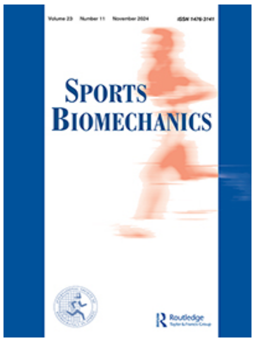

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A comparison of maximal isometric force in the first pull, transition and second pull of the clean and their contribution to predict performance in national and international level weightlifters

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ABSTRACT

This study aimed to examine differences in isometric peak force (PF) at the start of the first pull, transition, and second pull phases of the clean, and determine their contribution in explaining the variance in snatch and clean & jerk (C&J) performance. Thirty-one national and international level male and female weightlifters participated. Isometric start position pull (ISPP), isometric transition position pull (ITPP), and isometric mid-thigh pull (IMTP) PF, along with competition performance, were analysed both in absolute and allometrically scaled terms. Partial Least Squares Regression identified a single latent variable explaining 81.4% of the variance in Snatch and 79.6% in C&J. ISPP PF alone significantly contributed to explaining the variance the snatch and C&J. For allometrically scaled values, a single latent variable accounted for and 62.8% variance in Snatch and 60.7% of the variance in C&J, with ISPP PF significantly contributing to the Snatch and approached significance for C&J ($p = 0.056$). These results underscore the importance of evaluating maximal force in the initial lift phase and suggest that training to enhance strength in this phase may be crucial for improving weightlifting performance.

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KEYWORDS
Strength; force; snatch; Clean and Jerk; determinants

Introduction

Weightlifting performance is determined based on the highest cumulative weight successfully lifted in the Snatch and Clean & Jerk (C&J). The pull is a critical component to either lift, as this constitutes the phase where net vertical ground reaction forces (VRGF) are applied, causing the vertical acceleration and projection of the barbell. For a successful catch in the snatch or clean, the barbell must attain a minimum vertical displacement, allowing the lifter sufficient time to drop underneath it (Sandau et al.,

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2021). Given that the displacement of the barbell is determined by the net impulse (force x time) applied to the ground, relative to the system mass (body mass + bar mass) across the entire pull phase, the capacity to generate force across all positions of the pull is likely a key limiting factor to performance. The pull phase occurs from the moment the barbell breaks contact with the floor until the final maximum extension angle of the knee, yet it is further divided into three sub-phases; the first pull, transition and second pull (Chavda et al., 2021; Garhammer, 1982). Each of these sub-phases demonstrates unique vertical ground reaction force-time profiles, influenced by differences in external joint moments and functioning across different regions of the length-tension and force–velocity curves (Kipp & Harris, 2014; Kipp et al., 2012). Considering that the cumulative impulse generated throughout these phases directly influence the vertical velocity and displacement of the barbell at the end of the pull, it is plausible that assessing maximal isometric force at positions consistent with these phases, could provide a deeper insight into the athlete's force generating capabilities pertaining to the pull.

The evaluation of maximal isometric force capacity at different key positions within the pull was first proposed by Vorobyev (1978), advocating for testing the start position, near maximal leg extension (bar positioned at mid-thigh with a slight knee bend) and at maximal leg extension with the bar positioned at the waist with a slight arm bend. It was reported that these positions produced 1471–2649 N, >4905 N and 1079–1962 N, respectively. This indicates that there is an increase in force capacity throughout the pull, followed by a decrease once peak extension was achieved and the arms had proceeded to bend. Within the contemporary peer-reviewed literature and applied sports science practices in weightlifting, the assessment of maximal isometric force capacity in the pull has predominantly been conducted using the isometric mid-thigh pull (IMTP) (Beckham et al., 2013; Hornsby et al., 2017; Stone et al., 2019). This test was purposefully designed to correspond to the start of the second pull (Haff et al., 1997) as the greatest force, velocity and power output are generated during this phase (Comfort et al., 2023). The IMTP has been investigated extensively in its relationship with weightlifting performance, with a recent meta-analysis summarising these studies, revealing *very large* correlations between its peak force (PF) measures with snatch and C&J performance ($r = 0.83$, [95%CI 0.73–0.90] $r = 0.85$ [95%CI 0.76–.91], respectively) in national and international level male and female weightlifters (Joffe et al., 2023). Several researchers have also recently examined isometric force capacity in positions corresponding to the start of the first pull and transition phases, using the isometric start position pull (ISPP) and isometric transition position pull (ITPP) (Ben-Zeev et al., 2023; Joffe et al., 2021). Collectively, these investigations illustrate significantly higher PF in the IMTP compared to both the ISPP and ITPP (Ben-Zeev et al., 2023 IMTP 3680 ± 920 N, ITPP 2495 ± 694 N, ISPP 2463 ± 642 N, respectively, $p < 0.001$; Joffe et al. IMTP 2640 ± 767 N, ISPP 1443 ± 425 N, $p < 0.001$). Interestingly, despite their lower force production, significantly stronger correlations between ISPP and ITPP and weightlifting total compared to IMTP were reported (Ben-Zeev et al. ISPP $r = 0.95$, ITPP $r = 0.95$, and IMTP $r = 0.88$, $Z = 1.7$, $p < 0.05$; Joffe et al, ISPP $r = 0.95$, IMTP $r = 0.86$, $Z = 2.05$, $p < 0.05$). These findings imply that maximal force generation in the earlier, weaker phases of the lifts may be a more critical determinant of performance, than in the latter portion of the lift. This observation finds support in a variety of other studies.

