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Neuromuscular Capabilities in Top-Level Weightlifters and Their Association with Weightlifting Performance

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Abstract: The aim of this study was to determine the associations between the front and back squat, countermovement jump (CMJ) and deep squat jump (DSJ) force–time metrics, and weightlifting performance in top-level weightlifters. Thirteen top-level weightlifters who classified for the World Championship 2023 participated. The heaviest successful snatch and clean and jerk were recorded within a preparation session as performance indicators. The front and back squat one-repetition maximums (1RMs) were evaluated in separate training sessions. The average of three maximum CMJs and DSJs were recorded using a force plate, and jump height, propulsive net impulse, and peak power were calculated for further analysis. Pearson's correlation coefficients were used to determine the associations between variables. Statistical significance was set at $p \leq 0.05$. The front and back squat 1RMs were significant and nearly perfectly associated with weightlifting performance ($p < 0.001$, r = 0.98–0.99). CMJ and DSJ propulsive net impulse displayed nearly perfect associations with weightlifting performance ($p < 0.001$, r = 0.96–0.99), while jump height is a less promising metric to assess the weightlifters' ballistic capabilities. This study reinforces that lower body maximum strength and ballistic capabilities are closely associated with top-level weightlifters' performance and are of practical importance to monitor their neuromuscular function.

Keywords: force plates; vertical jumps; snatch; clean and jerk; maximum strength

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1. Introduction

In weightlifting, an athlete's performance is determined by the sum of their heaviest successful competitive lifts: snatch and clean and jerk [1]. The snatch and clean and jerk are complex multi-joint movements, performed by a series of high-intensity muscular contractions [1–3]. Weightlifters must generate impulse, which is the product of force and time, to increase the momentum of the system mass (the lifter's bodyweight plus the barbell) and ultimately transfer it to the barbell to result in a sufficient displacement to complete the lift. Weightlifting performance is therefore largely determined by the lower body maximum strength and ballistic neuromuscular capabilities because weightlifters are required to generate a high magnitude of force within the technical and time constraints imposed by the competitive lifts [1,4,5].

The assessment of lower body neuromuscular capabilities in weightlifters is of interest to researchers and practitioners [4,6,7]. Previously reported by Canavan et al. [8], and recently reviewed by Joffe et al. [4], incorporating multi-joint performance tests that have similar mechanics to the snatch and clean and jerk, such as squats and vertical jumps, can provide valuable information and enable practitioners to effectively evaluate the neuromuscular capabilities that underpin weightlifting performance. For example, the foundation strength exercises front and back squat one-repetition maximums (1RMs), as a measure of weightlifters' maximum strength capacity, have high to nearly perfect associations with the snatch and clean and jerk (r = 0.73–0.95) [4,9–13]. Moreover, strong associations have been identified between the countermovement jump (CMJ) and deep squat jump (DSJ) peak displacement (jump height), as a measure of weightlifters' rapid force production and ballistic capabilities, and weightlifting performance (r = 0.59–0.93) [4,6,14]. These findings suggest that adequately incorporating tests to evaluate maximum strength and ballistic capabilities can serve as a valuable method for assessing weightlifters' neuromuscular function and subsequently monitoring performance.

Vertical jumps, such as the CMJ and DSJ, are ballistic actions that share similar mechanics with weightlifting snatch and clean and jerk exercises and are frequently used to evaluate the rapid force production and ballistic capabilities of weightlifters by means of the jump height [4,8,12,15,16]. However, researchers have recommended to not only report jump height but also other force–time metrics such as propulsive impulse and peak power to monitor weightlifters' neuromuscular capabilities [4,7]. For example, Chavda et al. [7] investigated a broad range of CMJ force–time metrics and their relationship with weightlifting performance and documented that reporting propulsive impulse may better reflect any alterations in the neuromuscular capabilities of weightlifters. Similarly, Joffe et al. [12] demonstrated that adding the countermovement jump peak power in addition to the isometric mid-thigh peak force (i.e., ballistic and maximum strength capabilities) increased the explained variance in the snatch and clean and jerk performance up to 95 and 92%, respectively. To the best of our knowledge, researchers have not studied the force–time metrics during the DSJ and their relationship with weightlifting performance to date. Furthermore, only a few researchers have evaluated the relationships between weightlifting performance, maximum strength in foundation exercises, and ballistic capabilities (i.e., jump height, propulsive impulse, and peak power) during vertical jump tests in top-level weightlifters competing at international tournaments [12,17,18].

The primary objective of this study was therefore to determine the associations between maximum strength in foundation exercises (i.e., front and back squat), ballistic capabilities in vertical jumps (i.e., CMJ and DSJ), and performance in snatch and clean and jerk in top-level weightlifters. Furthermore, a secondary objective was to determine which force–time metrics (i.e., jump height, propulsive impulse, and peak power), measured in the CMJ and DSJ vertical jumps, were more strongly associated with weightlifting performance in top-level weightlifters. Based on previous evidence, we hypothesized strong associations between the maximum strength in foundation exercises and weightlifting performance in top-level weightlifters [4,9–13]. We also hypothesized that force–time metrics from the DSJ and CMJ may exhibit strong associations with performance in the snatch and clean and jerk as a result of analogous mechanical principles [6,7].

2. Materials and Methods

2.1. Design

This study consisted of a cross-sectional assessment of the neuromuscular capabilities of top-level international weightlifters using foundation strength exercises (i.e., front and back squat), vertical jump tests (i.e., CMJ and DSJ), and their relationship to weightlifting performance. All tests were conducted two weeks prior to the International Weightlifting Federation (IWF) World Weightlifting Championships 2023 of Riyadh as part of the Spanish Weightlifting National Team routine of the sports science service within the tapering period. Weightlifting performance was evaluated as the heaviest successful snatch and clean and jerk. Maximum strength was evaluated using the front and back squat 1RMs, while the ballistic capabilities were evaluated during the CMJ and DSJ force–time metrics on a force plate.

