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Longitudinal Associations Between Isometric Peak Force in Key Pull Positions with Weightlifting Performance in International-Level Female Weightlifters

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ABSTRACT

Purpose: The aim of this study was to investigate the longitudinal associations between peak force (PF) in the isometric start position pull (ISPP), isometric transition position pull (ITPP) and isometric mid-thigh pull (IMTP) with weightlifting performance. **Methods:** A retrospective longitudinal analysis was conducted using isometric assessment and performance data collected over a period of up to three years from seven international-level female weightlifters (age 26.8 ± 7.4 years; body mass 59.9 ± 7.0 kg). The dependent variables were absolute (Total) and allometrically scaled competition performance (Total_a). The independent variables were absolute (ISPP, ITPP, IMTP) and allometrically scaled (ISPP_a, ITPP_a, IMTP_a) PF in the three pull positions and Time (3-month intervals). Separate linear mixed models were used to examine their longitudinal associations. **Results:** The ISPP and ISPP_a showed significant positive associations with Total and Total_a ($p < 0.01$), explaining 31% and 12% of the variance. Time as a fixed-factor was not significant ($p > 0.05$), and reduced models (omitting Time) explained greater variance of 45% and 18%, respectively. The ITPP, IMTP, ITPP_a and IMTP_a were not significant in full models, yet reduced models identified these as significant predictors ($p < 0.05$) but with poorer model fit. **Conclusions:** The ISPP demonstrates the strongest and most stable longitudinal predictor of weightlifting performance, supporting its use as a primary assessment for monitoring performance changes.

Key words: Maximal Strength, Neuromuscular, Isometric Mid-Thigh Pull, Scaling

INTRODUCTION

Weightlifting performance is determined by the heaviest loads successfully lifted in the snatch and clean & jerk (C&J). Central to these lifts is the 'pull' phase, where vertical impulse (the integral of force with respect to time) is applied to the athlete-barbell system (bar mass + body mass), causing the vertical acceleration, and projection of the barbell in the turnover phase¹. The pull involves three distinct sub-phases (first pull, transition, and second pull) each uniquely contributing to the total impulse applied². Accordingly, each sub-phase exhibits distinct force-, velocity-, and power-time characteristics, which is primarily attributed to the phase-specific changes in external joint moments and in the contractile conditions of the involved musculature (e.g., muscle length and contractile velocity)^{3,4}.

The isometric mid-thigh pull (IMTP) has been the predominant strength assessment used to evaluate maximal and time-dependant force characteristics in weightlifters^{5,6}. The body is purposefully aligned with the start of the second pull phase where the greatest force, velocity and power outputs occur in the snatch and clean⁷. This position is considered critical to these lifts, prompting research to examine IMTP maximal force capabilities, and their relationship with weightlifting performance^{5,8-10}. A Meta-Analysis by Joffe et al.⁹ synthesised six studies examining the relationship between IMTP peak force (PF) with snatch and C&J, revealing very large correlations ($r = 0.83$, [95%CI 0.73–0.90] $r = 0.85$, [95%CI 0.76-0.91], respectively). Several investigations have been conducted since, corroborating these findings revealing similar correlations ($r = 0.69 - 0.88$)¹¹⁻¹⁵. While the IMTP may provide valuable insight into the maximal force production capabilities specific to the second pull, recent evidence indicates that evaluating positions corresponding with the start of the first pull (isometric start position pull [ISPP]) and transition phase (isometric transition position pull [ITPP]) may offer complimentary or even superior insights into the determinants of weightlifting performance.

Recent research has consistently shown that ISPP PF is a stronger predictor of weightlifting performance ($r = 0.78 - 0.95$) than the IMTP PF within male and female, youth, junior and senior, and national and international level weightlifters^{11-13,15-17}. Collectively, these data indicate maximal force production in the earlier phases of the pull is of greater importance compared with the second pull. This may be attributed to the need to overcome the inertia of the heavy barbell mass at the onset of the lift. In contrast, at the onset of the second pull, the barbell has already been accelerated and attained a vertical velocity of 1.6-2.0 m.s⁻¹^{4,18-21}. Consequently, isometric PF in the IMTP has less correspondence to the force-velocity characteristics of the second pull. These observations suggest the IMTP may not be

the gold standard for evaluating maximal force capabilities in weightlifting and underscores the necessity for a more comprehensive test battery that includes multiple isometric test positions.