For instance, elite weightlifters have been shown to produce greater peak VGRF relative to the system mass during the first pull in the snatch and clean compared with district-level weightlifters, with no differences observed in the transition and second pull phases of the lift between competitive levels (Häkkinen & Kauhanen, 1986; Häkkinen et al., 1984; Kauhanen et al., 1984). This indicates that elite weightlifters are required to produce a larger proportion of the total impulse during the first pull. Alternatively, this may be attributed to elite-level weightlifters displaying greater intent in this portion of the lift. Additionally, while both the mean resultant force in the first and second pull phases demonstrate strong correlations with the barbell load at 90% of clean 1RM ($r = 0.98$ vs. $r = 0.91$, respectively) (Sorensen et al., 2022), the first pull reveals a slightly higher correlation. Although this difference falls just short of statistical significance ($p = 0.08$), this indicates that force production during the earlier portion of the lift could have a greater influence on lift performance.

Furthermore, several studies have shown when performing the snatch and clean across incremental loads, the first pull experiences a greater attenuation in the ability to accelerate the barbell compared with the transition and second pull phases (Ammar et al., 2018; Hadi et al., 2012; Sandau & Granacher, 2020). These collective findings strongly support the notion that the strength capacity during the first pull is potentially a more critical determinant of weightlifting performance. This prompts a valid consideration, whether achieving a comprehensive understanding of the force generating capacity of the pull phase necessitates the inclusion of the ISPP, ITPP and IMTP, and if each offers unique insights into the neuromuscular characteristics of the pull which underpin performance.

The assessment of isometric force within these three positions each evaluate the force capacity of the hip, knee and ankle extensor muscle groups, albeit with slightly different mechanical demands. It is therefore logical to predict that the PF values measured from each position will exhibit high collinearity, which is consistent with previous reports (Joffe et al., 2021). This poses a challenge for employing multiple linear regression models to evaluate their collective contribution to performance, since highly collinear predictor variables are excluded based on several criteria in order to attain a more reliable regression model (Kim, 2019). To address this issue, Partial-Least Squares Regression (PLSR) is a viable alternative method of analysis, able to handle collinear predictor variables and produce reliable coefficient estimates and non-inflated standard errors (Abdi & Williams, 2013). Moreover, PLSR is appropriate for the analysis of small sample sizes (Hair et al., 2017), which is often the case in elite populations. Understanding the contribution of force production of each sub-phase of the pull to Snatch and C&J performance may offer valuable insights into the neuromuscular qualities which determine vertical barbell acceleration during the pull phase, and underpin superior weightlifting performance. This study offers a unique examination of how the three isometric pull assessments collectively explain the variance in snatch and C&J performance, employing a PLSR to account for the collinearity among predictor variables. The findings of this study may help to better understand factors that underpin weightlifting performance within implications for both monitoring and training practices. The aims of this study were 1) to investigate the differences in isometric PF between the ISPP, ITPP and IMTP and, 2) to determine their collective contribution in explaining the variance in snatch and C&J performance. It is hypothesised that there will be significant differences in force production between each pulling phase, illustrating a continual increase in force capacity across the ascending phases of the pull. Furthermore, it is hypothesised that the PF obtained from each isometric pull position will significantly contribute to the prediction of snatch and C&J performance.

Materials and methods

To address the research question, an investigation was conducted using physical assessment and competition performance data obtained through routine sports science practices of the British Weight Lifting Performance programme between 2014 and 2017. The physical assessment data included the measurement of net PF from the ISPP, ITPP, and the IMTP. The competition data included body mass recorded during the weigh-in, as well as the best successful attempts in both the snatch and C&J. A PLSR analysis was then used to investigate the whether these three isometric pull tests collectively explain a portion of the variance in Snatch and C&J performance.

