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ABSTRACT

The purpose of this meta-analysis was to examine the relationships between lower body multi-joint isometric and dynamic neuromuscular assessment variables with snatch (SN) and clean & jerk (C&J) performance in competitive weightlifters. Following a comprehensive search via three electronic databases (PubMed, SPORTDiscus and Web of Science), 12 studies were identified as eligible based upon the inclusion criteria. Meta-analyses were performed based on Pearson's correlation values between SN and C&J with 15 assessment variables from five neuromuscular assessments – countermovement jump, squat jump, isometric mid-thigh pull, and back squat and front squat one repetition-maximum (1-RM). Quality analysis of studies was performed using the appraisal tool for cross-sectional studies (AXIS tool). Each of the five neuromuscular assessments presented at least one variable that exhibited a *very large* correlation (r = 0.70) or greater with SN and C&J. The front squat and back squat 1-RM illustrated *nearly perfect* correlations with SN and C&J. Furthermore, countermovement jump and squat jump peak power illustrated *very large* to *nearly perfect* correlations, whereas the isometric mid-thigh pull peak force and force at 201-250 ms revealed *very large* correlations with SN and C&J. Multiple variables reflective of either maximal strength, peak power and rate of force development obtained from either isometric or dynamic assessments illustrated *very large* to *nearly perfect* correlations with weightlifting performance. Weightlifting coaches should at the very least consider monitoring back squat and/or front squat 1-RM, given they are low cost, easy to perform and appear to have the strongest relationship with weightlifting performance.

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 (34). 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 shown that higher competitive level weightlifters exhibit more technically efficient barbell and joint kinematic characteristics compared with their lower-level counterparts (8,21,28,37). In addition, elite weightlifters express greater relative force outputs for the same percentage of their maximum lift compared with sub-elite (21). These findings indicate that improvements in technical efficiency enable a greater capacity to generate a higher vertical impulse during the lifts. With long-term continued technical refinement, improvements in performance, therefore, increasingly rely upon increases in the rate and magnitude of vertical ground reaction forces produced 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 (43). It has also been suggested, however, that many of these assessment variables may serve as surrogate measures of weightlifting performance (32), offering coaches a means of evaluating 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 attempts in the SN and C&J both in training and at the competition itself.

Numerous studies have investigated the relationships between lower-body neuromuscular assessments with SN and C&J performance. However, to date, there has been no systematic synthesis to determine the overall relationships between each of these assessment variables and weightlifting performance. A better understanding of these relationships could help to inform coaches and sports scientists of the most appropriate assessments and variables to evaluate the strength characteristics of weightlifters, or to serve as surrogate measures of weightlifting performance. The aim of this meta-analysis was to conduct a comprehensive synthesis of the literature, to examine the relationships 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 (50). 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 "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 and/ or C&J; (IV) reported either Pearson's r or R^2 values; (V) reported kinetic, kinematic or absolute strength measures including, but not limited to peak force (PkF) or rate of force development (RFD) for isometric assessments; peak force (PkF), peak velocity (PkV), peak power (PkP), RFD or peak displacement (PkD) for multi-joint, dynamic jump-based assessments; or 1 repetition maximum (1-RM) for dynamic strength assessment. 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.

Information Sources and Selection Process

The literature search was performed using PubMed, SPORTDiscus and Web of Science electronic databases in December 2021. 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 was resolved by consulting with a third author (PP).

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 performance level.

- Weightlifting performance: Assessment conditions and 1-RM of the SN and/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 and/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. 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 into three categories based on their time intervals: 0 to 100 ms, 101 to 200 ms or 201 to 250 ms. Where studies included multiple time-dependent force-time variables within the same time interval, or where studies reported correlations at multiple time points of a training intervention (e.g., pre and post), the correlations were averaged once converted using the Fisher-Z transformation. $Z = \frac{1}{2}\ \ln\left(\frac{1+r}{1-r}\right)$.