2.2. Participants

Thirteen top-level international male (n = 6; age: 28.8 ± 4.5 years, height: 1.7 ± 0.1 m, body mass: 77.5 ± 12.7 kg, Sinclair's coefficient: 423.9 ± 15.8 points) and female (n = 7; age: 26.4 ± 3.9 years, height: 1.6 ± 0.1 m, body mass: 57.6 ± 6.8 kg, Sinclair's coefficient: 266.9 ± 9.5 points) weightlifters from the Spanish Weightlifting Team participated in this investigation. Subjects were included if they were classified and heading to compete in the International Weightlifting Federation (IWF) World Weightlifting Championships 2023 of Riyadh (Saudi Arabia) as a part of the Spanish Weightlifting National Team. Although some subjects moved between body weight categories during this period for strategic reasons, the distribution of athletes was as follows: 1 × 45, 3 × 49, 2 × 55, 1 × 59, 1 × 64, 1 × 67, 2 × 73, 1 × 8, and 1 × 89 kg. This study was approved by the institutional review board of the university of origin (16_23_RNM_FP), and all subjects provided written informed consent before participation. Subjects were asked to maintain their regular nutrition and use ergogenic aids as usual. In brief, the subjects followed a high-protein diet supplemented with whey protein and creatine monohydrate. Subjects were not using any pharmacological products considered as doping. Subjects were also free of injuries and had no medical contraindications for participating in this study. This study conformed to the principles of the Declaration of Helsinki of the World Medical Association. Given the strict criteria for subject selection, a post hoc power analysis was performed using G*Power (version 3.1); based on a coefficient of determination (r^2) of 0.6, a previous conservative effect size of 0.7 [13], and an alpha level of $p \leq 0.05$, our sample size (n = 13) revealed a statistical power of 95%.

2.3. Procedures

The snatch and clean and jerk were tested within the same training session two weeks prior to the international competition within the tapering period and corresponded to a programmed performance monitoring session. Snatch, clean, and jerk lifts have been described previously [1,16]. The training session was developed as a competition mock; therefore, subjects started by performing the snatch, followed by the clean and jerk. Briefly, subjects started the warm-up by performing self-selected mobility drills and multi-joint exercises (e.g., squats, overhead press, overhead snatch, and snatch balance) with barbell mass only. Subjects then performed the vertical jumps described in the next section. After that, the subjects rested for approximately 5 min and performed a self-selected incremental loading protocol, replicating their competition-specific warm-up, to achieve the heaviest load during the snatch exercise. After the snatch, subjects rested for approximately 5 min and replicated a similar self-selected incremental loading protocol for the clean and jerk. All subjects were encouraged and supervised by the national weightlifting coach during all the submaximal and maximal attempts. Weightlifting performance was recorded in absolute (i.e., kg) and relative to body mass (i.e., kg/kg) forms.

Front and back squat exercises were tested in different training sessions two weeks prior to the international competition within the tapering period and corresponded to a programmed performance monitoring session. Front and back squat exercises were tested at the beginning of the training session, as a primary exercise, after a general warm-up and a self-selected incremental loading protocol. The 1RM assessment started from a near-maximal load (95% of self-estimated 1RM), and each successful attempt was followed by an increment of the load of 2.5–5.0% until the 1RM was reached, allowing a maximum of five 1RM attempts, in accordance with the NSCA guidelines [9]. Subjects rested for 4 to 5 min between attempts. In the front and back squat, the barbell was taken out from a rack, and the subject's feet were shoulder-width apart, with their toes pointing forward and slightly outward. In the front squat, subjects positioned the barbell on their shoulders, in the front rack position, with extended wrists and flexed elbows. In the back squat, the barbell was placed in a high bar position because it is the style frequently used by weightlifters and had to remain in constant contact with the shoulders, whereas the feet were required to maintain contact with the floor [9,13,19]. Front and back squat maximum strengths were recorded in absolute (i.e., kg) and relative to body mass (i.e., kg/kg) forms.

The ballistic capabilities of the weightlifters were evaluated using vertical jump tests, specifically the CMJ and DSJ, on a force plate (Figure 1). Subjects performed three CMJs and DSJs, randomized with an approximately 1 min rest between each trial. For the CMJ, subjects stood upright and still on the force plate (Hawkin Dynamics Inc., Westbrook, ME, USA) with their feet positioned hip-width apart and their hands akimbo. To the audible beep signal of the connected software, subjects performed a CMJ to a self-selected depth and were instructed to "jump as high and as fast as possible" [7,12]. For the DSJ, subjects were asked to remain still on the force plate in a deep squat position, with their feet shoulder-width apart and their toes pointed forward or slightly outwards [6]. To the audible beep signal of the connected software, subjects performed the DSJ without any countermovement after maintaining the deep squat position to avoid taking advantage of elastic energy storage [6]. A wooden dowel was placed across the shoulders to eliminate the contribution of the arms during the DSJ. The force–time metrics selected for both jumps to assess ballistic capabilities were jump height, propulsive net impulse, and peak propulsive power, based on the previous literature [4,6,7,12]. Peak power metrics were recorded in absolute (i.e., W) and relative (i.e., W/kg) forms. A detailed explanation of the calculus for these metrics can be found on the manufacturer's website (https://www.hawkindynamics.com/hawkin-metric-database, accessed on 25 April 2024).