Participants

This study included thirty-one male and female weightlifters (male; $n = 15$, body mass 79.9 ± 20.8 kg, female; $n = 16$, 58.5 ± 7.7 kg), spanning across youth, junior (13–20 years of age) and senior (20+ years of age) categories. All individuals included in the study were affiliated with either the British Weight Lifting (BWL) Performance or Development Pathway programmes at the time of data collection. Ethical clearance for this project was obtained from a university ethics committee (SMU_ETHICS_2023-24_485), and further authorisation for utilising the data was secured from the BWL National Governing Body. Notably, the athletes' data, constituting part of their routine sport science support services, had been systematically collected as per established practices suitable for publication (Winter & Maughan, 2009). For each participant, the analysis included the most recent isometric assessment data collected on the same day, within 1–5 weeks of the respective competition with an average of 3.1 ± 1.6 weeks.

Predictor variables – Isometric pull assessments

All isometric assessment were performed using the bilateral ForceDecks force plate system (2 × 350 mm x 750 mm ForceDecks FD4000 Force Platforms, NMP Technologies, London, UK) with accompanying analysis software (NMP Technologies, London, UK), operating at a sampling frequency of 1000 hz. The isometric assessments were conducted using a customised rig featuring bar attachment points at 2.5 cm intervals along the vertical bar supports. The tests were performed in a standardised order: IMTP, ITPP, and the ISPP. Body mass was also collected for analysis at the start of each isometric assessment.

The IMTP test position was determined in accordance with established guidelines (Comfort et al., 2019). The knee and hip angles were set using a hand-held goniometer to between 125–145° and 140–150°, respectively, with the torso oriented vertically. The bar was held in a clean grip with straight arms, and the centre of the feet were placed directly beneath the centre of the bar and approximately hip-width apart. For the ITPP, the bar height was established at the centre of the knee joint, marking the end of the first pull and start of the transition phase (Ben-Zeev et al., 2023). The shoulders were oriented anteriorly relative to the bar; therefore, the torso was positioned with a positive angle. For the ISPP, a consistent bar position was utilised for all participants, aligned with the height of an Olympic bar loaded with IWF standard competition disks of 45 cm diameter, resulting in centre of the bar 22.5 cm from the floor. For each test, participants were instructed to adopt their 'natural' foot position as they would when performing lift, which was approximately hip width apart. Weightlifting shoes and pulling straps were mandatory, and standardised for all three tests. Example set-up for each isometric test is presented in Figure 1. The assessment occurred at the start of training sessions, following a standardised warm-up protocol encompassing bar warm-up drills and warm-up attempts of the first exercise of the day's training session. All assessments were conducted before the heaviest working set of the first exercise of the lifter's training session. As participants were highly familiar with the testing protocols, they each conducted a single warm-up attempt at ~ 90% perceived effort before their initial maximal attempt for each test. For all isometric assessments, participants were instructed to 'push as hard as possible' and to 'keep pushing until signalled to release' (Comfort et al. 2019). A signal to cease the test was given one second after the force trace plateaued or continued to decline, and each test lasted approximately 2 to 4 seconds. Instruction was provided participants that the test would be halted if any visible changes in spinal alignment were observed. Additionally, the cue to 'push as fast as possible' was deliberately omitted for the ISPP and ITPP positions, allowing athletes to apply force more gradually, thus

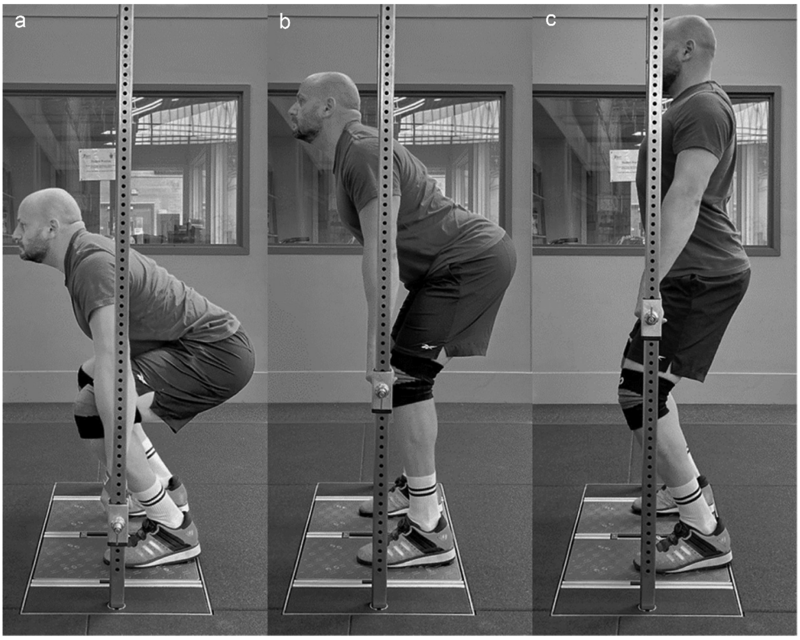

Figure 1. Set-up positions for isometric testing: (a) Isometric Start Position Pull (b) Isometric Transition Position Pull, and (c) Isometric Mid-Thigh Pull.