< Figure 1. Around here. >

Study Quality Analysis

The evaluation of each article's quality was performed by one author (SAJ) 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. The total score was presented as an absolute and percentage value.

Statistical Analysis

A meta-analysis was conducted using a random-effects model, as 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 and C&J. Different neuromuscular assessments representative of the same broad physical quality (e.g., maximal strength: IMTP PkF and Back Squat (BS) 1-RM), were purposefully analyzed independently as to determine both the assessment and variable correlations with performance. 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 (24). In accordance with The Cochrane Handbook for Systematic Reviews of Interventions (23) 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. Statistical analysis was performed using Comprehensive Meta-Analysis software (Version 3; BiostatInc. Englewood, USA). Statistical significance was set at $p < 0.05$. All meta-analyses are displayed in forest-plots. All correlations were interpreted with the following descriptive criteria: 0 = *trivial*, 0.1 = *small*, 0.3 = *moderate*, 0.5 = *large*, 0.7 = *very large*, 0.9 = *nearly perfect*, 1 = *perfect* (26).

RESULTS

Study Selection

The PRISMA flow chart illustrating the systematic search process is outlined in Figure 1. The initial database search returned 1,556 articles. Following the removal of duplicates, 879 articles remained and were screened for eligibility based on their title and abstract. Twenty-one articles were sought for full text, one of which were unobtainable (54). Unreported data were sought and obtained from five articles

(27,29,60,64,65), however data from one article was not available (59). Nineteen 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 number of 395 subjects (252 males, 143 females) across 12 studies were included in the analyses. All subjects were 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 (Pearson's correlation) between a lower body neuromuscular assessment with the SN and C&J performance. Weightlifting performance was measured within a weightlifting competition in eight studies (4,19,27,29,31,32,56,60), whereas three studies evaluated weightlifting performance under competition conditions in a laboratory (27,64,65). Three studies used self-reported 1-RM values for the SN and C&J (6,38,56). Two of the above studies used a combination of methods for the weightlifting performance assessment (27,56). Regarding the neuromuscular assessments, six studies investigated the IMTP (4,19,27,31,32,56), six studies investigated the countermovement jump (CMJ) (6,19,29,32,60,64), five studies investigated the squat jump (SJ) (6,19,27,29,60) three studies investigated BS (38,56,65) and two studies investigated the front squat (FS) (38,65). A detailed description of the study characteristics is outlined in Tables 1 and 2.

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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 PkD revealed 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 PkD with C&J (r = 0.66, 95% CI [0.48, 0.78], p < 0.001, n = 203), revealed 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. (18) 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 PkD and C&J (r = 0.69, 95% CI [0.59, 0.77], p < 0.001, n = 197) (Fig 3a). Countermovement jump PkP revealed 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 PkF revealed 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 PkF 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 revealed 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. (64) 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 PkV revealed 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 PkD revealed *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 PkP revealed *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 PkF revealed *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@0-100 ms and F@101-200 ms each revealed *large* correlations with SN ($r = 0.63$, 95% CI [0.20, 0.86], $p = 0.007$, n = 19 and $r = 0.67$, 95% CI [0.27, 0.88], $p = 0.003$, n = 19, respectively) (Fig 2h & 2i) and C&J ($r = 0.65$, 95% CI [0.23, 0.87], $p = 0.005$, n = 19 and $r = 0.67$, 95% CI [0.27, 0.88], $p = 0.003$, n = 19, respectively) (Fig 3h and 3i). Additionally, IMTP F@201-250 ms revealed *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- 1-100 ms revealed a *large* correlation with SN ($r = 0.51$, 95% CI [0.01, 0.80], $p = 0.044$, n = 19) (Fig 2k), however, exhibited 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- 100-200 ms revealed *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 PkRFD revealed a *large* correlation with SN ($r = 0.55$, 95% CI [0.10, 0.84], $p = 0.022$, n = 18) (Fig 2m), however, exhibited 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 revealed 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 examine the correlations between lower-body multi-joint isometric and dynamic neuromuscular assessments 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, PkP in both jump-based assessments (CMJ and SJ) illustrated *very large* to *nearly perfect* correlations, whereas PkF and F@201-250 ms in the IMTP revealed *very large* correlations. 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 evaluate weightlifting performance potential. However, it should be acknowledged that FS and BS 1-RM appeared to exhibit the greatest correlations with both lifts, and therefore may be the optimal and most accessible assessment.

