The relationship of lower-body, multi-joint isometric and dynamic neuromuscular assessment variables with snatch and clean & jerk performance in competitive weightlifters. A Meta-Analysis.

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ABSTRACT

The purpose of this meta-analysis was to synthesize the literature and provide a robust estimate of the correlations between lower body multi-joint isometric and dynamic neuromuscular assessment variables with Snatch (SN) and Clean & Jerk (C&J) performance in competitive weightlifters. A comprehensive search via three electronic databases (PubMed, SPORTDiscus and Web of Science) returned 12 studies that met the inclusion criteria. Meta-analyses were performed on Pearson's correlations between SN and C&J with 15 variables from five neuromuscular assessments – countermovement jump (CMJ), squat jump (SJ), isometric mid-thigh pull (IMTP), and back squat (BS) and front squat (FS) one-repetition-maximum (1-RM). The FS and BS 1-RM exhibited *nearly perfect* correlations (r = 0.93 to 0.94), whereas the IMTP peak force exhibited *very large* correlations (r = 0.83 to 0.85). The IMTP force at 250 ms exhibited *very large* correlations (r = 0.77 to 0.78) and the CMJ and SJ peak power exhibited *very large* to *nearly perfect* correlations (r = 0.88 to 0.92). These findings illustrate the importance of lower body maximal and time-limited force producing capabilities in weightlifters. Moreover, each assessment offers at least one variable that exhibit a correlation > 0.70, therefore may be used to gauge weightlifting performance potential.

KEY WORDS: mid-thigh pull, jump, force, power, rate of force development, weightlifting

INTRODUCTION

In the sport of weightlifting, performance is measured based on the combined weight (Total) of the heaviest successful attempts of the snatch (SN) and clean & jerk (C&J). From a fundamental mechanical standpoint, Newton's second law of motion (F = ma) states that to lift a greater mass over a set vertical displacement, a greater vertical impulse must be applied. However, it is widely accepted that in the SN and C&J, proficient technique is necessary to effectively transfer the applied impulse into the ground, to the vertical acceleration of the barbell (14,35). Plausibly, only once an efficient and stable technique has been established, is weightlifting performance then primarily limited by the capacity to generate impulse through the lower body.

Several studies have reported that weightlifters of a higher competitive level exhibit more technically efficient barbell and joint kinematic characteristics compared with their lower-level counterparts (8,22,29,38). In addition, elite weightlifters express greater relative force outputs for the same percentage of their maximum lift compared with sub-elite weightlifters (22). Based upon these findings, improvements in technical efficiency enable a greater capacity to generate vertical impulse during these lifts. With long-term continued technical refinement, improvements in performance, therefore, increasingly rely upon the adaptations to training that lead to a greater capacity to generate impulse by increasing the rate and magnitude of vertical ground reaction forces through the coordinated extension of the hip, knee, and ankle.

In the physical preparation of weightlifters, it is imperative that coaches evaluate the neuromuscular characteristics that closely associate with performance. This information can help to identify limitations in the athlete's physical profile, align specific training strategies to address these deficits, determine the efficacy of training interventions, and quantify any subsequent transfer to performance (44). It has also been suggested that many of these assessment variables may serve as surrogate measures of weightlifting performance (33), offering coaches a means of accurately gauging performance potential, eliminating the need to conduct maximal testing on the SN and C&J outside of competition phases of training. Alternatively, in the final training blocks leading into a competition, knowledge of this performance potential may also aid in the strategic planning of weight selection for attempts in the SN and C&J both in training and at the competition itself. Whilst the assessment of SN and C&J one-repetition maximum (1-RM) in training are important given that they provide the most valid representation of performance level and are easily integrated into the athletes training schedule, these data are limited in their ability to identify specific deficits in the athlete's neuromuscular characteristics that underpin performance. Rather, the addition of specific neuromuscular assessments that reflect these characteristics may provide coaches with the most complete set of objective data to inform their prescription of physical and technical training across different phases of the periodised cycle.

A series of lower body, multi-joint isometric and dynamic assessments have been used to evaluate these neuromuscular characteristics in weightlifters. Each of these assessments vary in their kinetic and kinematic properties, muscle contraction types and reliance on stretch-shortening cycle function, hence are reflective of different mechanisms of force production. The most common types of assessments include isometric and dynamic measures of maximal strength and rate of force development (RFD) and jump-based measures of propulsive force and power output. Each have been adopted based upon their biomechanical specificity to the SN and C&J (21,39,40).

Numerous studies have investigated the relationships between these lower-body neuromuscular assessments with weightlifting performance, however to date, there has been no systematic review of these findings. A meta-analysis would provide a comprehensive synthesis of multiple independent studies and provide a more accurate estimate of the correlations between lower body neuromuscular assessment measures and weightlifting performance. A better understanding of these relationships would help inform coaches and sports scientists of the most appropriate assessments and variables to examine the strength characteristics which underpin performance and evaluate performance potential of weightlifters, leading to better practices in the physical, technical, and tactical preparations for competition. Therefore, the aim of this meta-analysis is to conduct a comprehensive synthesis of the literature, to provide a robust estimate of the correlations between lower body multi-joint isometric and dynamic neuromuscular assessment variables with SN and C&J performance in competitive weightlifters.

METHODS

Search Strategy

The present meta-analysis was performed in accordance with the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (51). As no health-related outcomes were measured, this review was not registered. The following search string was used: ("Olympic Weightlifting" OR "Olympic weightlifter" OR "Olympic lifting" OR weightlifting OR weightlifter OR snatch OR "clean and jerk") AND (isometric OR "isometric mid-thigh pull" OR "mid-thigh pull" OR "start position" OR "first pull" OR "isometric squat" OR "back squat" OR "front squat" OR squat OR "countermovement jump" OR "squat jump" OR "jump squat" OR "vertical jump" OR strength OR "peak force" OR "peak power" OR "rate of force development" OR neuromuscular) AND (correlation OR determinant OR predictor OR relationship OR association OR difference).

Eligibility Criteria

Studies were considered eligible for inclusion if they met all of the following criteria: (I) were an original research study, published in a peer reviewed English language journal with available full-text; (II) examined competitive male or female weightlifters within the International Weightlifting Federation's defined youth, junior and senior level age group categories (ages 13 to 35 years old); (III) investigated the correlations between a lower body multi-joint isometric or dynamic neuromuscular assessment with SN or C&J; (IV) reported either Pearson's r or R^2 values; (V) reported kinetic, kinematic or absolute strength measures. Articles were excluded based upon the following criteria (I) were review articles, conference proceeding, book chapters or abstracts; (II) exclusively reported either performance or assessment variables as scaled to body mass, allometrically scaled to body mass or using the Sinclair formula, and correlation data between absolute measures were unobtainable from the authors. Relative and scaled measures were excluded considering that weightlifting performance is fundamentally determined by the absolute load lifted in the SN and C&J irrespective of body mass. The focus of this investigation was to examine the correlates of performance as measured in competition.

Information Sources and Selection Process

The literature search was performed using PubMed, SPORTDiscus and Web of Science electronic databases in July 2022. The reference lists of the retained articles were examined for further relevant articles not identified through the database searches. The articles retrieved from the search strategy were exported into a customized Microsoft Excel spreadsheet. Once duplicates were removed, two of the authors (SAJ and JT) independently examined each article's title, abstract and full text to determine their fulfilment of the inclusion and exclusion criteria. Any disagreement between authors on articles for inclusion was resolved by consulting a third author (PP).

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Data Collection Process & Data Items

Data from the included studies were extracted by one author (SAJ) and compiled in a customized spreadsheet in Microsoft Excel. All data were verified by a second author (JT) and were agreed upon prior to analysis. The following information was extracted from the available texts.

- Subject descriptive data: sample size, sex, age, body mass and competitive level.
- Weightlifting performance: Assessment conditions and 1-RM of the SN or C&J
- Neuromuscular assessment data: Assessment type, relevant equipment specifications, and variables examined
- Pearson's correlations between neuromuscular assessment and weightlifting performance measures

Where weightlifting performance or neuromuscular data were reported relative to body mass, allometrically scaled to body mass, using the Sinclair formula, or where there were missing data; and were within ten years from the date of the literature search, the lead authors of the articles were contacted requesting the mean ± standard deviation for all absolute performance and assessment variables and their correlations. Where these data were not obtained from the authors, the articles were excluded from analysis. Study data were collected and arranged according to assessment type and reported variables. Different neuromuscular assessments representative of the same broad physical quality (e.g., maximal strength: IMTP PF and Back Squat (BS) 1-RM), were purposefully analyzed independently through separate meta-analyses to determine the specific assessment variable correlations with performance. Due to the large number of time-dependent force-time variables and inconsistencies in the time intervals over which they are examined between studies, these variables were grouped within 0-100 ms, 101-200 and ms 201-250 ms time epochs. For example, where a study reports F@90 ms or RFD0-90 ms, these would fall within the F@100 ms and RFD0-100 ms groups, respectively.

Study Quality Analysis

The evaluation of each article's quality was performed by two authors (SAJ and SC) using the Appraisal Tool for Cross-Sectional Studies (AXIS Tool) (11). Studies were evaluated against 17 criteria as three of the original 20 criteria (7, 13 and 14) were excluded from the analysis as they were not relevant to the type of study included in this meta-analysis. For each criterion, studies were awarded one point if the requirements were met, or zero points if not met.