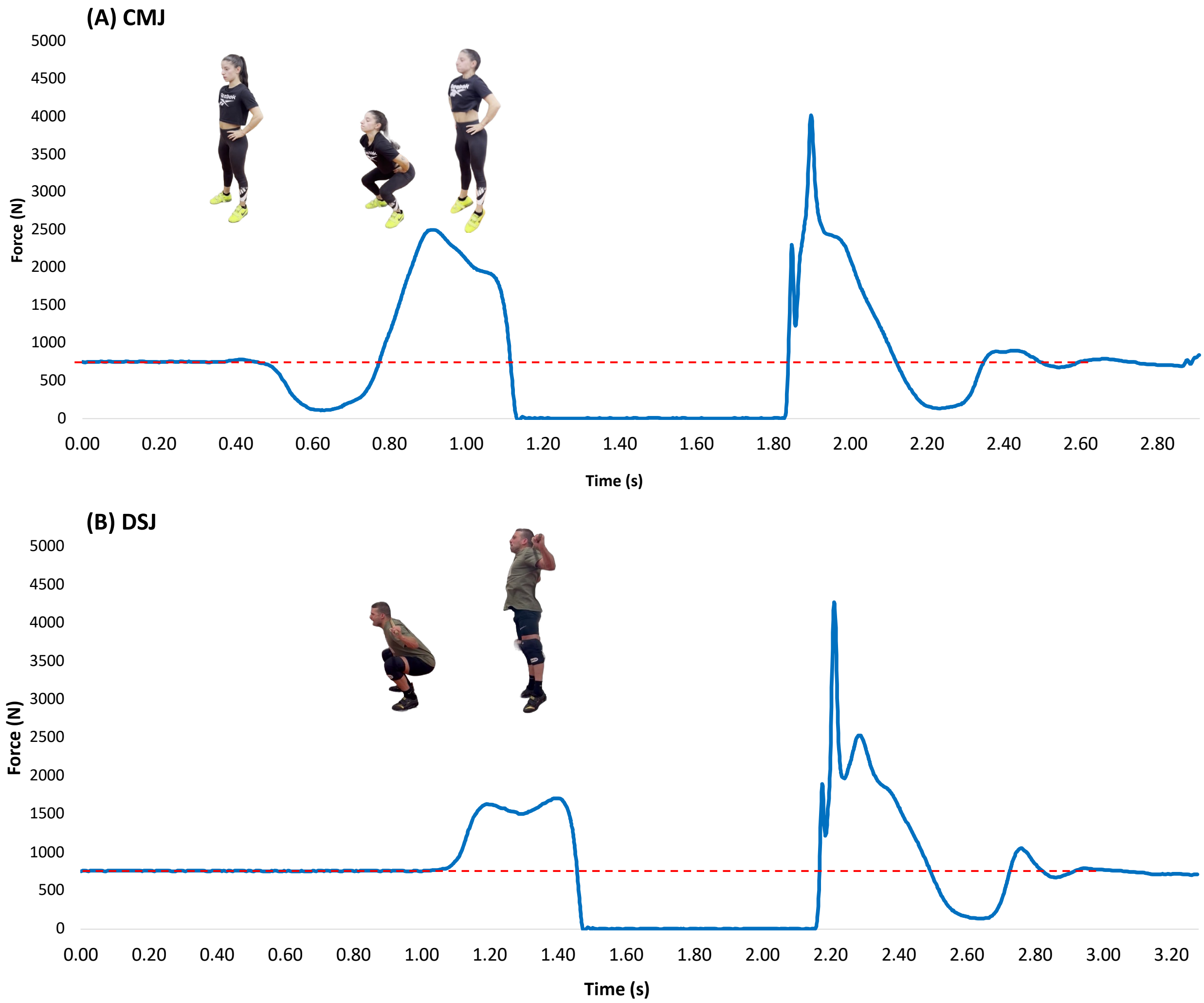


Figure 1. An example of the force–time traces for the countermovement jump (CMJ; panel (**A**)) and deep squat jump (DSJ; panel (**B**)). The red dashed line denotes the body weight.

2.4. Measurement Equipment and Data Analysis

The heaviest successful snatch and clean and jerk were recorded as the weightlifting performance indicators. The front and back squat foundation strength exercises were selected to assess the weightlifters' maximum strength capability (i.e., 1RM). The snatch, clean and jerk, and front and back squat were performed using standardized and calibrated barbells, weightlifting plates (Eleiko, Halmstad, Sweden), lifting platforms, and barbell supports (squats only). A 20 kg Olympic barbell was used for men, whereas a 15 kg Olympic barbell was used for women. Previous studies have demonstrated high reproducibility of the test–retest reliability of highly trained weightlifters [20].

The vertical ground reaction force (vGRF) applied to the whole-body centre of mass during each jumping test was recorded using a wireless dual force plates system with a sample rate of 1000 Hz. The Hawkin Dynamics software (version 4.3.1) operates via an Android tablet that connects with the force plate system via Bluetooth and automatically analyses the vGRF before immediately transferring the data via Wi-Fi to the Hawkin Dynamics cloud server [21]. The force plates were calibrated and placed on flat ground and zeroed before each test/trial was recorded, following the manufacturer's details. The accuracy of the Hawkin Dynamics hardware and software has been validated in previous studies [21,22]. The vGRF data for each trial were automatically low-pass-filtered (50 Hz cut-off frequency). Movement onset for each trial was identified when the vGRF decreased or increased below/above (i.e., CMJ and DSJ, respectively) the system weight by more than 5 standard deviations (SD) [21] (Figure 1). The system weight was calculated using the Hawkin Dynamics guidelines, where participants stood still on the force plates for one second, and the average force was recorded. All metrics were obtained from the propulsive phase (green area) to allow comparisons between the jumps (Figure 1). The averages across the three trials were used for statistical analyses. The intra-session reliability using the intraclass correlation coefficient (ICC) and % coefficient of variation (CV) and their associated 95% confidence intervals were calculated for all selected metrics and interpreted based on Koo et al. [23]. All metrics had excellent reliability for the CMJ and DSJ (ICC = 0.95–1.00) with low variability (%CV = 0.98–7.23).

2.5. Statistical Analyses

A descriptive analysis of the weightlifting performance, front and back squat maximum strength, and CMJ and DSJ force–time metrics with the mean, standard deviation (SD), 95% confidence interval (CI), CV, and range (min and max) was performed for all subjects and males and females separately. The Shapiro–Wilk test of normality revealed that all metrics were normally distributed ($p > 0.05$); therefore, Pearson's r correlation coefficients with their associated 95% CI were used to determine the relationship between front and back squat maximum strength, CMJ and DSJ ballistic capability, and weightlifting performance for all subjects and males and females separately. Pearson's r correlational values were assigned descriptors using the following thresholds: 0.00–0.10 = "very weak", 0.11–0.30 = "weak", 0.31–0.50 = "moderate", 0.51–0.70 = "strong", 0.71–0.90 = "very strong", and 0.91–1.00 = "nearly perfect" [24]. Furthermore, a Fisher's r-z transformation was performed to compare the magnitude of the effect in the correlations. A linear regression analysis was performed to determine the variance of the snatch and clean and jerk performance, explained by the front and back squat 1RMs, CMJ and DSJ height, propulsive net impulse, and peak power, in males and females. All statistical analyses were performed using JASP (JASP Team, version 0.17.3 [Computer Software], Amsterdam, The Netherlands). Statistical significance was set at $p \leq 0.05$.