minimising the risk of a sudden ‘jerk’ at the onset of the pull. Two to three trials were performed for each athlete with 2 to 3 minutes rest between attempts. The number of trials performed was based on the on whether the athlete felt that they had achieved their maximal effort on the test and considered factors such as their perception of accumulating fatigue across trials. The net PF was collected, and the maximum value of all trials was utilised for analysis. The test-retest reliability for net PF for the IMTP, ITPP and ISPP was ICC = 0.97 (95% CI 0.92–0.99) and CV = 2.8%, ICC = 0.90 (95% CI 0.76–0.96) and CV = 5.0%, ICC = 0.98 (95% CI 0.95–0.99) and CV 1.3%, respectively.

Outcome Variables - competition performance

The competition performance data (Snatch and C&J) were collected from national championship competition in the United Kingdom, IWF-sanctioned competitions, and the European U23 Championships (an event not sanctioned by the IWF), spanning from January 2014 to December 2017. All competition data were obtained from publicly available sources, including the BWL, IWF, and European Weightlifting Federation (EWF) websites (www.britishweightlifting.org; www.IWF.net; www.ewfed.com). Test–retest reliability of weightlifting performance in international male and female weightlifters has been reported as 2.5% to 3.2% (McGuigan & Kane, 2004).

Statistical analysis

All data are presented as Mean and Standard Deviation (SD). Normality of the isometric assessment and competition performance data was evaluated using the Shapiro-Wilks test and through visual inspection of Q-Q plots. Isometric assessment and competition performance data are presented in absolute values and allometrically adjusted to body mass, utilising a power exponent of 0.67 (Jaric et al., 2005). Allometric scaling was used to normalise competition and isometric strength measures to body mass, accounting for the non-linear relationship between strength and body size. This was done to control for the influence of body mass on the study results. To explore differences among the three isometric testing positions a one-way analysis of variance (ANOVA) was employed. In instances where Mauchly’s test of sphericity was violated, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom. Subsequently, *post hoc* analysis was conducted using the Bonferroni method to identify specific pairwise differences among the isometric testing positions. Pearson’s correlation coefficient was used to assess the collinearity between the three isometric pull positions. These analyses were performed using IBM SPSS Statistics for Windows, Version 28.0 (IBM Corp., Armonk, NY, USA). A PLSR was utilised to explore the variance in Snatch and C&J Performance (response variables) based on the ISPP, ITPP, and IMTP (predictor variables). This test was chosen for its adeptness in managing high collinearity among predictor variables, due to the large intercorrelations between the three isometric pull positions. In PLSR analysis, predictor variables are projected onto latent variables to extract the fundamental components necessary to elucidate the maximum variance in the response variable. The root mean square error of prediction (RMSEP) cross validation (CV) was computed for each PLSR latent factor, with the lowest residual error of prediction selected as the most suitable model for predicting each performance variable. The PLSR model was cross-

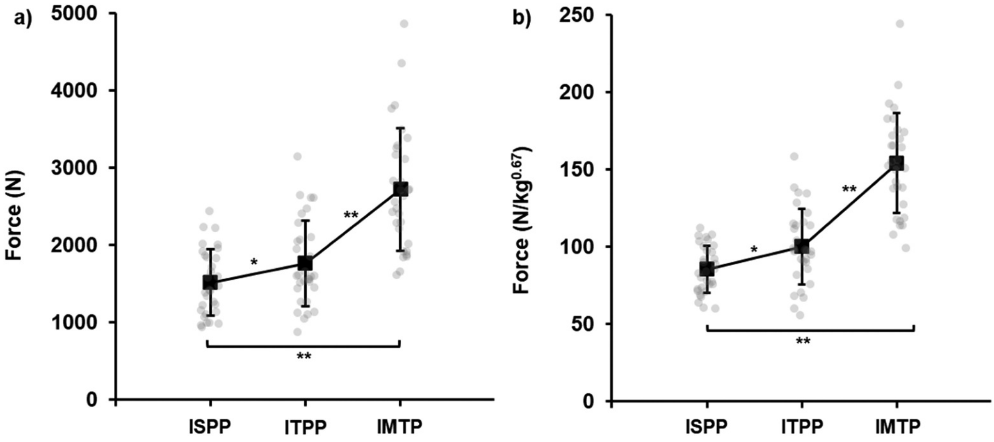

Figure 2. Absolute (a) and allometrically scaled (b) net peak force for ISPP, ITPP and IMTP. IPSS = Isometric Start Position Pull, ITPP = Isometric Transition Position Pull, IMTP = Isometric Mid-Thigh Pull. * = $p < 0.01$, ** = $p < 0.001$.