Despite these advances, it should be acknowledged that all studies which examine the relationships between lower-body neuromuscular characteristics with weightlifting performance are cross-sectional^{9,14,22-24} limiting our ability to establish causal links. Only four training intervention studies have investigated the effects of weightlifting-specific training on lower-body isometric force-time characteristics in competitive weightlifters over 11 to 16 weeks²⁵⁻²⁸, with the majority reporting non-significant changes. Nonetheless, Zaras et al.²⁸ did report a significant increase in snatch and C&J performance, and rate of force development (RFD) in the leg press between 0-200 ms. However, the authors did not examine if changes in competition performance were associated with changes in neuromuscular measures, thus precluding our ability to draw conclusions about causal relationships.

Evidently, there is a need to conduct longitudinal investigations, examining how neuromuscular measures respond following a weightlifting-specific training intervention, and their subsequent impact on performance. However, conducting randomised-controlled intervention studies, although considered the gold standard, present practical and logistical challenges in high-performance sport environments. Alternatively, retrospective analysis of routinely collected assessment and performance data provides a practical and ecologically valid approach to explore potential causal relationships. Therefore, the purpose of this study was to examine longitudinal strength assessment data in the ISPP, ITPP and IMTP and determine their associations with performance in international level female weightlifters. It is hypothesised that PF measured in the ISPP will demonstrate the strongest and most temporally stable association with performance compared to the ITPP, and IMTP.

< Table 1 here >

METHODS

A retrospective longitudinal design was used to investigate the associations between isometric assessment and competition performance in international level female weightlifters. Isometric assessment data were comprised of the net PF (N) and body mass (BM, kg) obtained during the ISPP, ITPP, and IMTP tests collected as part of the routine sports science practices delivered in a national weightlifting performance programme. Weightlifting competition data consisted of BM (kg) recorded during weigh-in and Total (kg), which is the sum of the heaviest

Snatch and C&J. Isometric assessment data collection relative to competition dates ranged from less than ± 1 week to ± 6 weeks. To ensure consistent alignment between isometric assessment and performance data, data were averaged within a 91-day window surrounding each competition date, with 2–3 assessments occurring within this period. Each aggregated data point was then organised into sequential 3-month blocks. This approach standardises the resolution of analysis, accommodates variability in testing frequency typical of high-performance sport environments and enables robust longitudinal comparisons across athletes and time points. This approach is consistent with recommendations for longitudinal monitoring in elite sport²⁹ is employed in several similar investigations^{16,30}.

Subjects

Seven international-level female weightlifters (Age 26.8 ± 7.4 years; Height 1.58 ± 0.10 m; Body Mass 59.9 ± 7.0 kg) were included in the study. Baseline descriptive data are presented in Table 1. All participants were affiliated with a national weightlifting performance programme at the time of data collection. As part of their contractual agreement with the National Governing Body (NGB), participants provided consent that anonymised data collected during routine sports science testing and monitoring services could be used for research purposes. Written permission was provided by the NGB for the publication. This study was approved by the institutional ethics board and aligns with established guidelines for secondary data use³¹. All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki.

Methodology

Isometric Pull Assessments

Isometric assessments were performed on a bilateral force plate system sampling at 1000 Hz ($2 \times 350 \times 750$ mm; ForceDecks FD4000, NMP Technologies, London, UK). Force onset was identified using a threshold of 20 N above the participant's measured body weight (BW, N). Force–time signals were analysed without filtering (raw data), and no additional smoothing was applied prior to outcome variable calculation. The isometric assessments were performed in a customised rig with bar attachment points located 2.5 cm intervals along the vertical supports. The tests were performed in a standardised order: IMTP, ITPP and ISPP. The IMTP position was determined in accordance with established protocol guidelines⁷. For the ITPP, the bar height was set to the closest position to or below the centre of the knee joint, marking the start of the transition phase¹³. The shoulders were positioned anteriorly relative to the bar, and torso positioned with a positive angle. For the ISPP, a consistent bar position was utilised for all participants, as this was set to the height of an Olympic bar

loaded with IWF standard weightlifting competition disks of 45 cm diameter, resulting in a bar height of 22.5 cm. Weightlifting shoes and pulling straps were mandatory for all participants across all three tests. An example set-up for each isometric test is presented in figure 1. The assessments took place at the start of training sessions, following a standardized warm-up protocol encompassing bar warm-up drills and warm-up attempts of the first exercise of the day's training session. As participants were highly familiar with these test protocols, a single warm-up attempt at ~90% perceived effort was completed before their initial maximal attempt for each test. For all isometric assessments, participants were instructed to "push as hard as possible" and "keep pushing until signalled to release"⁷. 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. Two attempts were performed for each athlete, with a third allowed at the participants discretion. 2 to 3 minutes rest was provided standardised between attempts. BW (N) was measured on the force plates during quiet standing before the test, with participants wearing all clothing, footwear, and equipment as during the assessment. The highest Net PF value from the trials was used for analysis, calculated by subtracting BW (N) from the gross PF. Within-session reliability (ICC and CV, all 95% CIs; n = 20) for net PF (N) across all isometric tests was: IMTP, ICC = 0.97 (0.92–0.99), CV = 2.8% (2.1–4.1%); ITPP, ICC = 0.90 (0.76–0.96), CV = 5.0% (3.8–7.3%); and ISPP, ICC = 0.98 (0.95–0.99), CV = 1.3% (1.0–1.9%).