3. Results

3.1. Descriptive Results

The descriptive results of males' and females' weightlifting performances, front and back squat maximum strength, and selected CMJ and DSJ force–time metrics are shown in Table 1.

Table 1. Results of weightlifting performances and CMJ and DSJ force–time metrics for males and females.

Metrics	Mean ± SD	LL 95% CI	UL 95% CI	CV (%)	Min	Max
Males						
Snatch (kg)	141.33 ± 13.78	130.31	152.36	10	118.00	155.00
Relative snatch (kg/kg)	1.94 ± 0.14	1.73	1.95	8	1.63	2.00
C&J (kg)	171.5 ± 19.92	155.56	187.44	12	140.00	193.00
Relative C&J (kg/kg)	2.23 ± 0.14	2.12	2.34	6	2.02	2.38
Back squat (kg)	211.67 ± 22.29	193.83	229.50	11	185.00	240.00
Relative back squat (kg/kg)	2.76 ± 0.22	2.58	2.93	8	2.52	3.14
Front squat (kg)	192.67 ± 23.85	173.59	211.75	12	160.00	225.00
Relative front squat (kg/kg)	2.51 ± 0.24	2.32	2.70	10	2.15	2.80
CMJ height (m)	0.53 ± 0.07	0.48	0.58	12	0.45	0.60
CMJ prop net impulse (N·s)	251.81 ± 39.58	220.14	283.48	16	178.59	285.36
CMJ PP (W)	5498.40 ± 1062.84	4647.97	6348.83	19	3646.13	6497.64
CMJ relative PP (W/kg)	70.74 ± 6.65	65.42	76.07	9	61.87	77.41
DSJ height (m)	0.51 ± 0.06	0.46	0.56	12	0.41	0.58
DSJ prop net impulse (N·s)	247.67 ± 35.45	219.31	276.04	14	182.33	273.17
DSJ PP (W)	4921.07 ± 710.21	4352.799	5489.34	14	3592.13	5452.99
DSJ relative PP (W/kg)	63.77 ± 5.31	59.52	68.01	8	54.76	69.52
Females						
Snatch (kg)	81.43 ± 7.61	75.80	87.07	9	72.00	92.00
Relative snatch (kg/kg)	1.42 ± 0.07	1.37	1.47	5	1.32	1.51
C&J (kg)	100.14 ± 9.94	92.78	107.51	10	83.00	115.00
Relative C&J (kg/kg)	1.74 ± 0.06	1.70	1.74	4	1.68	1.85
Back squat (kg)	131.43 ± 13.76	121.24	141.62	11	105.00	150.00
Relative back squat (kg/kg)	2.29 ± 0.12	2.20	2.38	5	2.17	2.53
Front squat (kg)	114.29 ± 10.95	106.17	122.40	10	94.00	127.00
Relative front squat (kg/kg)	1.99 ± 0.07	1.94	2.04	4	1.87	2.10
CMJ height (m)	0.40 ± 0.07	0.35	0.45	16	0.28	0.46
CMJ prop net impulse (N·s)	161.46 ± 21.15	145.79	177.13	13	136.63	194.60
CMJ PP (W)	3329.47 ± 455.85	2991.78	3667.17	14	2755.31	4057.07
CMJ relative PP (W/kg)	58.11 ± 6.95	52.96	63.27	12	47.78	65.65
DSJ height (m)	0.37 ± 0.07	0.32	0.42	19	0.27	0.44
DSJ prop net impulse (N·s)	157.50 ± 19.96	142.71	172.28	13	137.24	187.61
DSJ PP (W)	2886.35 ± 435.76	2563.90	3208.81	15	2213.12	3384.73
DSJ relative PP (W/kg)	50.52 ± 7.98	44.61	56.43	16	38.37	58.26

SD, standard deviation; LL, lower limit; UL, upper limit; CI, confidence interval; CV, coefficient variation; C&J, clean and jerk; CMJ, countermovement jump; PP, peak power; DSJ, deep squat jump.

3.2. Associations for All Subjects

Pearson's correlation coefficients with their associated 95% CI of the relationship between front and back squat foundation strength exercises, CMJ and DSJ force–time metrics, and weightlifting performance are shown in Figure 2 and Table 2. Briefly, the front and back squat 1RMs were significant ($p < 0.001$) and nearly perfectly correlated with snatch and clean and jerk weightlifting performance for all subjects (r = 0.98–0.99). Countermovement jump and DSJ height, propulsive net impulse, and peak power were significant ($p < 0.05$), and strong to nearly perfect correlations were reported for weightlifting performance (r = 0.64–0.98).