validated using $k = 10$ folds, with the RMSEP CV reported. The number of latent variables selected were based on the optimal fit of the model according to the R^2 value and the minimum RMSEP CV. The weights and loadings for each predictor variable were calculated for the latent variables. The weights represent the coefficients that determine the linear combination of predictor variables used to construct the latent variables. Loadings indicate the coefficients that describe the relationship of each predictor variable to the latent variables. The individual contribution of predictor variables to the PLSR model was assessed using a Jack-knife t-test. The Alpha level was set at 0.05. These analyses were conducted in R (version 4.2.3 R Foundation for Statistical Computing, Vienna, Austria).

Results

The mean ± SD for Snatch and C&J were 96.7 ± 28.5 kg and 120.2 ± 33.3 kg, respectively. When allometrically scaled to body mass, the mean ± SD for Snatch and C&J were 5.6 ± 1.1 $kg.kg^{0.67}$ and 7.0 ± 1.2 $kg.kg^{0.67}$, respectively. The mean ± SD and results of the One-way ANOVA comparing PF across the three isometric assessment positions in absolute and allometrically scaled terms are presented in Figure 2. The analysis revealed significant effects for both absolute PF ($F(2,28) = 33.404$, $p < 0.001$) and allometrically scaled PF ($F(2,28) = 65.467$, $p < 0.001$) across all testing positions.

To illustrate the collinearity between predictor variables, a Pearson's Correlation Coefficient's matrix is presented in Table 1. The results of the PLSR analysis, based on the RMSEP minimisation from k-fold cross-validation, revealed that a single latent variable was optimal for predicting performance in both the Snatch and C&J. The weights and loadings of the latent variable in each PLSR analysis are presented in Table 2. The RMSEP CV values were 13.3 ± 4.1 kg for the Snatch and 16.6 ± 6.4 kg for the C&J, with corresponding R^2 values of 81.4% and 79.6%, respectively. Furthermore, a single latent variable was revealed as optimal to predict Snatch Al and C&J Al. The

Table 1. Collinearity matrix of predictor variables.

	ISPP	ITPP	IMTP	ISPP AI	ITPP AI	IMTP AI
ISPP	1	0.89 (0.78–0.94) **	0.88 (0.66–0.91) **	–	–	–
ITPP	0.89 (0.78–0.94) **	1	0.83 (0.67–0.92) **	–	–	–
IMTP	0.88 (0.66–0.91) **	0.83 (0.67–0.92) **	1	–	–	–
ISPP AI	–	–	–	1	0.82 (0.66–0.91) **	0.60 (0.31–0.79) **
ITPP AI	–	–	–	0.82 (0.66–0.91) **	1	0.64 (0.36–0.81) **
IMTP AL	–	–	–	0.60 (0.31–0.79) **	0.64 (0.36–0.81) **	1

Isometric Start Position Pull, ITPP = Isometric Transition Position Pull, IMTP = Isometric Mid-Thigh Pull, AI = Allometrically scaled. ** = $p < 0.01$.

Table 2. Weight and loading of predictor variables of the latent variable for the partial least squares regression analyses: absolute and allometrically scaled weightlifting performance measures.

	Snatch		Clean & Jerk	
Variable	Weight	Loading	Weight	Loading
ISPP PF	0.616	0.584	0.621	0.584
ITPP PF	0.568	0.583	0.571	0.583
IMTP PF	0.546	0.567	0.537	0.566
Response Variable	0.550	1	0.545	1
	Snatch AI		Clean & Jerk AI	
Variable	Weight	Loading	Weight	Loading
ISPP PF AI	0.652	0.603	0.660	0.607
ITPP PF AI	0.596	0.605	0.612	0.609
IMTP PF AI	0.469	0.525	0.436	0.520
Response Variable	0.516	1	0.508	1

Isometric Start Position Pull, ITPP = Isometric Transition Position Pull, IMTP = Isometric Mid-Thigh Pull, AI = Allometrically scaled.

RMSEP CV values were 0.69 ± 0.25 $kg/kg^{0.67}$ for the Snatch AI and 0.84 ± 0.35 $kg/kg^{0.67}$ for the C&J AI, with corresponding R^2 values of 62.8% and 60.6%, respectively. The contribution of each predictor variable in each of the analyses, are presented in Table 3.