Association between CMJ and SJ variables with Performance.

The CMJ and SJ revealed similar correlations between their respective PkD and PkP variables with SN and C&J performance. 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 the concentric portion of the movement (25,44). Furthermore, they consistently show *nearly perfect* correlations ($r \geq 0.90$) with each other (6,19,29,60,61). Indeed, this suggests that the CMJ and SJ largely reflect a similar ability to generate 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 PkD or PkP. However, these tests may each offer unique insight into muscle-contraction specific or time-dependent characteristics (12,25), 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 performance.

The observed *large* to *very large* correlations between CMJ and SJ PkD and weightlifting performance is anticipated, given the 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 (5,39) and the drive phase of the jerk (10). It should be considered, however, that the PkD variable reflects the capacity to express vertical impulse relative to body mass (35). Given the non-linear relationship between maximal muscular force capacity with increasing body mass (30), 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 has been reported across different phases of the training cycle (57). The PkD variable, therefore, may be suboptimal as a metric to evaluate ballistic contractile characteristics of the lower body in weightlifters.

The CMJ and SJ PkP exhibited similar *very large* to *nearly perfect* correlations with SN and C&J performance, and noticeably larger than that with PkD. This trend is consistent with all studies that have examined correlations between both CMJ PkP and PkD in relation to weightlifting performance (6,19,32). 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 (16), PkP 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 (63). 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 PkP with SN and C&J compared with PkD, 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 (52).

Across all the included studies, PkV and PkF were only evaluated in the CMJ assessment. Unsurprisingly, CMJ PkV showed a similar *large* correlation with SN and C&J, to that with PkD. This is to be expected given that jump PkD can be calculated from the take-off velocity (46) which coincides with the PkV of a body weight vertical jump (7). Hence, the CMJ PkV corresponds directly to CMJ PkD and consequently, is reflective of the same physical capacity. The CMJ PkV, however, may provide additional information on the load/force/power-velocity relationships when combined with the analysis of additional loaded jumps (47).

The meta-analysis examining the relationship between CMJ PkF 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. (64), resulting in a *large* correlation and *low risk* of heterogeneity. On the contrary, no significant correlation was observed between CMJ PkF 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 PkF with SN performance may also be attributed to PkF 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. However, these findings are partly in agreement with previous reports that have found very large correlations (r = 0.79 to 0.84) between CMJ PkF and BS-1-RM and power clean 1-RM performance in a non-weightlifting athletic population (49). Similarly, CMJ absolute and relative PkF have illustrated *very large* to *nearly perfect* correlations (r = 0.70 to 0.91) with 10 m and 60 m sprint performance in track and field athletes (41,42). The CMJ PkF variable may provide some insight into the ballistic force-generating characteristics that are relevant to athletic performance. Future studies examining vertical jump-based assessments in relation to weightlifting performance should consider investigating the characteristics of impulse (force and time), particularly during the concentric phase to enable a better mechanistic understanding of changes in force expression and how this can be associated with weightlifting performance, thus providing coaches and scientists with appropriate training direction.

Association Between Isometric Mid-Thigh Pull Variables and Performance.