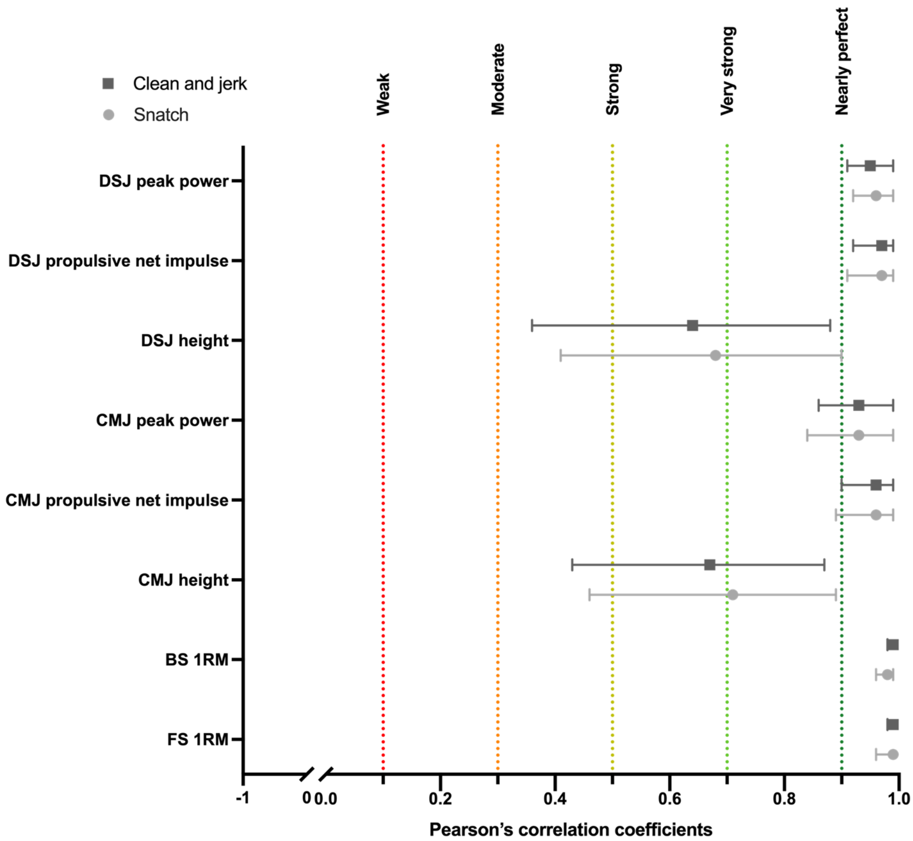


Figure 2. Pearson's correlation coefficients of the relationships between front and back squat foundation strength exercises, vertical jump force–time metrics, and weightlifting performance. DSJ, deep squat jump; CMJ, countermovement jump; BS, back squat; 1RM, one-repetition maximum; FS, front squat. Symbols represent the mean, while bars represent the lower and upper 95% confidence interval.

Table 2. Associations between weightlifting performance, front and back squat maximum strength, and CMJ and DSJ force–time metrics for males and females.

		Males		Females	
Test	**Metrics**	**Snatch Performance (kg)**	**Clean and Jerk Performance (kg)**	**Snatch Performance (kg)**	**Clean and Jerk Performance (kg)**
FS	**1RM** (95% CI) [Interpretation] [Fisher's z]	**r = 0.92** **(0.56–1.00) [Nearly perfect] [1.6]	**r = 0.92** ** (0.57–1.00) [Nearly perfect] [1.6]	**r = 0.88** ** (0.74–1.00) [Very strong] [1.4]	**r = 0.98** *** (0.94–1.00) [Nearly perfect] [2.2]
BS	**1RM** (95% CI) [Interpretation] [Fisher's z]	**r = 0.93** * (0.79–1.00) [Nearly perfect] [1.6]	**r = 0.94** * (0.80–1.00) [Nearly perfect] [1.8]	**r = 0.84** * (0.66–1.00) [Very strong] [1.2]	**r = 0.97** *** (0.84–1.00) [Nearly perfect] [2.2]
CMJ	**Jump height** (95% CI) [Interpretation] [Fisher's z]	r = 0.05 (−0.97–0.92) [Very weak] [0.1]	r = −0.05 (−0.97–0.92) [Very weak] [0.1]	r = −0.02 (−0.95–0.69) [Very weak] [0.0]	r = 0.67 (0.43–0.87) [Strong] [0.81]
	Prop net impulse (95% CI) [Interpretation] [Fisher's z]	**r = 0.96** ** (0.25–1.00) [Nearly perfect] [1.9]	**r = 0.93** ** (0.30–1.00) [Nearly perfect] [1.7]	**r = 0.87** * (0.46–0.99) [Very strong] [1.3]	**r = 0.81** * (0.33–1.00) [Very strong] [1.1]
	Peak power (95% CI) [Interpretation] [Fisher's z]	**r = 0.84** * (−0.22–1.00) [Very strong] [1.6]	**r = 0.81** * (−0.20–0.94) [Very strong] [1.4]	r = 0.67 (−0.05–0.95) [Strong] [0.8]	r = 0.65 (−0.09–0.99) [Strong] [0.8]
DSJ	**Jump height** (95% CI) [Interpretation] [Fisher's z]	r = −0.12 (−0.93–0.97) [Very weak] [0.1]	r = −0.22 (−0.94–0.98) [Very weak] [0.2]	r = 0.67 (−0.05–0.95) [Strong] [0.8]	r = 0.65 (−0.09–0.99) [Strong] [0.8]
	Prop net impulse (95% CI) [Interpretation] [Fisher's z]	**r = 0.96** ** (0.16–1.00) [Nearly perfect] [2.0]	**r = 0.93** ** (0.25–1.00) [Nearly perfect] [1.7]	**r = 0.80** * (0.08–0.99) [Very strong] [1.1]	**r = 0.76** * (0.14–0.99) [Very strong] [1.0]
	Peak power (95% CI) [Interpretation] [Fisher's z]	**r = 0.84** * (−0.22–1.00) [Very strong] [1.6]	**r = 0.81** * (−0.20–0.94) [Very strong] [1.4]	r = 0.53 (−0.24–0.96) [Strong] [0.6]	r = 0.44 (−0.34–0.98) [Moderate] [0.5]

1RM, one-repetition maximum; FS, front squat; BS, back squat; CMJ, countermovement jump; DSJ, deep squat jump; CI, confidence interval. Significant correlations are presented in **bold**. *** $p < 0.001$. ** $p < 0.01$. * $p < 0.05$.

3.3. Associations for Males

The front and back squat 1RMs were significant ($p \leq 0.05$) and nearly perfect correlated with weightlifting performance for males (r = 0.92–0.95) (Table 2 and Figure 3). The countermovement jump and DSJ propulsive net impulse and peak power were significant ($p \leq 0.05$), and very strong to nearly perfect correlations were reported for weightlifting performance (r = 0.81–0.96). In contrast, CMJ height and peak power and DSJ height were not significantly correlated with weightlifting performance for males ($p > 0.05$) (Table 2, Figures 4 and 5).