Discussion and implications

The aims of this study were 1) to investigate the differences in isometric PF between the ISPP, ITPP and IMTP and, 2) to determine their collective contribution in predicting snatch and C&J performance. Significant differences were observed in PF between all isometric testing position illustrating a continual increase in maximal force capacity across the ascending phases of the pull, therefore the first hypothesis is accepted. The

Table 3. Partial least square regression model predicting snatch and Clean & Jerk performance and the contribution from each predictor variable.

Snatch Model				Clean & Jerk Model		
Latent Variables	1			1		
RMSEP CV (kg)	13.3 ± 4.1			16.6 ± 6.3		
R^2	81.4%			79.6%		
Predictor Variables	Estimate	t	p	Estimate	t	p
ISPP PF	***20.3298***	***4.4284***	***0.002*****	***24.8082***	***4.1897***	***0.002*****
ITPP PF	2.2534	0.4460	0.666	3.3994	0.4997	0.629
IMTP PF	4.4657	0.9810	0.352	2.9479	0.4956	0.632
Snatch AI Model				Clean & Jerk AI Model		
Latent Variables	1			1		
RMSEP CV ($kg/kg^{0.67}$)	0.69 ± 0.25			0.84 ± 0.35		
R^2	62.8%			60.6%		
Predictor Variables	Estimate	t	p	Estimate	t	p
ISPP PF AI	***0.62318***	***2.7797***	***0.021****	0.708930	2.1923	0.056
ITPP PF AI	0.19107	0.6247	0.54769	0.307947	0.8976	0.392
IMTP PF AI	0.11430	0.5472	0.59753	0.021465	0.1693	0.869

RMSEP = Root mean Square Error of Prediction, CV = Cross-Validation, Isometric Start Position Pull, ITPP = Isometric Transition Position Pull, IMTP = Isometric Mid-Thigh Pull, PF = Peak Force, AI = Allometrically scaled. * = $p < 0.05$, ** = $p < 0.01$.

PLSR analyses revealed a single latent factor was included for each model of the response variables (Snatch and C&J), therefore the second hypothesis is rejected. The models accounted for 80–81% of the variance in absolute performance measures, 61–63% of the variance in allometrically scaled performance measures. Further analysis revealed that only the ISPP was a statistically significant predictor for all performance measures, with the exception for the C&J Al, where it approached statistical significance ($p = 0.056$). The results of the PLSR align with several previous studies, demonstrating the superior predictive capability of the ISPP PF for snatch and C&J performance compared to IMTP PF (Ben-Zeev et al., 2023; Joffe et al., 2021; Rochau et al., 2024). However, it is important to note that the similarity in weights and loadings suggests that all predictor variables contribute approximately equally to the latent variables. This could be due to the predictors being highly correlated with each other or containing similar information about the response variable. Despite the similar loadings and weights, the jack-knife t-test indicates that only ISPP PF is statistically significant. This implies that ISPP PF has a unique or stronger association with the response variable. A key contribution of this study to the subject area is its examination of all isometric pulling positions aligned with the sub-phases of the pull and their collective contribution in explaining the variance in snatch and C&J performance while accounting for the collinearity among these measures. Whilst previous studies have identified the greater correlation between ISPP PF and weightlifting performance compared with the IMTP PF (Ben-Zeev et al., 2023; Joffe et al., 2021; Rochau et al., 2024), the results of the present study further support the value of the ISPP, by showing that incorporating ITPP PF and IMTP PF does not enhance the prediction of performance beyond what ISPP PF alone provides. These findings, in conjunction with previous research, indicate that the ISPP PF offer the greatest prediction of performance and therefore, may be considered the optimal position for evaluating maximal isometric pull strength in weightlifters.