The IMTP PkF 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 (2,33,34,53), power output and barbell velocity (16,18,22,36) 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 these phases of the pull may also be important limiting factors to performance. A recent study by Joffe et al. (31) showed that PkF 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 PkF 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 at 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 (14–18), the maximal force applied within a comparable time interval should plausibly exhibit greater correlations with performance measures than IMTP PkF. Surprisingly, the F@0-100 ms, F@101-200 ms, RFD0- 1-100 ms, RFD0- 101-200 ms and PkRFD revealed only *large* correlations or no correlation (RFD0- 1-100 ms vs C&J and PkRFD vs C&J) with weightlifting performance, while F@201-250 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 maybe a greater determinant of weightlifting performance than RFD. However, a 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 (40), 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 PkRFD in a dynamic clean pull at 30% of IMTP and at 100 kg in relation to SN, C&J, and Total performance (19). Haff et al. (19) found that PkRFD in the 100 kg pull condition exhibited a *very large* correlation ($r = 0.82$) with SN performance, which was comparably less than the correlation with PkF ($r = 0.93$). Whilst this trend leans toward the notion that maximal isometric strength is a better predictor of weightlifting performance than RFD, 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 (20). The influence of greater grip width in the SN evidently alters some of 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.

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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 (13,16). Therefore, it is reasonable that maximal squat strength is also a limiting factor to the force expression during the pull phases, thus further attesting to the strength of these correlations.

Unlike maximal isometric strength assessments, which are typically performed in the strongest mechanical position (55,62), 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 (66). 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 (1,3,31,45,48). 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 used specific strength development exercises as part of a weightlifters' program, athletes will be well familiarized with these techniques, therefore 1-RM testing will likely produce highly reliable data. 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 (51). It is therefore imperative that any future studies with a cross-sectional/ correlational design suitably justify the sample size based on published guidelines (58). 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/or 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, it is erroneous to draw conclusions about the causal effects of the independent variables (assessment variables) on the dependent variables (performance measures). These causal effects are best determined through intervention-based investigations. 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 (32), a stepwise multiple regression analysis showed that the IMTP PkF and CMJ PkP 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 with weightlifting performance.

PRACTICAL APPLICATIONS

The present meta-analysis shows that BS and FS 1-RM exhibit *nearly perfect* correlations with SN and C&J. As these assessments represent the maximal dynamic force capacity of the lower body, they provide vital information about weightlifting performance potential. Based upon these findings, it is the recommendation of the authors that at the very least weightlifting Coaches should monitor of BS and/ or FS 1-RM within a weightlifter's training program. Whilst the BS and FS 1-RM assessments are highly accessible, simple to perform and easily implemented, frequent maximal strength testing using these exercises may not always be compatible with the different phases of training, due to the potential of large residual fatigue (55). Furthermore, these assessments do not allow for the examination of both maximal and time-dependent strength characteristics, limiting our analyses of the athlete's physical profile and specific adaptations in response to training (43). Alternatively, maximal force capacity may be assessed using the IMTP, which is logistically easier to perform, requires less preparation time and causes less residual fatigue (55). Although not to the same magnitude, both maximal and time-dependent force characteristics (PkF and F@201-250 ms) in the IMTP, exhibited *very large* correlations with SN and C&J performance. These findings also emphasize the importance of developing maximal strength in the squat and pull components of the lifts, therefore should be addressed through specific training. Of the CMJ and SJ assessments, PkP showed the greatest correlations with weightlifting performance and is therefore arguably the most appropriate jump variable to examine as an indicator of performance potential. However several recent studies have suggested this variable is unlikely to change in response to long-term weightlifting training (27,32), therefore may not reflect the relevant neuromuscular adaptations. Only a limited number of variables within these jumps have been examined in the literature, therefore future studies may consider examining additional muscle contraction specific or time-dependent variables in relation to performance.

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Table 1. Study Characteristics. Methodological Factors with AXIS tool quality checklist.