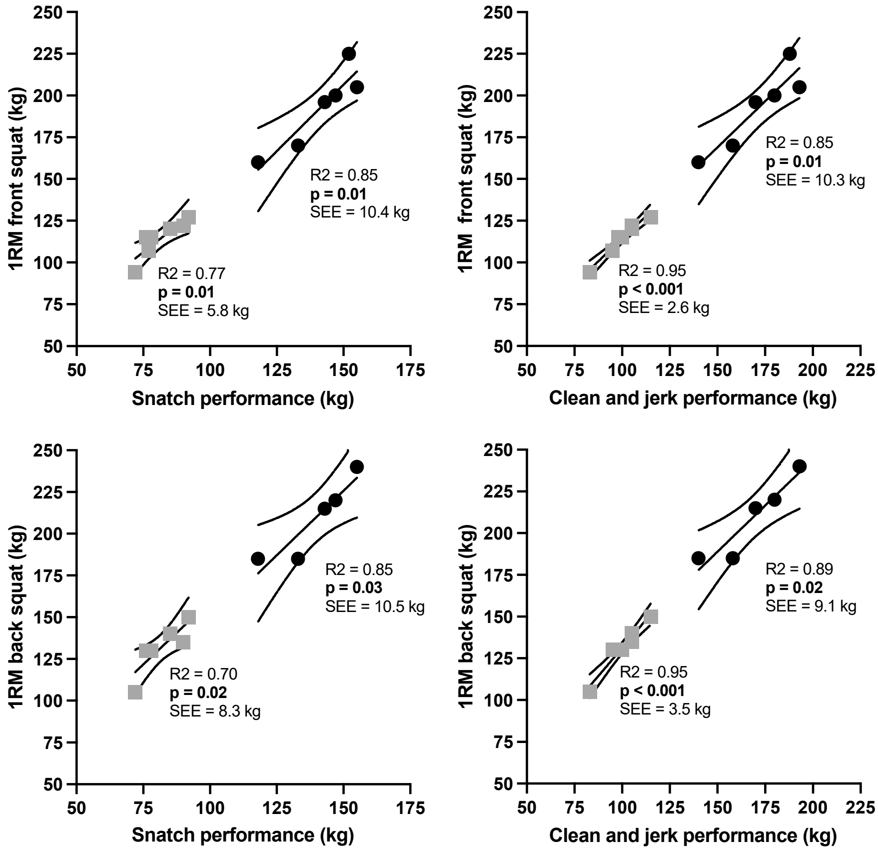


Figure 3. Scatterplots with a linear regression analysis of the front and back squat 1RMs and snatch and clean and jerk performance for males and females separately. Black circles represent male weightlifters. Grey squares represent female weightlifters. 1RM, one-repetition maximum; R2, coefficient of determination; SEE, standard error of the estimate. Statistical significance is presented in **bold**.

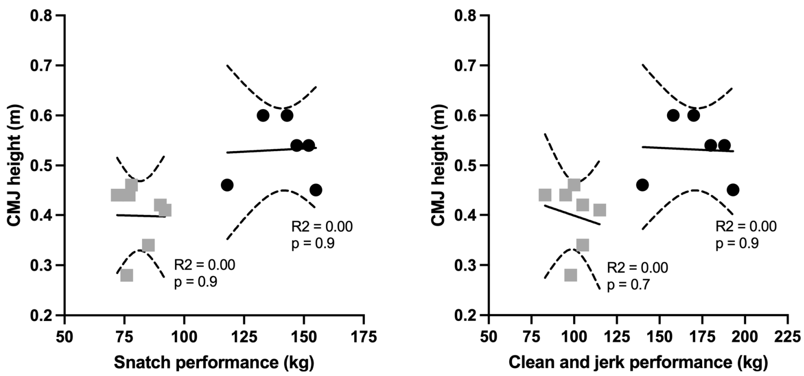


Figure 4. *Cont.*

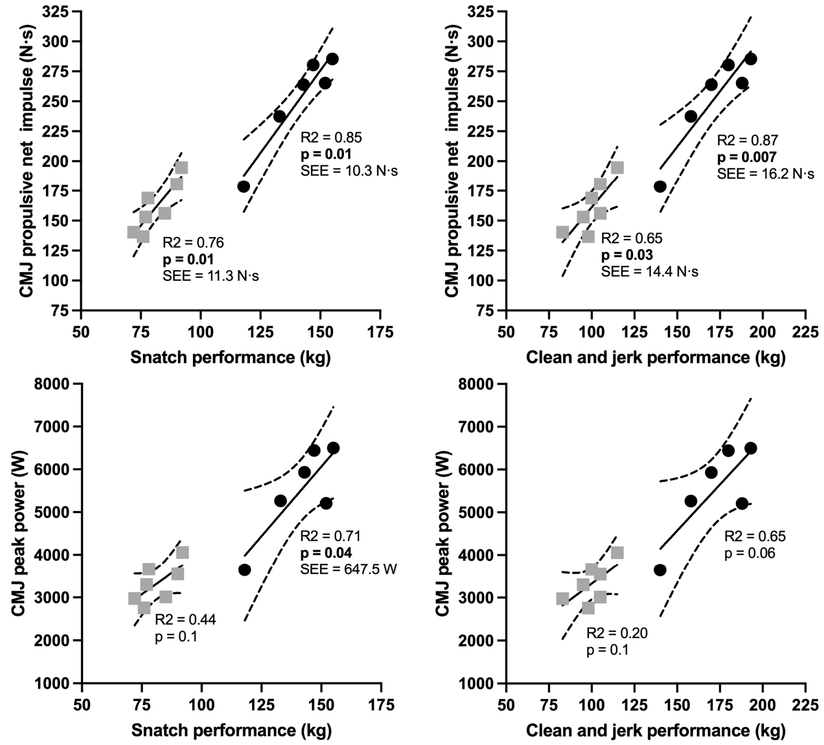
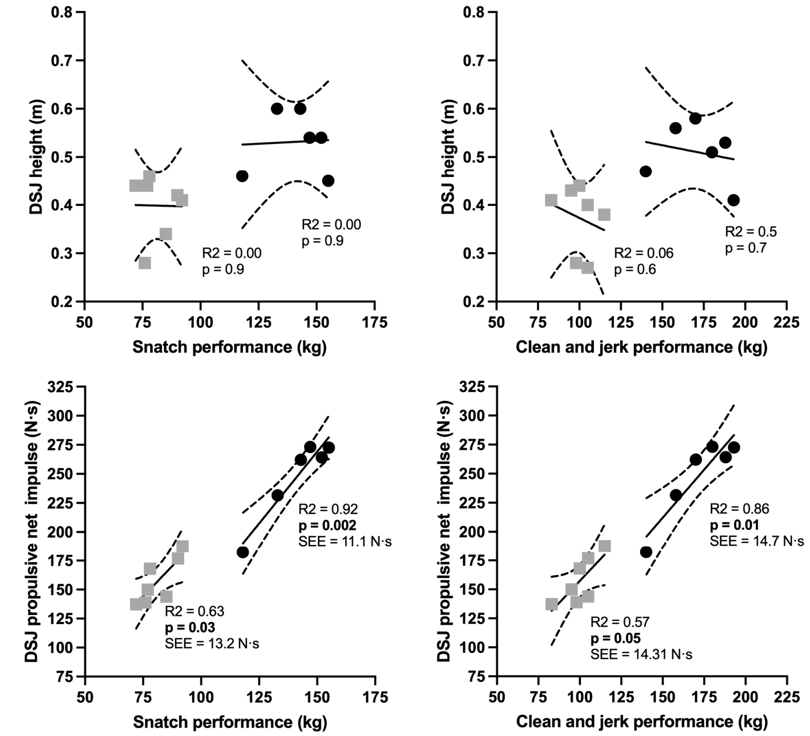


