLJ, and MT performance. PT resulted in improved MT performance, whereas FEOT showed a non-significant positive trend. To optimize the benefits of PT, exercises should be selected based on whether the goal is to enhance the SSC-related performance or to emphasize concentric force production. Adjusting the relative emphasis on FEOT and PT according to the goals of different training phases may help support strength and neuromuscular performance development in wrestling and judo athletes.

Author Contributions: Conceptualization: Z.Q., W.Z., M.L., J.S., P.Y. and D.L.; methodology: Z.Z., Z.Q., W.Z., P.Y. and D.L.; software: Z.Z., Z.Q. and W.Z.; validation: Z.Z. and Z.Q.; formal analysis: Z.Z. and Z.Q.; investigation: Z.Z. and Z.Q.; resources: M.L., J.S., P.Y. and D.L.; data curation: Z.Z., Z.Q. and W.Z.; writing—original draft preparation: Z.Z. and Z.Q.; writing—review & editing: Z.Z.; visualization: Z.Q.; supervision: M.L. and J.S.; project administration: P.Y.; funding acquisition: P.Y. Additionally, Z.Z. and Z.Q. share the first authorship and contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding Information: The article was funded by the Shanghai Sports Science and Technology Project (Applied Research on Key Technologies for Training Monitoring in Combat Sports Preparing for the 15th National Games, 25J019) and the Major Project of Jiangsu Provincial Sports Administration (Research and Application of Key Technologies for Injury Risk Prevention and Return-to-Play in Judo and Wrestling, ST241105).

Institutional Review Board Statement: This study was conducted following the principles of the Declaration of Helsinki, and approved by the ethics committee of the Guangzhou Sport University, Guangzhou, Guangdong, China (protocol code: 2023LcLL-72; approval date: 26 December 2023).

Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Received: 31 July 2025

Accepted: 09 June 2026

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

References

Asadi, A., Arazi, H., Young, W. B., & Sáez de Villarreal, E. (2016). The Effects of Plyometric Training on Change-of-Direction Ability: A Meta-Analysis. *International Journal of Sports Physiology and Performance*, *11*(5), 563–573. https://doi.org/10.1123/ijspp.2015-0694.

Bobbert, M. F., & Van Soest, A. J. (1994). Effects of muscle strengthening on vertical jump height: a simulation study. *Medicine & Science in Sports & Exercise*, *26*(8), 1012–1020. https://doi.org/10.1249/00005768-199408000-00013.

Cabanillas, R., Serna, J., Muñoz-Arroyave, V., & Ramos, J. A. E. (2020). Effect of eccentric overload through isoinertial technology in basketball players. *Revista Brasileira de Cineantropometria & Desempenho Humano*, *22*, e59831. http://dx.doi.org/10.1590/1980-0037.2020v22e59831.

Chaabene, H., Negra, Y., Moran, J., Prieske, O., Sammoud, S., Ramirez-Campillo, R., & Granacher, U. (2021). Plyometric Training Improves Not Only Measures of Linear Speed, Power, and Change-of-Direction Speed But Also Repeated Sprint Ability in Young Female Handball Players. *Journal of Strength and Conditioning Research*, *35*(8), 2230–2235. https://doi.org/10.1519/jsc.0000000000003128.

Coratella, G., Beato, M., Cè, E., Scurati, R., Milanese, C., Schena, F., & Esposito, F. (2019). Effects of in-season enhanced negative work-based vs traditional weight training on change of direction and hamstrings-to-quadriceps ratio in soccer players. *Biology of Sport*, *36*(3), 241–248. https://doi.org/10.5114/biolsport.2019.87045.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sports & Exercise*, *42*(9), 1731–1744. doi: 10.1249/MSS.0b013e3181d392e8.

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017). Chronic adaptations to eccentric training: a systematic review. *Sports Medicine*, *47*(5), 917–941. https://doi.org/10.1007/s40279-016-0628-4.

Fagerlund, R. (1991). Strength profile of Finnish judoists-measurement and evaluation. *Biology of Sport*, *8*, 143–149.

Franchini, E., Del Vecchio, F. B., Matsushigue, K. A., & Artioli, G. G. (2011). Physiological profiles of elite judo athletes. *Sports Medicine*, *41*(2), 147–166. https://doi.org/10.2165/11538580-000000000-00000.

Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise: mechanisms and recommendations for training practices. *Sports Medicine*, *36*(2), 133–149. https://doi.org/10.2165/00007256-200636020-00004.

Galiano, C., Floria, P., Muñoz-López, A., Sáez de Villarreal, E., & Nuñez, F. J. (2024). Accentuated eccentric resistance training: Effects on physical performance in male and female athletes. *Journal of Sports Sciences*, *42*(17), 1627–1634. https://doi.org/10.1080/02640414.2024.2404327.

García-Pallarés, J., López-Gullón, J. M., Muriel, X., Díaz, A., & Izquierdo, M. (2011). Physical fitness factors to predict male Olympic wrestling performance. *European Journal of Applied Physiology*, *111*, 1747–1758. https://doi.org/10.1007/s00421-010-1809-8.