Study	Physical assessment relative to performance assessment	Equipment Detail	Performance assessment	Isometric Strength Assessment	Dynamic Strength Assessment	Jump Assessment	AXIS Tool Score
Stone et al. (56) i	Self-reported at time of physical assessment	-	Self-reported: SN and C&J	-	Self-reported: BS 1-RM	-	12
Stone et al. (56) ii	1.5 weeks pre-competition	Force Plate 600 Hz: IMTP	Competition: SN and C&J	IMTP: PkF	-	-	
Beckham et al. (4)	10 days post-competition	Force Plate 1000 Hz: IMTP	Competition: SN and C&J	IMTP: PkF, F@100, 150, 200, 250 ms, RFD0- 100, 150, 200, 250 ms, PkRFD	-	-	15
Joffe & Tallent (32)	1 year average	Force Plate 1000 Hz: IMTP, CMJ	Competition: SN and C&J	IMTP: PkF	-	CMJ PkD; PkP (Force-time derived); PkCONF, PkV	15
Haff et al. (19)	Physical assessment relative to performance assessment not specified	Force Plate 600 Hz: IMTP; Jump Mat: CMJ, SJ	Competition: SN and C&J	IMTP: PkF, PkRFD	-	CMJ PkD, PkP (Sayers equation); SJ PkD, PkP (Sayers equation).	14

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 PkD, PkP (Sayers equation); SJ PkD, PkP (Sayers equation).	12
Lucero et al. (38)	Self-reported physical assessment and performance assessments	-	Self-reported SN and C&J	-	Self-reported: BS, FS 1-RM	-	14
Zaras et al. (64)	48 hours pre-performance Assessment	Force Plate 1000 Hz: CMJ	Laboratory-based: SN and C&J	-	-	CMJ PkD, CMJ PkP (Sayers equation), PkV.	15
Zaras et al. (65)	Pre and Post 16-week intervention. Physical relative to performance assessment not specified	Force Plate 1000 Hz: CMJ	Laboratory-based: SN and C&J	-	-	-	13
Joffe et al. (31)	4 to 8 weeks Pre/ Post-Competition	Force Plate 1000 Hz: IMTP	Competition: SN and C&J	IMTP: PkF	-	-	16
Ince & Ulupinar (29)	7- to 10 days post-competition	Opto-Jump: CMJ, SJ	Competition: SN and C&J	-	-	CMJ PkD; SJ PkD.	13

Ulupinar & Ince (60)	7 to 10 days post-competition	Opto-Jump: CMJ, SJ	Competition: SN and C&J	-	-	CMJ PkD; SJ PkD.	15
Hornsby et al. (27)	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: PkF; F@50, 90, 200, 250; RFD0- 50, 90, 200, 250 ms.	-	SJ PkD, SJ PkP (Force-Time Derived).	16

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, PkF = Peak Force, F@ = Force at specified time point, RFD = Rate of Force Development, PkRFD = Peak Rate of Force Development, PkD = Peak Displacement, PkP = Peak Power, PkV = Peak Velocity. Stone et al. (56) i and ii refers to two separate groups examined in this study.

Table 2. 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. (56) 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. (56) 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*: PkF 4420 ± 1191 N	*IMTP*: PkF: 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*: PkF 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; PkRFD 33231 ± 13296 N.s	*IMTP*: PkF: 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. PkRFD: SN *r* = 0.43; C&J *r* = 0.36.