Figure 4. Scatterplots with a linear regression analysis of the CMJ height, propulsive net impulse, and peak power force–time metrics for males and females separately. Black circles represent male weightlifters. Grey squares represent female weightlifters. CMJ, countermovement jump; R2, coefficient of determination; SEE, standard error of the estimate. Statistical significance is presented in **bold**.



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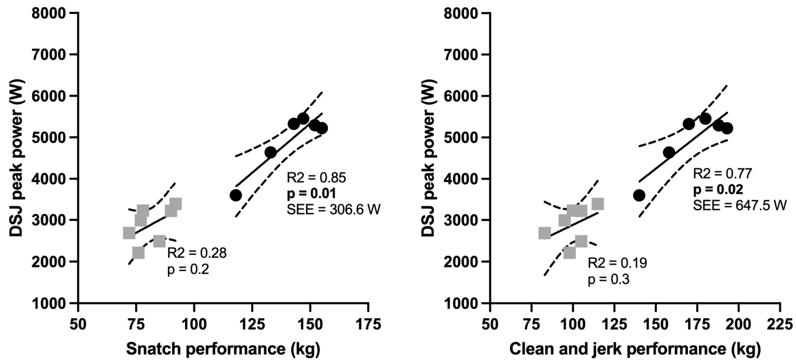

Figure 5. Scatterplots with a linear regression analysis of the DSJ height, propulsive net impulse, and peak power force–time metrics for males and females separately. Black circles represent male weightlifters. Grey squares represent female weightlifters. DSJ, deep squat jump; R2, coefficient of determination; SEE, standard error of the estimate. Statistical significance is presented in **bold**.

3.4. Associations for Females

The front and back squat 1RMs were significant ($p \leq 0.05$), and very strong to nearly perfect correlations were reported with weightlifting performance for females (r = 0.84–0.98) (Table 2 and Figure 3). Countermovement jump and DSJ propulsive net impulse was significant ($p \leq 0.05$), and very strong correlations (r = 0.63–76) were reported with weightlifting performance. In contrast, CMJ and DSJ height and peak power were not significantly correlated with weightlifting performance for females ($p > 0.05$) (Table 2, Figures 4 and 5).

4. Discussion

The aim of this study was to investigate the associations between the front and back squat foundation strength exercises, CMJ and DSJ force–time metrics, and snatch and clean and jerk performance in top-level weightlifters. Based upon the findings of this study, the front and back squat and CMJ and DSJ force–time metrics are closely associated with weightlifting performance during the snatch and clean and jerk in top-level weightlifters. Furthermore, a secondary objective was to determine the force–time metrics that were more strongly associated with weightlifting performance in top-level weightlifters. The findings were two-fold: (1) The CMJ and DSJ propulsive net impulse displayed the closest associations with weightlifting performance (r = 0.76–0.96) for male and female weightlifters. (2) Despite the strong associations between CMJ and DSJ height and weightlifting performance when all subjects were analysed together (r = 0.64–0.71), jump height may be seen as a less promising metric to monitor the neuromuscular capabilities of top-level weightlifters due to the lack of associations when males and females were analysed separately (r = −0.05–0.67). These findings may serve as a useful guidance to weightlifting coaches for selecting adequate tests and force–time metrics to assess the neuromuscular capabilities in top-level weightlifters.

Maximum strength capacity, evaluated using the front and back squat 1RMs, was nearly perfectly correlated with weightlifting performance (r = 0.98–0.99) (Figure 2), as hypothesized. Furthermore, the front and back squat 1RMs were also closely associated with weightlifting performance when males (r = 0.92–0.94) and females (r = 0.84–0.98) were analysed separately (Table 2 and Figure 3). These results are in line with previous work on foundation strength exercises and their association with weightlifting performance [10,11,14]. For example, Lucero et al. [10], Stone et al. [11], and Carlock et al. [14] reported that the front and back squat 1RMs were significant ($p < 0.05$) and nearly perfectly correlated with snatch and clean and jerk performance (r = 0.91–0.95). In contrast, Zecchin et al. [13] found weaker correlations between the front squat and snatch and clean and jerk performance (r = 0.67–0.72). The researchers recruited a sample of 19 male weightlifters, although they were not top-level weightlifters, which may explain the weaker associations. In this study, the six male top-level weightlifters included had higher relative strength levels compared to the data reported by Zecchin et al. [13] for the snatch (1.94 vs. 1.2 kg/kg, respectively), clean and jerk (2.2 vs. 1.5 kg/kg, respectively), and front squat (2.5 vs. 1.8 kg/kg, respectively). Collectively, these results reinforce that the maximum strength in foundation exercises such as the front and back squat is closely associated with weightlifting performance, especially in top-level weightlifters, independently of sex.