Statistical Analysis

Meta-analyses were conducted using a random-effects model to account for the standard error associated with each included study, and because it was assumed that the correlation between neuromuscular assessment variables and weightlifting performance across all studies were *not* estimating the same effect. Separate meta-analyses were performed for correlation values for each assessment variable, where at least two studies examined the correlation with SN or C&J. The heterogeneity of studies was evaluated using Cochran's Q statistic and the inconsistency (I^2) statistic. The I^2 values were interpreted as < 25% = low risk, 25 to 75% = moderate risk, > 75% = high risk of heterogeneity (25). In accordance with The Cochrane Handbook for Systematic Reviews of

Interventions (24) section 9.5.3 ‘strategies for addressing heterogeneity’, where I^2 values exceeded 50%, a ‘one-study-removed’ analysis was performed in addition, as part of a sensitivity analysis to determine the influence of any outlying studies. The one-study-removed analysis retained the meta-analysis which resulted in the lowest heterogeneity based on the I^2 value, however, the data are reported for both models. The meta-analyses were performed using Comprehensive Meta-Analysis software (Version 3; BiostatInc. Englewood, USA) correlation analysis function. The correlation effect size for each meta-analysis were calculated using Fisher-Z transformation, subsequently allowing for the calculation of the standard error and 95% confidence intervals (CI). Z-transformed correlation values were calculated using the following formula:

$$z_r = 0.5 \times \ln\left(\frac{1+r}{1-r}\right)$$

where *r* is the Pearson’s correlation *r* value and ln is the natural logarithm. The variance was calculated as:

$$V_z = \frac{1}{n-3}$$

where n is the sample size. The standard error (SE) was calculated using the following formula:

$$SE_z = \sqrt{V_z}$$

and the 95% confidence intervals for z_r were calculated as:

$$\left[z_r - z_{c/100} \times \frac{1}{\sqrt{n-3}}, z_r + z_{c/100} \times \frac{1}{\sqrt{n-3}}\right]$$

where $z_{c/100}$ is the critical z value (95% CI = $z_{0.95}$ =1.96), and where $1 / \sqrt{n-3}$ s the SE_z. To convert the data back to Pearson’s *r,* from z_r, the inverse equation for Fisher-Z was used:

$$r = \frac{e(2 \times z_r) - 1}{e(2 \times z_r) + 1}$$

where *e* is the natural logarithm base and z_r is the z-transformed correlation value. Each studies relative weighting was determined according to their standard error within the random effects model. Where studies included multiple time-dependent force-time variables within the same time epoch, reported correlations at multiple time points of a training intervention (e.g., pre and post) or reported gross and net measures of force output, the correlations were converted to z_r, then averaged and subsequently converted back to r using the same formulas stated above. Statistical significance was set at $p < 0.05$. All meta-analyses are displayed in forest-plots with 95% CI's. All correlations were interpreted with the following descriptive criteria: 0 to 0.09 = *trivial*, 0.10 to 0.29 = *small*, 0.30 to 0.49 = *moderate*, 0.50 to 0.69 = *large*, 0.70 to 0.89 = *very large*, 0.9 to 0.99 = *nearly perfect*, 1 = *perfect* (27).

RESULTS

Study Selection

The PRISMA flow chart illustrating the systematic search process is outlined in Figure 1. The initial database search returned 1,592 articles. Following the removal of duplicates, 1220 articles remained and were screened for eligibility based on their title and abstract. Twenty-three articles were sought for full text, one of which was unobtainable (55). Unreported data were sought and obtained from five articles (28,30,61,65,66), however data from one article were not available (60). Twenty-one full text articles were evaluated for eligibility, of which seven were excluded, leaving 12 articles for inclusion in the meta-analyses.

Study Characteristics

A total of 395 subjects (252 males, 143 females) across 12 studies were included in the analyses. All subjects were reported as competitive collegiate, national, or international level weightlifters. The mean age range across studies was between 15 and 30 years old. All included studies examined the relationship between a lower body neuromuscular assessment with the SN and C&J performance. Weightlifting performance was measured within a weightlifting competition in eight studies (4,20,28,30,32,33,57,61), whereas three studies evaluated weightlifting performance under competition conditions in a laboratory (28,65,66). Three studies used self-reported 1-RM values for the SN and C&J (6,39,57). Two of the above studies used a combination of methods for the weightlifting performance assessment (28,57). Regarding the neuromuscular assessments, six studies investigated the IMTP (4,20,28,32,33,57), six studies investigated the countermovement jump (CMJ) (6,20,30,33,61,65), five studies investigated the squat jump (SJ) (6,20,28,30,61) three studies investigated BS (39,57,66) and two studies investigated the front squat (FS) (39,66). A detailed description of the study characteristics is outlined in Tables 2 and 3.

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Quality Assessment

The results of the quality analysis of the articles using the Downes et al. (11) AXIS tool is outlined in Table 1. The included studies scores ranged between 11 to 16 (65 to 94%) and a mean ± SD of 13.7 ± 1.5 (81% ± 9%). One study scored 16 (94%), four studies scored 15 (88%), two studies scored 14 (82%), two studies scored 13 (76%), two studies scored 12 (71%) and one study scored 11 (65%).

Correlation Between Countermovement Jump Variables with Weightlifting Performance

Countermovement jump PD exhibited a *large* correlation with SN (r = 0.68, 95% CI [0.54, 0.79], p < 0.001, n = 203) (Fig 2a). However, the meta-analysis of correlations between CMJ PD with C&J (r = 0.66, 95% CI [0.48, 0.78], p < 0.001, n = 203), showed a *moderate* level of heterogeneity between studies with an I^2 value exceeding 50% (Q = 12.8, I^2 = 53%, p = 0.046). Therefore, the study by Haff et al. (20) was removed based on the 'one-study-removed' process. This resulted in low heterogeneity between studies (I^2 = 15.9%, p = 0.312) and an overall *large* correlation between CMJ PD and C&J (r = 0.69, 95% CI [0.59, 0.77], p < 0.001, n = 197) (Fig 3a).

Countermovement jump PP exhibited a *nearly perfect* correlation with SN (r = 0.92, 95% CI [0.88, 0.95], p < 0.001, n = 94) (Fig 2b) and a *very large* correlation with C&J (r = 0.88, 95% CI [0.82, 0.93],

$p < 0.001$, n = 94) (Fig 3b). Furthermore, CMJ PF showed no statistically significant correlations with SN (r = 0.43, 95% CI [-0.27, 0.83], p = 0.225, n = 24) (Fig 2c). The meta-analysis of correlations between CMJ PF with C&J also exhibited no significant correlation with C&J (r = 0.44, 95% CI [-0.03, 0.75], p = 0.067, n = 24), however showed a *moderate* level of heterogeneity between studies with an I^2 value exceeding 50% (Q = 4.96, I^2 = 59.7%, p = 0.084). Therefore, the study by Zaras et al. (65) was removed based on the 'one-study removed' process. This resulted in a significant *large* correlation (r = 0.69, 95% CI [0.22, 0.90], p = 0.008, n = 18), and low heterogeneity (Q = 0.88, I^2 = 0%, p = 0.349). (Fig 3c). Lastly, CMJ PV exhibited similarly *large* correlations with SN (r = 0.66, 95% CI [0.28, 0.86], p = 0.002, n = 24) (Fig 2d) and C&J (r = 0.69, 95% CI [0.24, 0.89], p = 0.006, n = 24) (Fig 3d).

Correlation Between Squat Jump Variables with Weightlifting Performance

Squat Jump PD exhibited *very large* correlations with SN (r = 0.70, 95% CI [0.50, 0.80], $p < 0.001$, n = 186) (Fig 2e) and C&J (r = 0.70, [0.53, 0.79], $p < 0.001$, n = 186) (Fig 3e). Furthermore, SJ PP exhibited *nearly perfect* correlations with SN (r = 0.92, 95% CI [0.87, 0.95], $p < 0.001$, n = 77) (Fig 2f) and C&J (r = 0.90, 95% CI [0.75, 0.96], $p < 0.001$, n = 77) (Fig 3f).

Correlation Between Isometric Mid-Thigh Pull Variables with Weightlifting Performance

Isometric mid-thigh pull PF exhibited *very large* correlations with SN (r = 0.83, 95% CI [0.73, 0.90], $p < 0.001$, n = 71) (Fig 2g) and C&J (r = 0.85, 95% CI, [0.76, 0.91], $p < 0.001$, n = 71) (Fig 3g). Furthermore, both IMTP F@100 ms and F@200 ms each exhibited *large* correlations with SN (r = 0.61, 95% CI [0.17, 0.85], p = 0.010, n = 19 and r = 0.66, 95% CI [0.24, 0.87], p = 0.004, n = 19, respectively) (Fig 2h & 2i) and C&J (r = 0.62, 95% CI [0.18, 0.85], p = 0.005, n = 19 and r = 0.66, 95% CI [0.24, 0.87], p = 0.004, n = 19, respectively) (Fig 3h and 3i). Additionally, IMTP F@250 ms exhibited *very large* correlations with SN (r = 0.77, 95% CI [0.44, 0.91], $p < 0.001$, n = 19) (Fig 2j) and C&J (r = 0.78, 95% CI [0.47, 0.92], $p < 0.001$, n = 19) (Fig 3j).

Isometric mid-thigh pull RFD0-100 ms exhibited a *large* correlation with SN ($r = 0.51$, 95% CI [0.01, 0.80], $p = 0.044$, n = 19) (Fig 2k), however, showed no statistically significant correlation with C&J ($r = 0.49$, 95% CI [-0.01, 0.79], $p = 0.052$, n = 19) (Fig 3k). Furthermore, IMTP RFD0-200 ms exhibited *large* correlations with SN ($r = 0.60$, 95% CI [0.15, 0.84], $p = 0.013$, n = 19) (Fig 2l) and C&J ($r = 0.56$, 95% CI [0.09, 0.83], $p = 0.021$, n = 19) (Fig 3l). Lastly, IMTP PRFD Exhibited a *large* correlation with SN ($r = 0.55$, 95% CI [0.10, 0.84], $p = 0.022$, n = 18) (Fig 2m), however, showed no statistically significant correlations with C&J ($r = 0.46$, 95% CI [-0.07, 0.79], $p = 0.087$, n = 18) (Fig 3m).