Joffe & Tallent (32)	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*: PkF 2572 ± 496.3 N. *CMJ*: PkD 37.55 ± 5.51 cm; PkP 3324 ± 534.2 W; CON PkF 2572 ± 496.3 N; PkV 2.82 ± 0.29 m.s	*IMTP*: PkF: SN *r* = 0.83; C&J *r* = 0.90. *CMJ*: PkD: SN *r* = 0.48; C&J *r* = 0.43. PkP: SN *r* = 0.88; C&J *r* = 0.76. CON PkF: SN *r* = 0.53; C&J *r* = 0.56. CMJ PkV: SN *r* = 0.51; C&J *r* = 0.44.
Haff et al. (19)	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*: PkF 3649.2 ± 824.3 N; PkRFD 13997 ± 1879.3 N.s. *CMJ*: PkD 31.0 ± 4.0 cm; PkP 3661.6 ± 728.9 W. *SJ*: PkD 29.0 ± 5.0 cm; PkP 3524.5 ± 711.5 W	*IMTP*: PkF: SN *r* = 0.93; C&J *r* = 0.64. PkRFD: SN *r* = 0.79; C&J *r* = 0.69. PkD: SN *r* = -0.34; C&J *r* = -0.59. PkP: SN *r* = 0.82; C&J *r* = 0.60. *SJ*: PkD: SN *r* = -0.25; C&J *r* = -0.49. PkP: 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*: PkD 41.3 ± 8.8 cm; PkP 3985 ± 1188 W. *SJ*: PkD 37.5 ± 7.5 cm; PkP 3750 ± 1157 W	*CMJ*: PkD: SN *r* = 0.60; C&J *r* = 0.59. PkP: SN *r* = 0.93; C&J *r* = 0.91. *SJ*: PkD: SN *r* = 0.64; C&J *r* = 0.64. PkP: SN *r* = 0.92; C&J *r* = 0.90.
Lucero et al. (38)	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. (64)	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*: PkD 29.6 ± 5.3 cm; PkP 2623.1 ± 418.7 W; PkF *NR;* PkV 2.5 ± 0.4 m.s.	*CMJ*: PkD: SN *r* = 0.84; C&J *r* = 0.89. PkP: SN *r* = 0.86; C&J *r* = 0.79. PkF: SN *r* = -0.23; C&J *r* = -0.26. PkV: SN *r* = 0.83; C&J *r* = 0.89.
Zaras et al. (65)	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*: PkD 46.85 ± 6.1 cm; PkP 4782.85 ± 660.9 W; PkF 1551.5 ± 316.9 N; PkV 3.85 ± 0.5 m.s; *BS 1-RM*: 223.9 ± 28.7 kg; *FS 1-RM*: 197.5 ± 27.2 kg.	*CMJ*: PkD: SN *r* = 0.57; C&J *r* = 0.59. PkP: SN *r* = 0.84; C&J *r* = 0.88. PkF: SN *r* = 0.82; C&J *r* = 0.86. PkV: 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. (31)	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*: PkF 2640 ± 76 N.	*IMTP*: PkF: SN *r* = 0.83; C&J *r* = 0.88.
Ince & Ulupinar (29)	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*: PkD 41.54 ± 8.88 cm. *SJ*: PkD 32.27 ± 9.94 cm.	*CMJ*: PkD: SN *r* = 0.86; C&J *r* = 0.83. *SJ*: PkD: SN *r* = 0.78; C&J *r* = 0.75.
Ulupinar & Ince (60)	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*: PkD 32.52 ± 6.54 cm. *SJ*: PkD 30.12 ± 3.68 cm	*CMJ*: PkD: SN *r* = 0.80; C&J *r* = 0.77. *SJ*: PkD: SN *r* = 0.73; C&J *r* = 0.73.
Hornsby et al. (27)	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*: PkF 4966.6 ± 969.4 N; F@0-50 ms 1704.7 ± 713.4 N; F@90 ms	*IMTP*: PkF: SN *r* = 0.72; C&J *r* = 0.79. F@50 ms: SN *r* = 0.57; C&J *r* = 0.66.

2436 ± 1024.7 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*: PkD: 31.46 ± 6.58 cm; PkP 4521.9 ± 1215.1 W.	F@90 ms: SN *r* = 0.60; C&J *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*: PkD: SN *r* = 0.70; C&J *r* = 0.71. PkP: 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, PkF = Peak Force, F@ = Force at specified time point, RFD = Rate of Force Development, PkRFD = Peak Rate of Force Development, PkD = Peak Displacement, PkP = Peak Power, PkV = Peak Velocity. Stone et al. (56) i and ii refers to two separate groups examined in this study.