In previous studies, the CMJ and squat jump height have frequently been correlated with weightlifting performance because of their ballistic nature, kinetic and kinematic similarities, and practicality to the strength and conditioning coach [4,8,15,25]. In 2009, Vizcaya et al. [6] introduced a novel method for performing a squat jump test from a deep squat position (i.e., DSJ) in weightlifters. The authors found significant ($p < 0.05$) and positive correlations between the DSJ height and weightlifting performance during the snatch, clean and jerk, and weightlifting total (r = 0.75–0.78) and suggested that performing DSJs is highly specific to weightlifters for several reasons. First, the DSJ has a longer distance to accelerate the centre of mass of the lifter throughout the triple extension of the hips, knees, and plantar flexion of the ankles. This longer distance could, in turn, allow the weightlifter more time to apply force, which is common in weightlifting movements, as weightlifters work with a full range of motion (i.e., snatch and clean catch phases, overhead squats, and back and front squats to full depth) [1,16]. Second, because the snatch and clean start from a static position with the muscles stretched and require the lifter to exert rapid concentric forces against the floor with no previous countermovement, the DSJ could be a better reflection of the force exertion at the starting and catching positions of the snatch and clean [6,14]. In contrast, researchers have related the rapid stretch–shortening cycle of the CMJ with the double knee bending of the snatch and clean exercises and the rapid change in the direction of the jerk [25,26]. In our study, very strong to nearly perfect correlations were observed between the CMJ and DSJ propulsive net impulse and peak power and weightlifting performance during the snatch and clean and jerk (Figure 2), suggesting that these metrics evaluated during both tests could be a suitable option to assess the neuromuscular capabilities in top-level weightlifters.

In this study, the CMJ and DSJ heights were significant ($p < 0.05$) and strongly correlated with weightlifting performance (r = 0.65–0.71) for all subjects (Figure 2). However, when they were separated by sex, there were no significant correlations between the jump height and weightlifting performance in males and females (Table 2 and Figures 4 and 5). Weightlifters must generate a net impulse during the propulsive phase of each lift to increase the momentum of the system mass and ultimately transfer it to the barbell [2,7]. The higher the net impulse, the higher the system momentum transferred to the barbell, and, consequently, a higher barbell displacement may be achieved [2]. Similarly, during vertical jumps, weightlifters must generate a net impulse to increase the body mass momentum; the higher the relative net impulse, the higher the resulting take-off velocity, which ultimately determines the jump height. However, the jump height is dependent on the subject's body mass, and therefore, higher jump heights are biased to lighter subjects, although these investigations did not include weightlifters [27,28]. Since weightlifting is a sport that includes weight categories, some weightlifters usually go down in weight category prior to competitions and they may jump higher (i.e., positive change) with negative or no changes in their associated propulsive net impulse [7]. Consequently, the jump height may not reflect the actual neuromuscular capabilities in top-level weightlifters, especially when males and females are evaluated separately, and the use of force–time metrics such as the net impulse may be critical to adequately assess their ballistic performance.

The utilization of force plates as an affordable option for practitioners has resulted in an increasing interest in force–time metrics and their associated methodology to assess the neuromuscular capabilities of weightlifters [4,7]. For example, Chavda et al. [7] found that the CMJ propulsive impulse, which is dependent on the force generated and duration of the propulsion phase, was significantly and strongly correlated with weightlifting performance ($p < 0.004$, r = 0.68–0.82). However, they found that the CMJ propulsive impulse duration was not significant and was weakly correlated with weightlifting performance ($p > 0.004$, r = 0.22–0.28), suggesting that the net force developed during the propulsive phase of the CMJ was the primary factor between CMJ propulsion impulse and weightlifting performance. These findings align with our results, where we also found significant and nearly perfect correlations between CMJ and DSJ propulsive net impulse and weightlifting performance ($p < 0.001$, r = 0.96–0.98) for all subjects and also when differentiating by sex (males: $p < 0.05$, r = 0.93–0.96; females: $p < 0.05$, r = 0.76–0.87) (Table 2, Figures 4 and 5). Since weightlifters are heavily dependent on their lower body force generation capacity, the force–time metrics during the CMJ and DSJ can potentially be a better reflection of the ballistic neuromuscular capabilities of top-level weightlifters.

To the best of our knowledge, this is the first study that includes a correlation analysis of front and back squat maximum strength, CMJ and DSJ force–time metrics, and weightlifting performance in top-level weightlifters. In our study, prediction equations from the regression analysis are not shown since the biggest limitation of this study is the inclusion of a small and heterogenous sample size (n = 13; 6 males and 7 females) of selected top-level weightlifters, which may be difficult to extrapolate to weightlifters of other levels (i.e., national and amateur). Additionally, because weightlifters were in different weight categories and weightlifting performance is ultimately related to weight category, predicting the snatch and clean and jerk performance could have been an important flaw. Furthermore, Joffe et al. [12] used a stepwise multiple regression analysis to predict weightlifting performance in top-level female weightlifters and found that the isometric mid-thigh pull peak force and CMJ peak power accounted for 91–95% of the variance for the snatch, clean and jerk, and weightlifting total. However, Joffe et al. [12] employed a longitudinal analysis to test the feasibility of the cross-sectional evaluations in female weightlifters and reflect how the changes in their neuromuscular capabilities affect weightlifting performance over the season. Future research with top-level weightlifters should address this issue with a similar approach to offer guidance to the strength and conditioning professionals working with male and female top-level weightlifters [12,17,18]. Individual confounding factors such as the subjects' diet, sleep, or recovery may have influenced the results of this study. These results were taken during the tapering prior to the IWF World Weightlifting Championships and may not represent other phases of a given training cycle.

5. Conclusions

In conclusion, front and back squat foundation strength exercises and CMJ and DSJ force–time metrics are closely associated with weightlifting performance during the snatch and clean and jerk in top-level weightlifters. The CMJ and DSJ propulsive net impulse displayed the closest associations with weightlifting performance, while jump height may be seen as a less promising metric to monitor the neuromuscular capabilities of top-level weightlifters. Therefore, practitioners should monitor the maximal strength and ballistic capabilities of top-level weightlifters, as well as their performance in snatch and clean and jerk, during every training cycle. This approach will provide a more detailed description of the changes in their neuromuscular performance. Practitioners are also encouraged to use propulsive net impulse and peak power force–time metrics instead of jump height to provide a more accurate description of the association between the neuromuscular capabilities and weightlifting performance in top-level weightlifters.

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