Correlation Between Back Squat and Front Squat 1-RM with Weightlifting Performance

The BS and FS 1-RM exhibited similar *nearly perfect* correlations with SN ($r = 0.93$, 95% CI [0.90, 0.95], $p < 0.001$, n = 145 and $r = 0.94$, 95% CI [0.84, 0.98], $p < 0.001$, n = 77, respectively) (Fig 2n and 2o) and C&J ($r = 0.93$, 95% CI [0.90, 0.95], $p < 0.001$, n = 145 and $r = 0.94$, 95% CI [0.91, 0.96], $p < 0.001$, n = 77, respectively) (Fig 3n and 3o).

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DISCUSSION

The aim of this meta-analysis was to conduct a comprehensive synthesis of the literature to provide a robust estimate of the correlations between lower body multi-joint isometric and dynamic neuromuscular assessment variables with SN and C&J performance in competitive weightlifters. Analyses were performed across five neuromuscular assessments which yielded fifteen assessment variables. The FS and BS 1-RM illustrated *nearly perfect* correlations with both competition lifts. Furthermore, PP in both jump-based assessments (CMJ and SJ) illustrated *very large* to *nearly perfect* correlations, whereas PF and F@250 ms in the IMTP revealed *very large* correlations. These findings firmly support the importance of maximal and time-limited force producing capabilities of the lower body in weightlifters. Moreover, these findings illustrate that each of the assessments commonly used to evaluate neuromuscular characteristics in weightlifters, offer at least one variable that exhibits a correlation > 0.70 (*very large*), and therefore may be used to gauge weightlifting performance potential.

Association between CMJ and SJ variables with Performance.

Similar *large* to *very large* correlations were observed between CMJ and SJ PD with SN and C&J. In addition, similar *very large* to *nearly perfect* correlations were observed between CMJ and SJ PP with both lifts. Although each of these jumps have distinctly different techniques, where the CMJ is initiated with an 'unweighting' and 'braking' eccentric phase and the SJ initiated from a static position, both jumps display similar kinetic and kinematic characteristics during their respective concentric phases (26,45). Furthermore, they consistently show *nearly perfect* correlations ($r \geq 0.90$) with each other (6,20,30,61,62). Indeed, this suggests that the CMJ and SJ largely reflect a similar ability to generate mean propulsive impulse to project one's body mass into a flight phase, albeit dependent on slightly different underpinning mechanisms. Given the similar correlations between the two jumps with SN and C&J performance, a testing battery for weightlifters may not warrant both jump assessments when evaluating PD or PP. However, these tests may each offer unique insight into muscle-contraction specific or time-dependent characteristics (12,26), which may be of particular interest to weightlifters. No studies to date appear to have investigated this, therefore future research should consider examining these vertical jump variables in relation to weightlifting performance.

The observed *large* to *very large* correlations between CMJ and SJ PD and PP with weightlifting performance is expected, given the temporal, kinetic and kinematic similarities of the concentric phase of the two jumping techniques with the transition and second pull phases of the SN and clean (5,14,40) and the drive phase of the jerk (10). Each of the studies to date examining the biomechanical similarity between the weightlifting movements and vertical jumping (5,10,14,40) collectively demonstrate distinct resemblances in their impulse curves, particularly the high RFD achieved through a coordinated patterns of hip, knee and ankle extension during the propulsive phase. This likely explain the strength of these correlations observed in the meta-analysis.

It should be considered, however, that the PD variable reflects the capacity to express vertical impulse relative to body mass (36). Given the non-linear relationship between maximal muscular force capacity with increasing body mass (31), this variable may underrepresent the relationship between jumping ability and weightlifting performance when evaluated across the breadth of weight categories, where body mass may range from ≤45 kg to >109 kg. The assessment of this jump variable may also be problematic in weightlifters given that considerable fluctuations in body mass within an individual athlete are commonly reported across different phases of the training cycle (58). The PD variable, therefore, may be suboptimal as a metric to evaluate and monitor ballistic contractile characteristics of the lower body in weightlifters over time.

The CMJ and SJ PP exhibited similar *very large* to *nearly perfect* correlations with SN and C&J performance, and noticeably larger than that with PD. This trend is consistent with all studies that have examined correlations between both CMJ PP and PD in relation to weightlifting performance (6,20,33). Power output describes the rate at which work is performed. Given the limited time and distance over which force can be applied in the second pull phase of the lifts (17), PP is reasonably considered a vital neuromuscular characteristic associated with superior weightlifting performance. However, this variable has also previously been scrutinized in its relationship to athletic performance (64). The ability to vertically displace an object into an arial phase (e.g., a vertical jump or snatch lift) is dependent on its final velocity achieved (release or take-off velocity), determined by the impulse-momentum relationship. The muscular capacity to generate impulse rather than power is ultimately the causal factor to an object's acceleration and is therefore arguably the more appropriate variable to evaluate ballistic contractile characteristics. The higher correlation between PP with SN and C&J compared with PD, may be attributed to the fact that body weight is included in the calculation of power output (7) which is a strong determinant of weightlifting performance (53).

Across all the included studies, PV and PF were only evaluated in the CMJ assessment. Unsurprisingly, CMJ PV showed a similar *large* correlation with SN and C&J, to that with PD. This is to be expected given that jump PD can be calculated from the take-off velocity (47) which coincides with the PV of a body weight vertical jump (7). Hence, the CMJ PV corresponds directly to CMJ PD and consequently, is reflective of the same physical capacity. The CMJ PV, however, may provide additional information on the load-, force- or power-velocity relationships when combined with the analysis of additional loaded jumps (48). To the best the authors knowledge, this has not been investigated in relation to weightlifting performance, therefore should also be a consideration for future research.

The meta-analysis examining the relationship between CMJ PF with C&J performance, initially exhibited no correlation. However, as the I^2 value exceeded 50%, a ‘one removed analysis’ was performed eliminating the study by Zaras et al. (65), resulting in a *large* correlation and *low risk* of heterogeneity. On the contrary, no significant correlation was observed between CMJ PF with SN performance. However, the I^2 value fell marginally below the criteria to conduct a ‘one removed analysis’ which would likely have resulted in a similar result observed for the C&J. The lack of correlation between CMJ PF with SN performance may also be attributed to PF only representing force output at an instantaneous time point, rather than the net impulse generated during the jump, which ultimately determines the acceleration and displacement of the mass to which it is applied. These findings are inconsistent with previous reports that have found *very large* correlations (r = 0.79 to 0.84) between CMJ PF and BS 1-RM and power clean 1-RM performance in a non-weightlifting athletic population (50). Similarly, CMJ absolute and relative PF have illustrated *very large* to *nearly perfect* correlations (r = 0.70 to 0.91) with other athletic performances such as 10 m and 60 m sprint times in track and field athletes (42,43). This discrepancy in the strength of the correlation between CMJ PF with athletic performance measures between studies in unclear. The CMJ PF variable may provide some insight into the ballistic force-generating characteristics that are relevant to athletic performance. However, future studies examining vertical jump-based assessments in relation to weightlifting performance should more importantly consider investigating the characteristics of the impulse curve to enable a better mechanistic understanding of changes in force expression and how this may associate with weightlifting performance.

Association Between Isometric Mid-Thigh Pull Variables with Performance.

The IMTP PF exhibited *very large* correlations with SN and C&J, which substantiates the importance of assessing and developing maximal force capacity in a mechanically specific position to the start of the second pull (9). Several studies have shown that the second pull phase of the SN and clean exhibit the greatest vertical ground reaction forces (2,34,35,54), power output and barbell velocity (17,19,23,37) compared with all other phases of the lift. Therefore, it is reasonably expected that the maximal force capacity within this position should demonstrate a *very large* correlation with the two competition lifts. However, it should also be considered that the final vertical velocity (and therefore vertical displacement) at the end of the pull, is a product of the impulse generated across all phases of the pull, including the first pull and transition. As the generated impulse during each of these phases contribute substantially to the final vertical barbell velocity, the maximal force capacity across each of the pull phases may also be important limiting factors to performance. A recent study by Joffe et al. (32) showed that PF in the isometric pull from the start position (IPSP) of the clean exhibited greater correlations with SN and Total compared with the IMTP (SN: $r = 0.94$ vs 0.83; Total: $r = 0.95$ and 0.86, respectively). Furthermore, when body mass was controlled for by allometrically scaling the assessment and performance variables, no significant correlations were observed between the IMTP and IPSP PF values, indicating that these are representative of separate neuromuscular capacities. This supports the importance of assessing and developing maximal strength, however, suggests that maximal strength should be evaluated in relation to the specific phases of the lifts. Unfortunately, as this is the only study to date to have investigated this assessment, it was therefore not included within the meta-analyses.

Given that the time available to express force during the second pull phase has been found to occur between 120 and 190 ms (15–19), the maximal force applied within a comparable time interval should plausibly exhibit greater correlations with performance measures than IMTP PF. Surprisingly, the F@100 ms, F@200 ms, RFD0-100 ms, RFD0-200 ms and PRFD revealed only *large* correlations or no correlation (RFD0-100 ms vs C&J and PRFD vs C&J) with weightlifting performance, while F@250 ms was the only time-dependent force-time variable that revealed *very large* correlations with SN and C&J. A discernible trend in the data indicates that for the IMTP force-time variables, the correlation with SN and C&J performance increases with increasing time available to produce force. This implies that maximal strength is a greater determinant of weightlifting performance than RFD. It should be acknowledged however, that the earlier time epochs of time-limited force-time variables in the IMTP exhibit weaker reliability statistics compared with the latter time epochs (4). This may conceivably influence the magnitude of the correlations causing the latter time epochs to exhibit the greater correlations with SN and C&J. Furthermore, the method for determining these time epochs is not reported within the included studies, therefore any inconsistencies between studies may also potentially lead to error in these results. These are important considerations for future studies intending to examine these variables in relation to weightlifting performance.