Grgic, J., Schoenfeld, B. J., & Mikulic, P. (2021). Effects of plyometric vs. resistance training on skeletal muscle hypertrophy: A review. *Journal of Sport and Health Science*, *10*(5), 530–536. https://doi.org/10.1016/j.jshs.2020.06.010.

Gu, Z., Chen, Z., Liao, K., Bishop, C., Gao, C., Zhong, F., Deng, S., Wang, X., Wei, J., & Li, Y. (2026). A novel approach to improving squat jump performance: The pre-loaded squat jumps. *Journal of Human Kinetics, 100*, 27–37. https://doi.org/10.5114/jhk/200809

Higbie, E. J., Cureton, K. J., Warren, G. L., 3rd, & Prior, B. M. (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *Journal of Applied Physiology (1985)*, *81*(5), 2173–2181. https://doi.org/10.1152/jappl.1996.81.5.2173.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278.

Hu, Z., Liu, Y., Huang, K., Huang, H., Zhang, Y., & Yuan, X. (2024). Effects of Inertial Flywheel Training vs. Accentuated Eccentric Loading Training on Strength, Power, and Speed in Well-Trained Male College Sprinters. *Life (Basel)*, *14*(9), 1081. https://doi.org/10.3390/life14091081.

James, L. P., Haff, G. G., Kelly, V. G., & Beckman, E. M. (2016). Towards a Determination of the Physiological Characteristics Distinguishing Successful Mixed Martial Arts Athletes: A Systematic Review of Combat Sport Literature. *Sports Medicine*, *46*(10), 1525–1551. https://doi.org/10.1007/s40279-016-0493-1.

Komi, P. (1986). The stretch-shortening cycle and human power output. In: Jones NL, McCartney L, McComas AJ (eds.), *Human muscle power*, pp. 27–39. Champaign, IL: Human Kinetics.

Kons, R. L., Ache-Dias, J., Estácio Costa, F., Dal Pupo, J., & Detanico, D. (2026). Effects of multiple judo bouts in the bilateral strength deficit on the countermovement jump metrics. *Journal of Human Kinetics*, *100*, 17–26. https://doi.org/10.5114/jhk/202147

Kuvačić, G., Krstulović, S., & Caput, P. (2017). Factors Determining Success in Youth Judokas. *Journal of Human Kinetics*, *56*, 207–217. https://doi.org/10.1515/hukin-2017-0038.

Leirdal, S., Roeleveld, K., & Ettema, G. (2008). Coordination specificity in strength and power training. *International Journal of Sports Medicine*, *29*(3), 225–231. https://doi.org/10.1055/s-2007-965128

Madruga-Parera, M., Esteves, P. T., Fernandes, J. F. T., Beltrán-Garrido, V., Bird, S., Leite, N., Romero-Rodriguez, D., & Arede, J. (2025). Inclusion of Game-Based Stimulus During Flywheel Resistance Training Positively Influences Physical Performance in Handball Players. *Research Quarterly for Exercise and Sport*, *96*(1), 1–10. https://doi.org/10.1080/02701367.2024.2359603

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine*, *41*(6), 349–355. https://doi.org/10.1136/bjsm.2007.035113

Markovic, G., & Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine*, *40*(10), 859–895. https://doi.org/10.2165/11318370-000000000-00000

Maroto-Izquierdo, S., García-López, D., Fernandez-Gonzalo, R., Moreira, O. C., González-Gallego, J., & de Paz, J. A. (2017a). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, *20*(10), 943–951. https://doi.org/10.1016/j.jsams.2017.03.004.

Maroto-Izquierdo, S., García-López, D., & de Paz, J. A. (2017b). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. *Journal of Human Kinetics*, *60*, 133–143. doi: 10.1515/hukin-2017-0096.

McGuigan, M. R., Doyle, T. L., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: effect of sport and phase of training. *Journal of Strength and Conditioning Research*, *20*(4), 992–995. https://doi.org/10.1519/r-19165.1

Moreno-Azze, A., Prad-Lucas, E., Fandos Soñén, D., Pradas de la Fuente, F., & Falcón-Miguel, D. (2023). Plyometric Training's Effects on Young Male Karatekas' Jump, Change of Direction, and Inter-Limb Asymmetry. *Sports (Basel)*, *12*(1), 1. https://doi.org/10.3390/sports12010001

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine & Rehabilitation*, *58*(3), 115–130.

O Brien, J., Browne, D., & Earls, D. (2020). The effects of different types of eccentric overload training on strength, speed, power and change of direction in female basketball players. *Journal of Functional Morphology and Kinesiology*, *5*(3), 50. https://doi.org/10.3390/jfmk5030050.