Several researchers have previously examined step-wise multivariate regression modelling techniques for predicting weightlifting performance based on neuromuscular assessment variables (Joffe & Tallent, 2020; Shetty, 1990). Shetty (1990) examined the predictive value of isolated knee extensor, back extensor strength performed using a spring dynamometer, and body mass for Jerk and Snatch performance. They report that back and leg extensor strength explained 75% of the variance in Jerk performance, while body mass and leg extensor strength explained 64% of the variance in Snatch performance. The author noted in their statistical analysis that variables were included in the model provided they did not increase the standard error. While this approach partially addresses the issue of collinearity among predictor variables, it does not directly mitigate it. Their correlation matrix of the predictor variables illustrates a strong correlation between leg strength and back strength ($r = 0.89$). However, neither this nor a variance inflation factor (VIF) was considered in determining which variables to include in the model, therefore could distort the model's estimates and interpretation. More recently, Joffe and Tallent (2020) investigated the predictive power of IMTP and countermovement jump (CMJ) variables in relation to snatch, C&J, and Total performance. In this study, the authors reported evaluating collinearity among predictor variables using a VIF tolerance threshold of < 0.10. They set the F value at 0.5 for entry and 0.10 for removal from the model which is within the standard practices in sport science research (Field, 2013). Their findings revealed that IMTP PF and CMJ peak power (PP) accounted for 95.1%, 91.2%, and 94.2% of the variance in snatch, C&J, and Total performance, respectively. However, when evaluating the annual percentage change in these measures in relation to annual percentage change in performance, solely IMTP PF remained significant in the regression model. This suggests that while both IMTP and CMJ are associated with performance, only maximal isometric strength appears to drive longitudinal changes in performance. Despite the robust statistical approach used in this study to manage collinearity, challenges remain in understanding predictors of performance. Although criteria to control for highly collinear variables can lead to more accurate estimates with reduced error, excluding these variables may overlook their potentially minor contributions to further explaining the variance in performance. Therefore, the PLSR approach as conducted in the present study, reduces multicollinearity in the constructed components and improves the stability and interpretability of the regression model, making it better at dealing with highly collinear predictors. The disparities in both the types of neuromuscular assessments used and the statistical methods applied between prior studies and the present investigation present challenges for direct comparisons. However, collectively, these studies underscore the importance of maximal force production in the muscle groups responsible for hip and knee extension in the pull.

To date, multiple researchers have reported similar findings to the present study, showing that isometric PF measured particularly during the initial, weaker phase of multi-joint ascending strength curve exercises (such as the back squat and deadlift) correlate more strongly with the exercise's 1RM than PF measured during the latter, stronger phase (Bartolomei et al., 2019; Bazyler et al., 2015; Ben-Zeev et al., 2023). These findings are somewhat in contrast with previous recommendations for isometric testing, which advocate for the assessment to be performed at the peak of the strength curve where isometric PF and rate of force development (RFD) are optimised (Wilson & Murphey, 1996). These recommendations were proposed to standardise the reference point for testing, ensuring consistency and aiming to enhance test reliability. However, the authors advised caution and called for additional research to confirm their preliminary conclusions. The greater correlation between isometric PF measures in the earlier portion of the movement and 1RM performance may be attributable to several factors. Firstly, isometric PF obtained from the weaker earlier portion of the concentric phase of a lift potentially serves as the limiting factor for the maximal load that can be lifted. Additionally, in the case of the snatch and clean lifts, the stronger relationship between ISPP PF and lift 1RM may be due to its greater specificity to the first pull compared with the IMTP to the second pull. For example, the first pull involves initiating the lift from a static position, requiring the overcoming of inertia and exhibiting a lower vertical barbell velocity, making it more similar to the isometric contraction of the ISPP due to their closer proximity on the force-velocity spectrum. In contrast, the isometric PF obtained from the IMTP is more dissimilar to the second pull phase, where the barbell is moving at between 1.7–2 m/s (Ammar et al., 2018; Cunanan et al., 2020; Korkmaz & Harbili, 2016), thereby showing lower proximity on the force-velocity spectrum. Thus, the degree of specificity according to the mode of muscle contraction may also contribute to the stronger association between isometric ISPP PF and 1RM performance in these lifts. Overall, the growing body of evidence appears to suggests that where isometric tests are used as a surrogate measure to infer lifting performance in ascending strength curve exercises, the assessment of isometric PF should be conducted at the weakest mechanical position, corresponding to the beginning of the concentric phase of the movement.

To date, this is only the second study to examine maximal force capacity in the ITPP, alongside the ISPP and IMTP. While these findings are generally consistent with previous reports (Ben-Zeev et al., 2023), this study reveals significant differences between all pulling positions, including the ITPP and ISPP, for both absolute and allometrically scaled measures, that were not previously identified. These results, along with several other recent reports (Ben-Zeev et al., 2023; Joffe & Tallent, 2020; Rochau et al., 2024) demonstrate that maximal isometric PF capacity increases continually across the ascending sub-phases of the pull. This is likely due to increasing mechanical advantage and a more optimal muscle length for force production in the extensor muscle groups of the hip and knee joints throughout the pull (Choe et al., 2018; Cotter et al., 2013; Flores et al., 2018). Given that the ISPP represents the weakest part of the lift, it is logical to conclude that this phase likely imposes the primary limitation on the maximal load that can be lifted, and therefore explains the greater correlation to lift performance. The significantly greater ITPP PF than the ISPP PF is somewhat contrary to the VGRF-time profiles typically observed in the snatch and clean lifts, where a noticeable decline in force occurs during the transition phase (Chavda et al., 2021; Häkkinen & Kauhanen, 1986; Häkkinen et al., 1984; Kauhanen et al., 1984; Sorensen et al., 2022). This finding indicates that maximal force capacity does not explain the observed decline in force output and barbell velocity and acceleration during this phase and instead is more likely influenced by technical factors. However, as no biomechanical analysis of this lifts themselves were conducted in this investigation, therefore further research is warranted to confirm this interpretation.