Another possible explanation for this trend, is that RFD is evaluated under isometric conditions. Whilst this has been suggested as a more appropriate method for evaluating RFD, controlling for changes in joint angular velocity and displacement (41), it does not reflect the dynamic conditions under which force is expressed during the pull phase of the SN or C&J. Only a single study has examined the relationship between PRFD in a dynamic clean pull at 30% of IMTP PF and at 100 kg in relation to SN and C&J performance (20). Haff et al. (20) found that PRFD in the 100 kg dynamic pull condition exhibited a *very large* correlation ($r = 0.82$) with SN performance, yet, was comparably less than the correlation with isometric PF ($r = 0.93$). However, further analysis comparing these correlations using Fisher-Z transformation indicate no significant difference between them ($p = 0.33$). Collectively, current research findings seem to support that maximal isometric strength is a better predictor of weightlifting performance than RFD (isometric or dynamic). However, considering the issues relating to the reliability of the RFD variables, this observation warrants further investigation.

It should be acknowledged that the IMTP assessment was originally devised based on the start of the second pull in the clean lift, therefore employs a corresponding grip width (21). The influence of greater grip width in the SN evidently slightly alters the joint and barbell kinematic characteristics during the pull, such as greater hip, knee, and ankle joint flexion angles in the start position, and higher barbell position relative to the thigh at the start of the second pull. However, no studies appear to have objectively compared these between the two lifts. Due to the influence of grip width on lifting technique of the SN and C&J, it is plausible that the assessment of the IMTP using a SN grip would elicit a greater correlation with SN performance. However, no studies to date have investigated this, therefore, future research should consider examining the effects of performing the IMTP using the SN grip and its correlation with performance.

< *Figure 4. Around here* >

< *Figure 5. Around here* >

Association between Back Squat and Front Squat with Performance

Both the BS and FS 1-RM illustrated *nearly perfect* correlations with the SN and C&J. These assessments are dynamic in nature and are identical to the ascent phase of the lifts. Whilst the pull phases of the lift exhibit several different temporal, kinetic and kinematic characteristics to the BS or FS, both pull and squat movements rely upon the maximal force capacity and coordination of the hip, knee, and ankle extensors (13,17). Therefore, it is reasonable that maximal squat strength is also a limiting factor to the force expression during the pull phases, further attesting to the strength of these correlations.

Unlike maximal isometric strength assessments, which are typically performed in the strongest mechanical position (56,63), maximal dynamic strength assessments are performed across the full range of motion of the exercise. The limiting factor to lifting a maximal weight through a full range of motion is the maximal force capacity at the weakest mechanical position of the movement (67). A 1-RM assessment therefore is representative of the weakest mechanical position. Several studies have also shown that isometric testing in comparably weaker, longer muscle-length positions exhibit greater correlations with dynamic strength performance compared with those at stronger, short muscle-lengths (1,3,32,46,49). As these 1-RM assessments describe the limiting factor to the maximal weight that could be lifted during the ascent phase, this may further explain the *nearly perfect* correlations observed between the 1-RM in the BS and FS with SN and C&J. Given that both the FS and BS are some of the most frequently used specific strength development exercises as part of a weightlifters' training program, athletes will be well familiarized with these techniques, therefore 1-RM testing will likely produce highly reliable data, although no studies to date have investigated this. Given the low cost and ease to conduct these assessments, coaches and practitioners at the very least should consider monitoring the 1-RM of these exercises.

Quality Analysis of Studies

The analysis of study quality via the AXIS tool for cross-sectional studies (11) showed a mean score of 81% (± 9%). The quality analysis results for each study are detailed in table 1. There were several methodological factors for which studies were penalized, however, common across all studies was the lack of justification for the sample size. An insufficient sample size increases the likelihood of a type-two error result, particularly when correlations are weaker (52). It is therefore imperative that any future studies with a cross-sectional or correlational design suitably justify the sample size based on published guidelines (59). The results of this meta-analysis may help to justify such decisions. The next two most penalized factors were a lack of discussion around the study limitations, and disclosure around funding sources and conflicts of interest by the study authors. Whilst these factors are not related to the methodological limitations of the study, both may potentially influence the authors' interpretation of the study findings, leading to bias in the discussion of the results. Future studies should also suitably discuss their limitations and disclose all relevant information.

Limitations

An important limitation of this meta-analysis is that it examines only cross-sectional studies. Whilst these findings are of considerable interest to practitioners working with weightlifters, conclusions about the causal effects of the independent variables (assessment variables) on the dependent variables (performance measures) should be considered with caution. Furthermore, several of the meta-analyses have low statistical power due to a small number of studies or a small sample size within the included studies. This low statistical power increase the likelihood of error in the study results (52), therefore these particular meta-analyses should be interpreted with caution. A further limitation of this meta-analysis is that each analysis of correlations between assessment variables and weightlifting performance are examined independently. This type of analysis does not consider either the covariance between variables, or alternatively how they collectively explain the degree of variance in SN and C&J performance. For example, in the study by Joffe & Tallent (33), a stepwise multiple regression analysis showed that the IMTP PF and CMJ PP predicted 91.8% and 95.1% of the variance in SN and C&J, respectively. This is the only study to date that has performed this type of analysis using these neuromuscular assessment variables. Future research should consider the influence of multiple neuromuscular characteristics on weightlifting performance.

PRACTICAL APPLICATIONS

The findings of this meta-analysis offer coaches and sport scientists information that may help to inform monitoring and training practices in the physical preparation of weightlifters. From a monitoring perspective, it is recommended that at the very least, weightlifting coaches monitor BS or FS 1-RM given their *nearly perfect* correlations with SN and C&J performance. These can be easily embedded within a weightlifter's training program and requires no additional equipment to perform. However, frequent maximal testing of the squat lifts may not be compatible with the different phases of training and potentially exhibit large residual fatigue (56). Furthermore, they do not allow for the examination of both maximal and time-dependent strength characteristics, limiting the analyses of the athlete's physical profile and specific adaptations in response to training (44). Alternatively, the IMTP offers this capability and is logistically easier to perform, requires less preparation time and has less residual fatigue (56). When employing the IMTP with weightlifters, it is recommended that the variables PF and F@250 ms are the primary variables collected for monitoring given their *very large* correlations with performance. The findings of this meta-analysis illustrate that CMJ or SJ PP are the optimal jump variables to evaluate ballistic contractile characteristics in relation to weightlifting performance. However, several recent studies indicate that this variable is unlikely to change in response to long-term weightlifting training (28,33), therefore may not reflect the relevant neuromuscular adaptations. No studies appear to have examined the temporal characteristics of the impulse curve in the CMJ or SJ in relation to performance and should be a consideration for future research.

Whilst the applications of these findings to inform training practices should be interpreted with caution given their cross-sectional nature, they do provide valuable insight to the trainable characteristics that underpin performance. Perhaps the standout finding from this analysis is the importance of lower-body maximal strength, particularly in the BS and FS and in the pull. Based on these findings, it is the authors recommendations that improvements in BS, FS and pull strength should be a continued focus of a lifters training program throughout the training year (except for peaking and tapering phases leading into competition) as it is fundamental limiting factor to the maximal load that can be lifted in either the SN or C&J.

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No funding sources to declare

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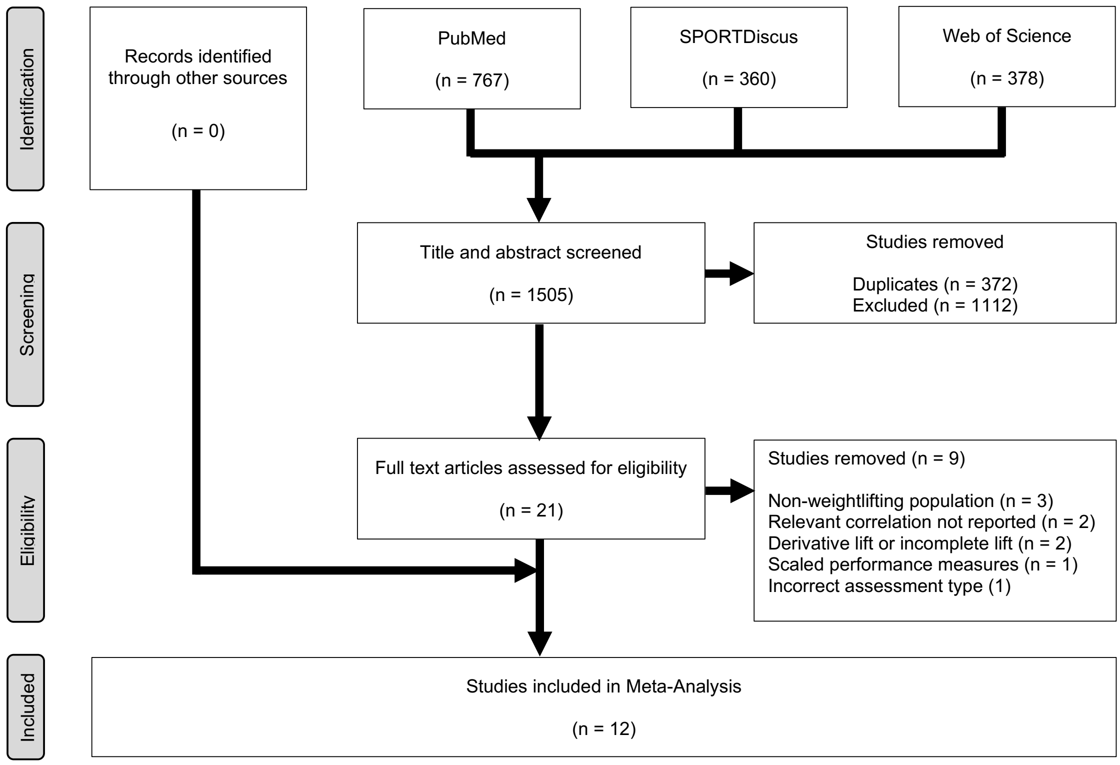


Figure 1. PRISMA Study flow chart detailing the process of study identification, screening, and eligibility of included studies.