Ojeda-Aravena, A., Herrera-Valenzuela, T., Garcia Garcia, J. M., & Ramirez-Campillo, R. (2020). Six weeks of HIIT based on repeated 5-meter sprints vs. countermovement jumps: effects on physical performance among karate athletes. A pilot-study. *Ido Movement for Culture. Journal of Martial Arts Anthropology*, *20*(2), 17–23. https://doi.org/10.14589/ido.20.2.4

Petré, H., Wernstål, F., & Mattsson, C. M. (2018). Effects of flywheel training on strength-related variables: A meta-analysis. *Sports Medicine-Open*, *4*, 1–15. https://doi.org/10.1186/s40798-018-0169-5

Ramírez-delaCruz, M., Bravo-Sánchez, A., Esteban-García, P., Jiménez, F., & Abián-Vicén, J. (2022). Effects of Plyometric Training on Lower Body Muscle Architecture, Tendon Structure, Stiffness and Physical Performance: A Systematic Review and Meta-analysis. *Sports Medicine-Open*, *8*(1), 40. https://doi.org/10.1186/s40798-022-00431-0

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B., & Reid, W. D. (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *British Journal of Sports Medicine*, *43*(8), 556–568. https://doi.org/10.1136/bjsm.2008.051417

Şahin, M. (2023). Effect Of 8-Week Plyometric Training On Physical Fitness Parameters In Wrestlers. *International Journal of Eurasian Education and Culture*, *8*(23), 2397–2406. http://dx.doi.org/10.35826/ijoecc.761.

Sassi, R. H., Dardouri, W., Yahmed, M. H., Gmada, N., Mahfoudhi, M. E., & Gharbi, Z. (2009). Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. *Journal of Strength and Conditioning Research*, *23*(6), 1644–1651. https://doi.org/10.1519/JSC.0b013e3181b425d2

Shimizu, T., Tsuchiya, Y., Ueda, H., Izumi, S., & Ochi, E. (2025). Eight-Week Flywheel Training Enhances Jump Performance and Stretch-Shortening Cycle Function in Collegiate Basketball Players. *European Journal of Sport Science*, *25*(2), e12257. https://doi.org/10.1002/ejsc.12257

Soyler, M., Gurkan, A. C., Kayantas, I., Aydin, S., Karatas, B., Eraslan, M., Sahin, M., Kucuk, H., Badau, A., & Badau, D. (2025). Investigation of the Effects of Different Plyometric Training Protocols on Punching Force and Muscle Performance in Male Boxers. *Applied Sciences-Basel*, *15*(12), 6532. https://doi.org/10.3390/app15126532

Stojanović, E., Ristić, V., McMaster, D. T., & Milanović, Z. (2017). Effect of Plyometric Training on Vertical Jump Performance in Female Athletes: A Systematic Review and Meta-Analysis. *Sports Medicine*, *47*(5), 975–986. https://doi.org/10.1007/s40279-016-0634-6

Tesch, P. A., Thorsson, A., & Essén-Gustavsson, B. (1989). Enzyme activities of FT and ST muscle fibers in heavy-resistance trained athletes. *Journal of Applied Physiology (1985)*, *67*(1), 83–87. https://doi.org/10.1152/jappl.1989.67.1.83

Uzun, A., & Karakoc, O. (2017). The Effects of Ten Weekly Plyometric Training of Judokas on Anaerobic Power. *Journal of Education and Training Studies*, *5*(13), 52–58.

Vazquez Romero, J., Nunez-Gonzalez, J. L., Valenzuela Barrero, C., Hernandez Abad, F., & Nunez, F. J. (2024). The Effects of Flywheel Training with a Portable Device on Physical Performance in Soccer Players. *Applied Sciences-Basel*, *14*(24), 11857. https://doi.org/10.3390/app142411857

Vicens-Bordas, J., Carrera-Prat, J., Biel-Costa, J., Piedra, A., Altarriba-Bartés, A., Chulvi-Medrano, I., Beato, M., & Peña, J. (2026). Acute responses of blood lactate, the countermovement jump, and the rating of perceived exertion after flywheel squats using varied power-loss thresholds. *Journal of Human Kinetics*. Advance online publication. https://doi.org/10.5114/jhk/216401

Walshe, A. D., Wilson, G., & Murphy, A. (1996). The validity and reliability of a test of lower body musculotendinous stiffness. *European Journal of Applied Physiology and Occupational Physiology*, *73*, 332–339. https://doi.org/10.1007/BF02425495.

Yoon, J. (2002). Physiological profiles of elite senior wrestlers. *Sports Medicine*, *32*(4), 225–233. https://doi.org/10.2165/00007256-200232040-00002

Younes-Egana, O., Mielgo-Ayuso, J., Stojanović, M. D. M., Bird, S. P., & Calleja-González, J. (2023). Effectiveness of eccentric overload training in basketball players: A systematic review. *Journal of Human Kinetics*, *88*, 243–257. https://doi.org/10.5114/jhk/167469

Yuan, Q., Deng, N., & Soh, K. G. (2025). A meta-analysis of the effects of plyometric training on muscle strength and power in martial arts athletes. *Bmc Sports Science, Medicine and Rehabilitation*, *17*(1), 12. https://doi.org/10.1186/s13102-025-01059-9

Zhao, J., Łosińska, K., Chen, L., & Aschenbrenner, P. (2026). Neuromuscular adaptation to varying drop jump heights: A muscle synergy approach in elite handball players. *Journal of Human Kinetics*, *101*, 147–164. https://doi.org/10.5114/jhk/217230