These findings not only have significant implications for selecting neuromuscular assessments for weightlifters but also potentially valuable insights for their training practices. The emphasised importance of maximal force production from the start position suggests that developing maximal strength in this phase of the lift is crucial, and should be targeted with the use of first pull-specific weightlifting derivatives. Whilst there is a notable absence of experimental research investigating the effects of different training methods targeted towards the development of specific phases of the pull, there is an extensive body of research investigating range-of-motion and muscle-length specific strength training that have potential implications for this. The results of several similar studies collectively demonstrate a more pronounced transfer of strength improvements from strength training at long muscle-lengths to short muscle-lengths, contrasting with the limited transfer in the opposite direction (Bloomquist et al., 2013; Graves et al., 1989; Hartmann et al., 2012; Kubo et al., 2019; Martínez-Cava et al., 2019; Oranchuk et al., 2019; Pallarés et al., 2020; Pedrosa et al., 2022; Rhea et al., 2016; Weiss et al., 2000). This would suggest that weightlifting pull derivatives performed from the knee or mid-thigh, which emphasise the transition and second pull, will likely have limited or no impact on force production capabilities in the first pull phase. On the contrary, pull derivatives performed from the start position will likely transfer to increases in strength across the entire pull phase, and therefore contribute to a greater overall lift performance.

One possible area for future consideration for research is to explore whether a deficit in isometric force capacity in either position in the pull corresponds to a deficit in vertical ground reaction force, or barbell acceleration corresponding to that particular sub-phase. A recent study by Sandau and Granacher (2020) investigated the load–velocity relationship for each sub-phase of the pull, showed that while most weightlifters display a greater decline in velocity with increasing load in the first pull, some lifters showed a greater decline in either the transition or second pull phase. They proposed that this may be the result of strength deficit specific to that portion of the lift and therefore quantifying this deficit may inform specific training strategies. However, it's crucial to emphasise the lack of literature examining the agreement between sub-phase-specific strength deficits using these two distinct assessment methods, as well as any longitudinal research on specific training interventions to address a specific strength deficit.

While these study findings provide valuable insights with implications for directing monitoring and training practices in weightlifters, it is crucial to acknowledge the high RMSEP values observed in our models for the Snatch and C&J. The combined RMSEP was approximately 30 kg, reflecting substantial prediction error when estimating the Total (Snatch + C&J). This poses a limitation when attempting to use these models to predict weightlifting performance, especially given that competition placings are separated by very narrow margins. To provide context, an analysis of historical performance data by Chavda et al. (2023) revealed that, at the Olympic level, a difference of 30 kg in Total is equivalent to the difference between 1st–3rd place zones and 9th–10th place zones across almost all men's weight categories. In this context, an RMSEP of 30 kg indicates that these models currently lack the precision necessary to distinguish between competition placings at the elite level.

A further important limitation of this study is that only net PF was measured during the isometric assessments. This approach neglects time-dependent force variables, such as the force attained within specific time epochs and RFD. Including these variables, especially in the latter portion of the lift, where a high RFD is evident, could provide a more comprehensive array of variables more specific and vital to the latter phases of the lift. A further limitation of this study to consider is that, although many of the conclusions are logically derived from the findings, the cross-sectional design prevents establishing causation between physical measures and performance. A final consideration of this study is the potentially increased injury risk during the ISPP and ITPP tests, as previous authors have suggested that the back is placed in a biomechanically weaker position (Rochau et al., 2024). In the present study, we sought to control for this risk through thorough familiarisation and clear instruction to participants and no injuries were sustained by any of the participants. Future research and practical applications of these tests should continue to explore and implement strategies to further mitigate these risks.

Conclusion

In conclusion, this study adds to the growing body of research highlighting the superior predictive ability of the ISPP over the ITPP and IMTP in evaluating performance in weightlifters. However, it is important to recognise that these findings do not diminish the potential value of the ITPP and IMTP to fully understand the physical factors which underpin performance. Each test represents the maximal force capacity in positions corresponding to the primary sub-phases of the pull, yet the impact of specific training strategies to optimise force production within each phase and their effects on vertical barbell acceleration remains poorly understood. Future research should prioritise longitudinal intervention-based studies to determine the causal effects of developing specific neuromuscular qualities on performance.

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