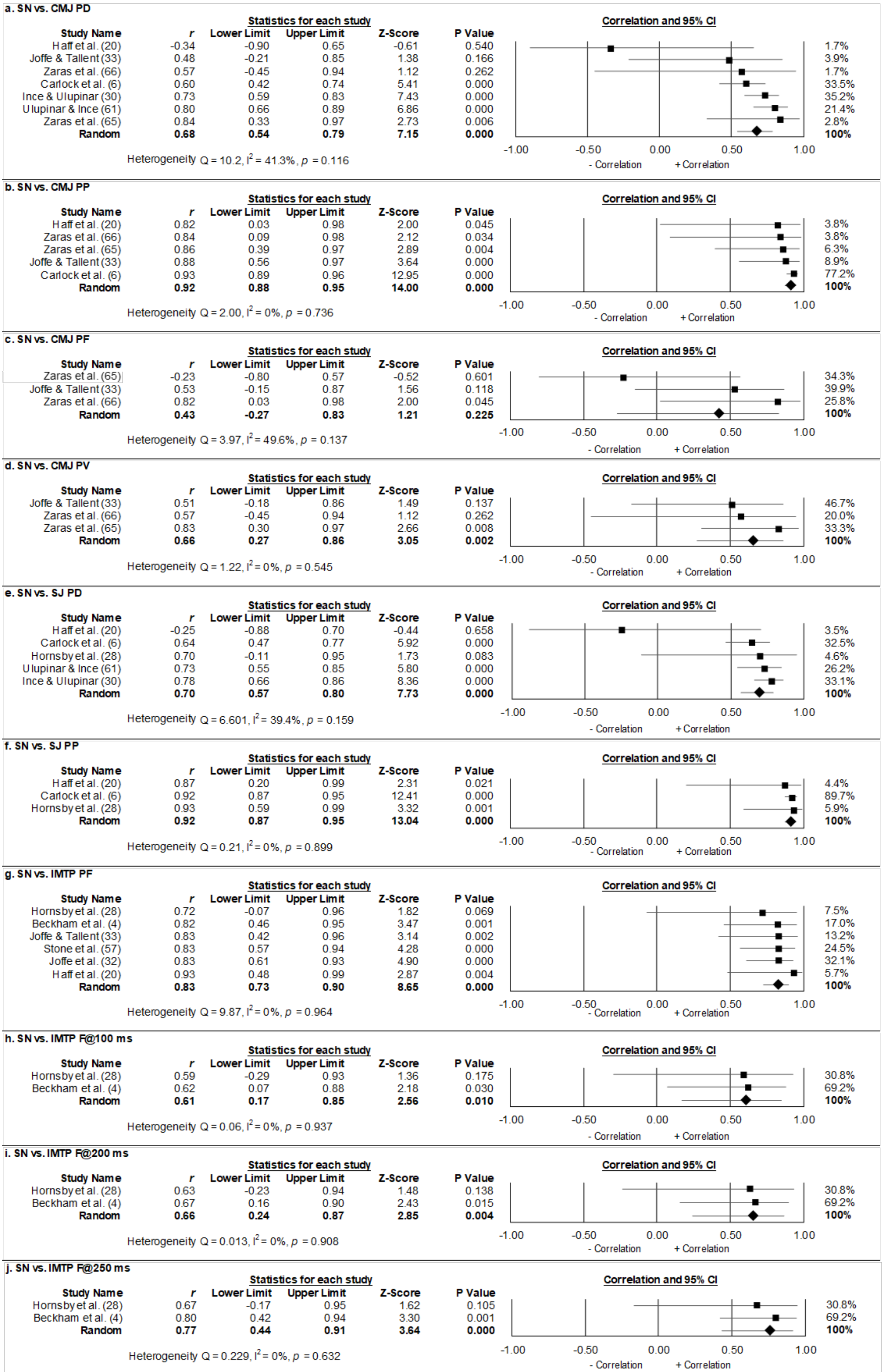


Figure 2. Continued on next page

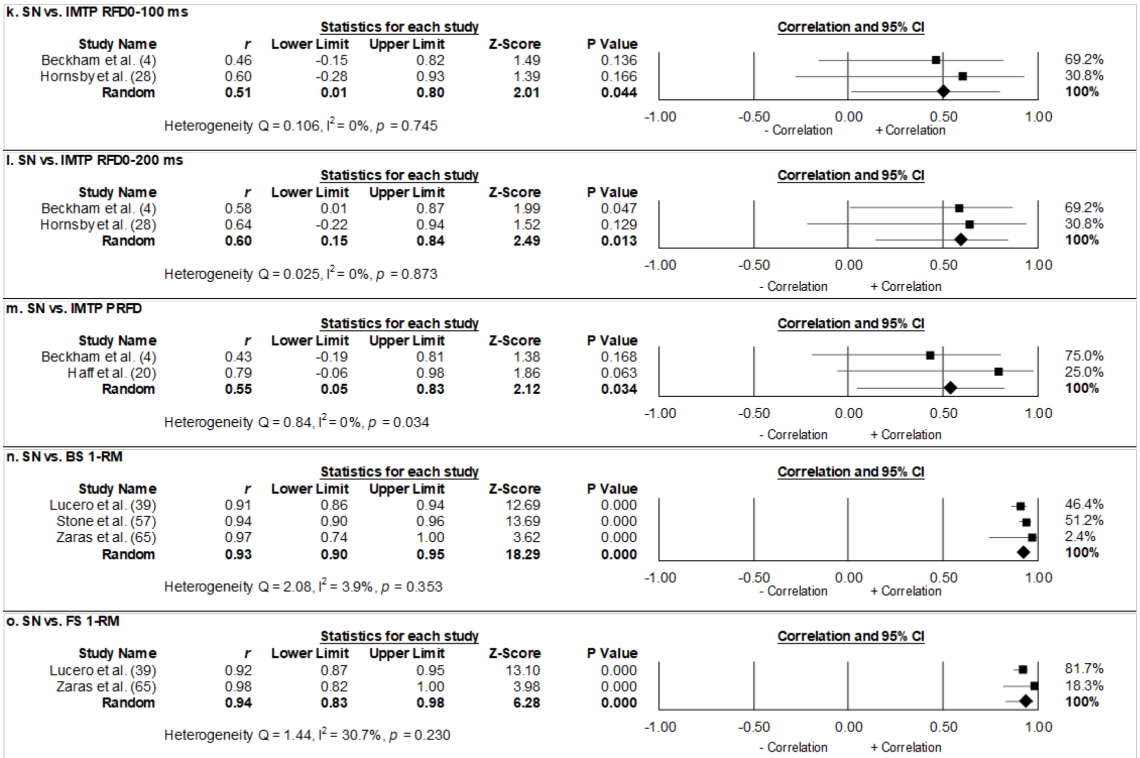
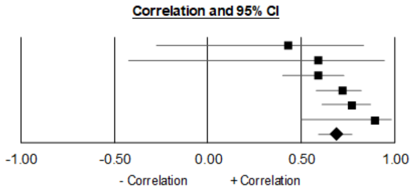


Figure 2. Forest plots of correlations (with 95% confidence intervals [CI's]) between neuromuscular assessment variables with Snatch performance. Square represents the correlations value for each study. Diamond represents the overall correlation. Horizontal lines represent 95% CI's.

a. C&J vs. CMJ PD

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Joffe & Tallent (2020)	0.43	-0.27	0.83	1.22	0.224	3.9%
Zaras et al. (2020b)	0.59	-0.43	0.95	1.17	0.240	1.7%
Carlock et al. (2004)	0.59	0.40	0.73	5.29	0.000	34.1%
Ince et al. (2020a)	0.72	0.58	0.82	7.26	0.000	35.8%
Ince et al. (2020b)	0.77	0.61	0.87	6.37	0.000	21.8%
Zaras et al. (2020a)	0.89	0.50	0.98	3.18	0.001	2.8%
Random	**0.69**	**0.59**	**0.77**	**9.69**	**0.000**	**100%**

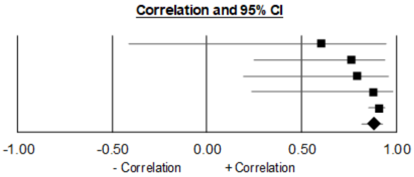


Heterogeneity Q = 5.94, I^2 = 15.9%, *p* = 0.312

b. C&J vs. CMJ PP

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Haff et al. (20)	0.60	-0.41	0.95	1.20	0.230	3.8%
Joffe & Tallent (33)	0.76	0.25	0.94	2.64	0.008	8.9%
Zaras et al. (65)	0.79	0.19	0.96	2.40	0.017	6.3%
Zaras et al. (66)	0.88	0.24	0.99	2.38	0.017	3.8%
Carlock et al. (6)	0.91	0.86	0.94	11.93	0.000	77.2%
Random	**0.88**	**0.82**	**0.93**	**11.13**	**0.000**	**100%**

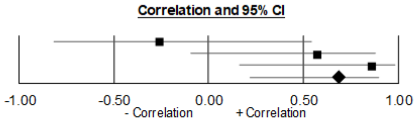


Heterogeneity Q = 4.16, I^2 = 3.8%, *p* = 0.385

c. C&J vs. CMJ PF

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Joffe & Tallent (33)	0.57	-0.09	0.88	1.71	0.087	70.0%
Zaras et al. (66)	0.86	0.16	0.98	2.24	0.025	30.0%
Random	**0.69**	**0.22**	**0.90**	**2.66**	**0.008**	**100%**

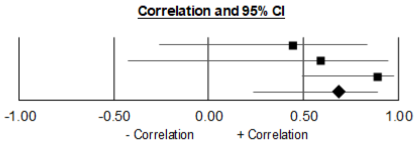


Heterogeneity Q = 0.88, I^2 = 0%, *p* = 0.349

d. C&J vs. CMJ PV

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Joffe & Tallent (33)	0.44	-0.26	0.84	1.25	0.212	43.0%
Zaras et al. (66)	0.59	-0.43	0.95	1.17	0.240	23.0%
Zaras et al. (65)	0.89	0.50	0.98	3.18	0.001	34.1%
Random	**0.69**	**0.24**	**0.89**	**2.75**	**0.006**	**100%**

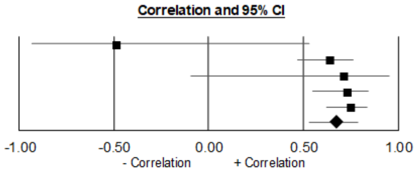


Heterogeneity Q = 2.72, I^2 = 26.4%, *p* = 0.257

e. C&J vs. SJ PD

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Haff et al. (20)	-0.49	-0.93	0.53	-0.93	0.353	4.1%
Carlock et al. (6)	0.64	0.47	0.77	5.92	0.000	31.8%
Hornsby et al. (28)	0.71	-0.09	0.95	1.77	0.076	5.3%
Ulupinar & Ince (61)	0.73	0.55	0.85	5.80	0.000	26.5%
Ince & Ulupinar (30)	0.75	0.62	0.84	7.78	0.000	32.4%
Random	**0.68**	**0.53**	**0.79**	**6.81**	**0.000**	**100%**

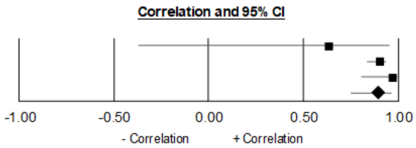


Heterogeneity Q = 7.489, I^2 = 46.5%, *p* = 0.112

f. C&J vs. SJ PP

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Haff et al. (20)	0.63	-0.37	0.95	1.28	0.199	15.9%
Carlock et al. (6)	0.90	0.84	0.94	11.50	0.000	19.8%
Hornsby et al. (28)	0.97	0.80	1.00	4.18	0.000	64.3%
Random	**0.90**	**0.75**	**0.96**	**5.71**	**0.000**	**100%**

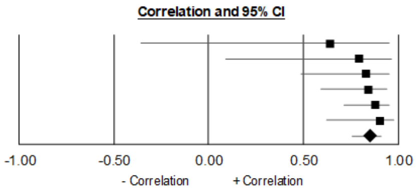


Heterogeneity Q = 3.14, I^2 = 36.2%, *p* = 0.208

g. C&J vs. IMTP PF

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Haff et al. (20)	0.64	-0.36	0.96	1.31	0.189	5.7%
Hornsby et al. (28)	0.79	0.09	0.97	2.14	0.032	7.6%
Beckham et al. (4)	0.83	0.49	0.95	3.56	0.000	17.0%
Stone et al. (57)	0.84	0.59	0.94	4.40	0.000	24.5%
Joffe et al. (32)	0.88	0.72	0.95	5.67	0.000	32.1%
Joffe & Tallent (33)	0.90	0.62	0.98	3.90	0.000	12.2%
Random	**0.85**	**0.76**	**0.91**	**9.22**	**0.000**	**100%**

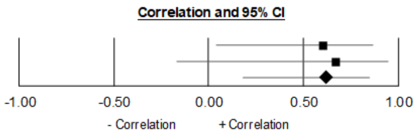


Heterogeneity Q = 1.51, I^2 = 0%, *p* = 0.912

h. C&J vs. IMTP F@100 ms

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Beckham et al. (4)	0.60	0.04	0.87	2.08	0.038	69.2%
Hornsby et al. (28)	0.67	-0.17	0.95	1.62	0.105	30.8%
Random	**0.62**	**0.18**	**0.85**	**2.63**	**0.009**	**100%**

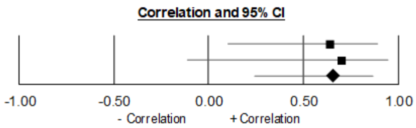


Heterogeneity Q = 0.04, I^2 = 0%, *p* = 0.845

i. C&J vs. IMTP F@200 ms

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Beckham et al. (4)	0.64	0.10	0.89	2.27	0.023	69.2%
Hornsby et al. (28)	0.70	-0.11	0.95	1.73	0.083	30.8%
Random	**0.66**	**0.24**	**0.87**	**2.85**	**0.004**	**100%**

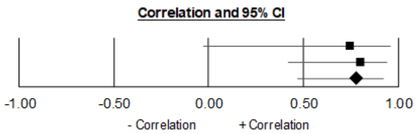


Heterogeneity Q = 0.033, I^2 = 0%, *p* = 0.856

j. C&J vs. IMTP F@250 ms

Statistics for each study

Study Name	*r*	Lower Limit	Upper Limit	Z-Score	P Value	Weight
Hornsby et al. (28)	0.74	-0.03	0.96	1.90	0.057	30.8%
Beckham et al. (4)	0.80	0.42	0.94	3.30	0.001	69.2%
Random	**0.78**	**0.47**	**0.92**	**3.80**	**0.000**	**100%**



Heterogeneity Q = 0.06, I^2 = 0%, *p* = 0.805

Figure 3. Continued on next page.

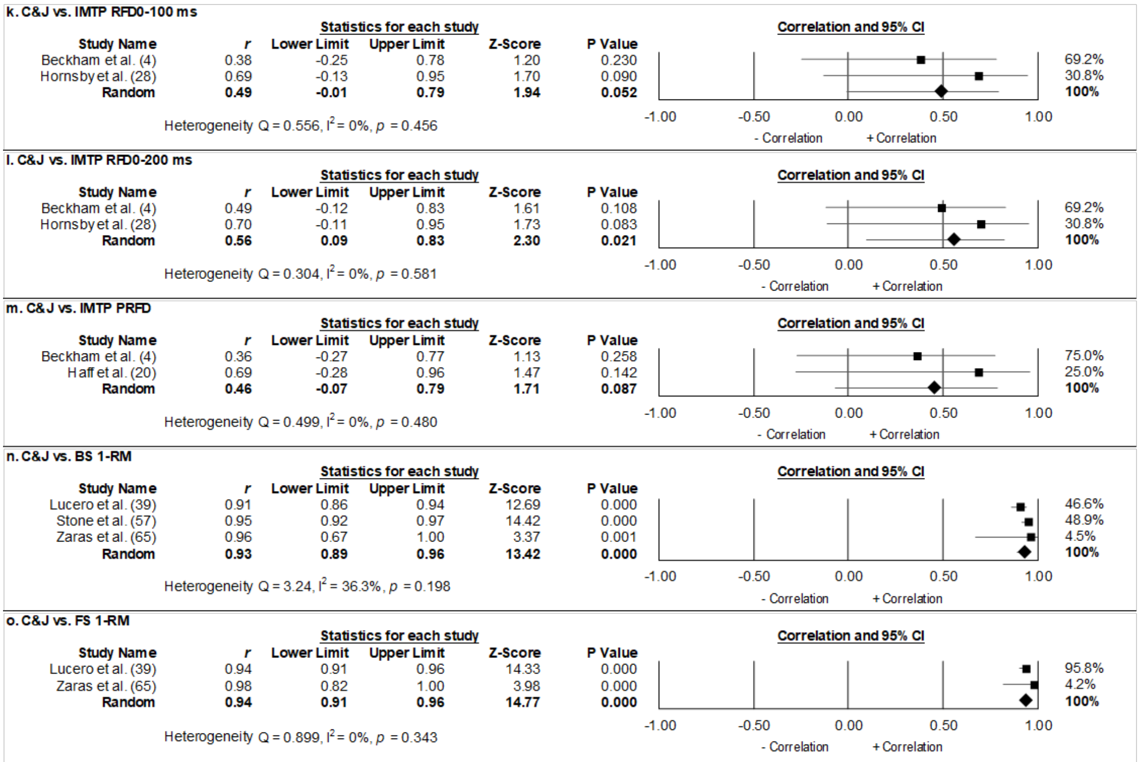


Figure 3. Forest plots of correlations (with 95% confidence intervals [CI's]) between neuromuscular assessment variables with Clean & Jerk performance. Square represents the correlations value for each study. Diamond represents the overall correlation. Horizontal lines represent 95% CI's.

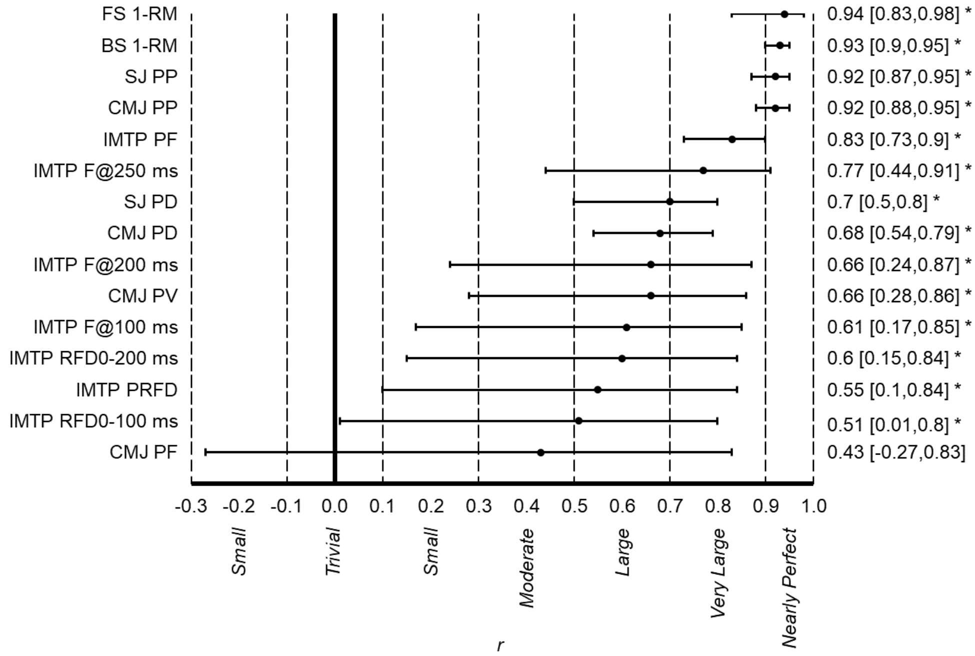


Figure 4. Forest plot summarizing all correlations (with 95% Confidence intervals [CI's]) between neuromuscular assessment variables with Snatch performance from separate meta-analyses. Circles represent the correlation value obtained from the meta-analysis for each assessment variable. Horizontal black lines represent 95% CI's. Vertical grey lines represent the criteria for interpretation of the correlation magnitude as described by Hopkins et al. (27).

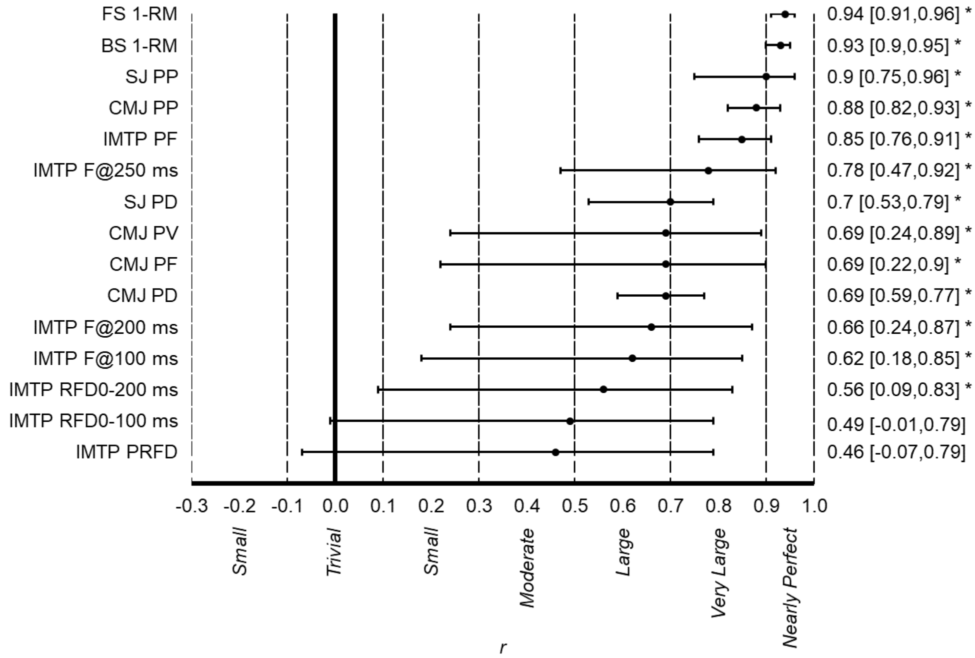


Figure 5. Forest plot summarizing all correlations (with 95% Confidence intervals [CI's]) between neuromuscular assessment variables with Clean & Jerk performance from separate meta-analyses. Circles represent the correlation value obtained from the meta-analysis for each assessment variable. Horizontal black lines represent 95% CI's. Vertical grey lines represent the criteria for interpretation of the correlation magnitude as described by Hopkins et al. (27).

Table 1. AXIS tool study quality checklist results.

Questions	Stone et al. (57)	Beckham et al. (4)	Joffe & Tallent (33)	Haff et al. (20)	Carlock et al. (6)	Lucero et al. (39)	Zaras et al. (65)	Zaras et al. (66)	Joffe et al. (32)	Hornsby et al. (28)	Ince & Ulupinar (30)	Ulupinar & Ince (61)
Were the aims/objectives of the study clear?	1	1	1	1	1	1	1	1	1	0	1	1
Was the study design appropriate for the stated aim(s)	1	1	1	1	1	1	1	1	1	1	1	1
Was the sample size justified?	0	0	0	0	0	0	0	0	0	0	0	0
Was the target population clearly defined?	1	1	1	1	1	1	1	1	1	1	1	1
Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	1	1	1	1	1	1	1	1	1	1	1	1
Was the selection process likely to select participants that were representative of the target/reference population under investigation?	1	1	1	1	1	1	1	1	1	1	1	1
Were the risk factor and outcome variables measured appropriate to the aims of the study?	0	1	1	1	0	0	1	1	1	1	1	1
Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted, or published previously? the measurement reliability of the study measures.	1	1	1	1	1	1	1	1	1	1	0	0
Is it clear what was used to determined statistical significance and/or precision estimates? (E.g., p values, CIs)	1	1	0	1	1	1	1	1	1	0	1	1
Were the methods (including data analysis and statistical methods) sufficiently described to enable them to be repeated?	1	1	1	1	1	1	0	0	1	1	1	1
Were the basic data adequately described?	1	1	1	1	1	1	1	1	1	1	1	1
Were the results internally consistent?	1	1	1	1	1	1	1	1	1	1	1	1
Were the results for the analyses described in the methods, presented?	1	1	1	1	1	1	1	1	1	0	1	1
Were the authors discussions and conclusions justified by the results?	1	1	1	1	1	1	1	0	1	0	0	1
Were the limitations of the study discussed?	0	1	1	0	0	0	1	1	1	0	0	1
Were there any funding sources or conflicts of interest that may affect the authors interpretation of the results? (Was this explicitly outlined)	0	0	1	0	0	1	1	0	1	1	1	1
Was ethical approval or consent of participants attained?	0	1	1	1	0	1	1	1	1	1	1	1
Total score of 17	**12**	**15**	**15**	**14**	**12**	**14**	**15**	**13**	**16**	**11**	**13**	**15**

Table 2. Study Characteristics. Methodological Factors.

Study	**Physical assessment relative to performance assessment**	**Equipment Detail**	**Performance assessment**	**Isometric Strength Assessment**	**Dynamic Strength Assessment**	**Jump Assessment**
Stone et al. (57) i	Self-reported at time of physical assessment	-	Self-reported: SN and C&J	-	Self-reported: BS 1-RM	-
Stone et al. (57) ii	1.5 weeks pre-competition	Force Plate 600 Hz: IMTP	Competition: SN and C&J	IMTP: PF (gross)	-	-
Beckham et al. (4)	10 days post-competition	Force Plate 1000 Hz: IMTP	Competition: SN and C&J	IMTP: PF, F@100, 150, 200, 250 ms, RFD0- 100, 150, 200, 250 ms, PRFD (gross and net)	-	-
Joffe & Tallent (33)	1 year average	Force Plate 1000 Hz: IMTP, CMJ	Competition: SN and C&J	IMTP: PF (net)	-	CMJ PD; PP (Force-time derived); PF, PV
Haff et al. (20)	Physical assessment relative to performance assessment not specified	Force Plate 600 Hz: IMTP; Jump Mat: CMJ, SJ	Competition: SN and C&J	IMTP: PF, PRFD (gross)	-	CMJ PD, PP (Sayers equation); SJ PD, PP (Sayers equation).
Carlock et al. (6)	Self-reported at time of physical assessment	Jump Mat: CMJ, SJ	Self-reported SN and C&J	-	Self-reported: BS 1-RM	CMJ PD, PP (Sayers equation); SJ PD, PP (Sayers equation).
Lucero et al. (39)	Self-reported physical assessment and performance assessments	-	Self-reported SN and C&J	-	Self-reported: BS, FS 1-RM	-

Zaras et al. (65)	48 hours pre-performance Assessment	Force Plate 1000 Hz: CMJ	Laboratory-based: SN and C&J	-	-	CMJ PD, CMJ PP (Sayers equation), PV.
Zaras et al. (66)	Pre and Post 16-week intervention. Physical relative to performance assessment not specified	Force Plate 1000 Hz: CMJ	Laboratory-based: SN and C&J	-	-	-
Joffe et al. (32)	4 to 8 weeks Pre/ Post-Competition	Force Plate 1000 Hz: IMTP	Competition: SN and C&J	IMTP: PF (net)	-	-
Ince & Ulupinar (30)	7- to 10 days post-competition	Opto-Jump: CMJ, SJ	Competition: SN and C&J	-	-	CMJ PD; SJ PD.
Ulupinar & Ince (61)	7 to 10 days post-competition	Opto-Jump: CMJ, SJ	Competition: SN and C&J	-	-	CMJ PD; SJ PD.
Hornsby et al. (28)	1 to 3 weeks pre/ post-competition. 4 competition and 7 assessment time points	Force Plate 1000 Hz, IMTP, SJ	Competition & Laboratory-based: SN and C&J	IMTP: PF; F@50, 90, 200, 250; RFD0- 50, 90, 200, 250 ms. (gross)	-	SJ PD, SJ PP (Force-Time Derived).

SN = Snatch, C&J = Clean & Jerk, IMTP = Isometric Mid-Thigh Pull, CMJ = Countermovement Jump, SJ = Squat Jump, BS = Back Squat, FS = Front Squat, 1-RM = one-repetition maximum, PF = Peak Force, F@ = Force at specified time point, RFD = Rate of Force Development, PRFD = Peak Rate of Force Development, PD = Peak Displacement, PP = Peak Power, PV = Peak Velocity. Gross = total force, Net = total force above body mass. Stone et al. (57) i and ii refers to two separate groups examined in this study.

Table 3. Study Characteristics. Participant Data and Study Results.

Study	**Participant Characteristics**					**Weightlifting Performance**	**Neuromuscular Assessment & Variables**	**Results (Correlations r)**
	N	**Age (Yrs)**	**Height (m)**	**Body Mass (kg)**	**Competitive Level**			
Stone et al. (57) i	M = 39 F = 26	15 to 30	1.69 ± 0.09	77.6 ± 25.0	National & International	SN 96.0 ± 29.5 kg C&J 120.0 ± 35.3 kg	*BS 1-RM*: 163.6 ± 51.2 kg	*BS 1-RM*: SN *r* = 0.94; C&J *r* = 0.95.
Stone et al. (57) ii	M = 9 F = 7	23.1 ± 4.2	1.67 ± 0.07	84.4 ± 19.5	International	SN 122.6 ± 30.7 kg C&J 148.4 ± 41.4 kg	*IMTP*: PF 4420 ± 1191 N	*IMTP*: PF: SN *r* = 0.83; C&J *r* = 0.84.
Beckham et al. (4)	M = 10 F = 2	-	1.70 ± 0.07	91.1 ± 20.1	Intermediate & Advanced	SN 89.9 ± 23.3 kg C&J 115.3 ± 23.3 kg	*IMTP*: PF 5576 ± 1147 N; F@100 ms 2672 ± 622 N; F@150 ms 3581 ± 848 N; F@200 ms 4044 ± 907 N; F@250 ms 4260 ± 943 N; RFD0-100 ms 14292 ± 5782 N.s; RFD0-150 ms 15582 ± 5450 N.s; RFD0-200 ms 14002 ± 4102 N.s; RFD0-250 ms 12066 ± 3174 N.s; PRFD 33231 ± 13296 N.s	*IMTP*: PF: SN *r* = 0.83; C&J *r* = 0.84. F@100 ms: SN *r* = 0.65; C&J *r* = 0.64. F@150 ms: SN *r* = 0.64; C&J *r* = 0.61. F@200 ms: SN *r* = 0.73; C&J *r* = 0.71. F@250 ms: SN *r* = 0.80; C&J *r* = 0.80. RFD0-100 ms: SN *r* = 0.46; C&J *r* = 0.40. RFD0-150 ms: SN *r* = 0.49; C&J *r* = 0.41. RFD0-200 ms: SN *r* = 0.65; C&J *r* = 57. RFD0-250 ms: SN *r* = 0.78; C&J *r* = 0.72. PRFD: SN *r* = 0.43; C&J *r* = 0.36.
Joffe & Tallent (33)	F = 10	23.4 ± 3.3	1.59 ± 0.06	63.3 ± 8.8	International	SN 76.8 ± 15.1 kg C&J 96.4 ± 18.3 kg	*IMTP*: PF 2572 ± 496.3 N. *CMJ*: PD 37.55 ± 5.51 cm; PP 3324 ± 534.2 W; CON PF 2572 ± 496.3 N; PV 2.82 ± 0.29 m.s	*IMTP*: PF: SN *r* = 0.83; C&J *r* = 0.90. *CMJ*: PD: SN *r* = 0.48; C&J *r* = 0.43. PP: SN *r* = 0.88; C&J *r* = 0.76. CON PF: SN *r* = 0.53; C&J *r* = 0.56. CMJ PV: SN *r* = 0.51; C&J *r* = 0.44.
Haff et al. (20)	F = 6	21.5 ± 3.1	1.67 ± 0.06	82.8 ± 18.9	National & International	SN 90.8 ± 8.0 kg C&J 111.7 ± 12.7 kg	*IMTP*: PF 3649.2 ± 824.3 N; PRFD 13997 ± 1879.3 N.s. *CMJ*: PD 31.0 ± 4.0 cm; PP	*IMTP*: PF: SN *r* = 0.93; C&J *r* = 0.64. PRFD: SN *r* = 0.79; C&J *r* = 0.69. PD: SN *r* = -0.34; C&J *r* = -

							3661.6 ± 728.9 W. *SJ*: PD 29.0 ± 5.0 cm; PP 3524.5 ± 711.5 W	0.59. PP: SN *r* = 0.82; C&J *r* = 0.60. *SJ*: PD: SN *r* = -0.25; C&J *r* = -0.49. PP: SN *r* = 0.87; C&J *r* = 0.63.
Carlock et al. (6)	M = 38 F = 26	18 ± 3.8	-	77.9 ± 21.7	International Junior & Senior	SN 95.7 ± 29.3 kg C&J 119.7 ± 35.3 kg	*CMJ*: PD 41.3 ± 8.8 cm; P 3985 ± 1188 W. *SJ*: PD 37.5 ± 7.5 cm; PP 3750 ± 1157 W	*CMJ*: PD: SN *r* = 0.60; C&J *r* = 0.59. PP: SN *r* = 0.93; C&J *r* = 0.91. *SJ*: PD: SN *r* = 0.64; C&J *r* = 0.64. PP: SN *r* = 0.92; C&J *r* = 0.90.
Lucero et al. (39)	M = 72	18 to 35	-	89.2 ± 22.1	National	SN 125.7 ± 47.7 kg C&J 156.3 ± 33.5 kg	*BS 1-RM*: 215.8 ± 47.7 kg. *FS 1-RM*: 182.7 ± 39.9 kg.	*BS 1-RM*: SN *r* = 0.91; C&J *r* = 0.91. *FS 1-RM*: SN *r* = 0.92; C&J *r* = 0.94.
Zaras et al. (65)	F = 8	23.5 ± 6.3	1.64 ± 0.05	63.3 ± 6.9	National & International	SN 63.8 ± 16.2 kg C&J 79.4 ± 18.7 kg	*CMJ*: PD 29.6 ± 5.3 cm; PP 2623.1 ± 418.7 W; PF *NR;* PV 2.5 ± 0.4 m.s.	*CMJ*: PD: SN *r* = 0.84; C&J *r* = 0.89. PP: SN *r* = 0.86; C&J *r* = 0.79. PF: SN *r* = -0.23; C&J *r* = -0.26. PV: SN *r* = 0.83; C&J *r* = 0.89.
Zaras et al. (66)	M = 6	23.3 ± 3.4	1.76 ± 0.07	88.7 ± 10.2	International	SN 146.7 ± 15.4 kg C&J 179.4 ± 22.1 kg	*CMJ*: PD 46.85 ± 6.1 cm; PP 4782.85 ± 660.9 W; PF 1551.5 ± 316.9 N; PV 3.85 ± 0.5 m.s; *BS 1-RM*: 223.9 ± 28.7 kg; *FS 1-RM*: 197.5 ± 27.2 kg.	*CMJ*: PD: SN *r* = 0.57; C&J *r* = 0.59. PP: SN *r* = 0.84; C&J *r* = 0.88. PF: SN *r* = 0.82; C&J *r* = 0.86. PV: SN *r* = 0.57; C&J *r* = 0.59. *BS 1-RM*: SN *r* = 0.97; C&J *r* = 0.96. *FS 1-RM*: SN *r* = 0.98; C&J *r* = 0.98.
Joffe et al. (32)	M = 7 F = 13	25.4 ± 6.1	1.64 ± 0.11	70.4 ± 15.2	National & International	SN 92 ± 30 kg C&J 114 ± 36 kg	*IMTP*: PF 2640 ± 767 N.	*IMTP*: PF: SN *r* = 0.83; C&J *r* = 0.88.
Ince & Ulupinar (30)	M = 67	16.6 ± 1.5	1.67 ± 0.05	67.0 ± 9.3	National	SN 103.6 ± 14.0 kg C&J 124.0 ± 16.9 kg	*CMJ*: PD 41.54 ± 8.88 cm. *SJ*: PD 32.27 ± 9.94 cm.	*CMJ*: PD: SN *r* = 0.86; C&J *r* = 0.83. *SJ*: PD: SN *r* = 0.78; C&J *r* = 0.75.
Ulupinar & Ince (61)	F = 42	17.8 ± 2.3	1.56 ± 0.06	56.59 ± 8.15	National	SN 68.6 ± 14.7 kg C&J 86.5 ± 18.9 kg	*CMJ*: PD 32.52 ± 6.54 cm. *SJ*: PD 30.12 ± 3.68 cm	*CMJ*: PD: SN *r* = 0.80; C&J *r* = 0.77. *SJ*: PD: SN *r* = 0.73; C&J *r* = 0.73.
Hornsby et al. (28)	M = 4 F = 3	26.7 ± 5.0	1.71 ± 0.06	83.4 ± 18.5	National	SN 84.4 ± 31.2 kg C&J 105.6 ± 40.5 kg	*IMTP*: PF 4966.6 ± 969.4 N; F@0-50 ms 1704.7 ± 713.4 N; F@90 ms 2436 ± 1024.7	*IMTP*: PF: SN *r* = 0.72; C&J *r* = 0.79. F@50 ms: SN *r* = 0.57; C&J *r* = 0.66. F@90 ms: SN *r* = 0.60; C&J

N; F@200 ms 3682.2 ± 1300.2 N; F@250 ms 3821.5 ± 1243.9 N.s; RFD0-50 ms 9612.5 ± 5174.8 N.s; RFD0-90 ms 13472.4 ± 6493.8 N.s; RFD0-200 ms 12295.3 ± 4436.2 N.s. *SJ*: PD: 31.46 ± 6.58 cm; PP 4521.9 ± 1215.1 W.	*r* = 0.69. F@ 200 ms: SN *r* = 0.63; C&J *r* = 0.70. F@ 250 ms: SN *r* = 0.67; C&J *r* = 0.74. RFD0-50 ms: SN *r* = 0.58; C&J *r* = 0.68. RFD0-90 ms: SN *r* = 0.62; C&J *r* = 0.70. RFD0-200 ms: SN *r* = 0.64; C&J *r* = 0.70. *SJ*: PD: SN *r* = 0.70; C&J *r* = 0.71. PP: SN *r* = 0.93; C&J *r* = 0.97.

SN = Snatch, C&J = Clean & Jerk, IMTP = Isometric Mid-Thigh Pull, CMJ = Countermovement Jump, SJ = Squat Jump, BS = Back Squat, FS = Front Squat, 1-RM = one-repetition maximum, PF = Peak Force, F@ = Force at specified time point, RFD = Rate of Force Development, PRFD = Peak Rate of Force Development, PD = Peak Displacement, PP = Peak Power, PV = Peak Velocity. Stone et al. (57) i and ii refers to two separate groups examined in this study.