< Figure 1 here >

Competition Performance

Competition performance data were collected from national championships in the United Kingdom, IWF-sanctioned competitions, and the European U23 Championships (an event not sanctioned by the IWF). 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 Total (kg) in international level female weightlifters has been reported as CV = 3.2%³².

Statistical Analyses

Descriptive statistics are presented as Mean $\pm$ Standard Deviation (SD). Isometric assessment and competition performance data are represented in absolute (N or kg) and allometrically scaled terms ($N^{0.67}$ or $kg^{0.67}$). A standard power exponent of 0.67 was used based on the assumption of geometric similarity of the sample, as they were homogenous in terms of

body mass and stature³³. Linear Mixed Models were used to assess the longitudinal associations between isometric measures (IMTP, ITPP and ISPP) with Total and between allometrically scaled isometric measures (IMTP_a, ITPP_a and ISPP_a) with Total_a. A Pseudo Variance Inflation Factor was examined and revealed a value of 8.6 for the ISPP, exceeding a cut-off threshold of 5, indicating it was very closely related to ITPP and IMTP. Therefore, each predictor was analysed in a separate model to distinguish their effects on performance.

For the LMM, Total was specified as the dependent variable with IMTP, ITPP, ISPP and Time included as fixed-effects. Random intercepts were included to account for between-participants variability in baseline Total. Random slopes for Time were initially included for participant-specific time-effects but were subsequently excluded due to convergence issues and likelihood ratio tests showing no significant improvement in the model fit. A compound symmetry covariance structure was applied, and the model was fitted using a Maximum-Likelihood estimation. The model fit was evaluated using the Akaike Information Criterion (AIC) and Log-Likelihood. The Likelihood Ratio test was used to compare full and reduced models. Residual vs. fitted value plots and Q-Q plots were performed to ensure model assumptions were met. The Effect size of the Fixed-Effects was analysed using Marginal R^2 . The alpha level was set to 0.05. All analyses were performed using RStudio with R (Version 4.4.2). The LMM were performed using the lme4 Package (version 1.1.35.5) and the nlme Package (version 3.1-152) for handling specific correlation structures. Model fit was evaluated using the Performance Package (version 0.12.4) and Marginal R^2 and Conditional R^2 values were calculated using MuMIn Package (version 1.43.17).

ISPP, ITPP, IMTP, and Total descriptive percentage change from the first to last available observation was calculated for each participant. These values are summarised across participants using the median (range). This descriptive approach is intended solely for visual inspection to compliment the LLM analysis and does not inform statistical inference.

RESULTS

Within-subject percentage-change trajectories for Total, ISPP, ITPP, and IMTP across the observation period are shown in Figure 2. The absolute between-subject median (range) percentage changes were +9% (−7 to +20), +13% (−4 to +23), +15% (−18 to +63), and +37% (+14 to +57), respectively. When expressed in allometrically scaled terms, between-subject median (range) percentage changes for Total_a, ISPP_a, ITPP_a and IMTP_a were +4% (−6 to +20), +6% (−3 to +17), +16% (−19 to +54) and +35% (+11 to +49), respectively.

The results of the LMM's are presented in Table 2. The random intercepts (participants) were statistically significant ($p < 0.05$) indicating that each model accounted for variability between participants at baseline. Analysis revealed significant positive associations between the ISPP and ISPP_a with Total and Total_a respectively ($p < 0.01$). However, Time as a fixed-effect did not reach significance in either model ($p > 0.05$). The marginal R^2 revealed that the ISPP and ISPP_a explained 31% and 12% of the variance in Total and Total_a, respectively. The LRT analysis of the reduced models (removing Time) had no impact on the model fit for ISPP or ISPP_a indicating longitudinal stability. However, the reduced models explained a greater proportion of the variance, with marginal R^2 increasing to 45% and 18% for Total and Total_a, respectively. Models evaluating the ITPP, IMTP and ITPP_a, IMTP_a reported no significant associations; however, Time showed a significant positive association with Total and Total_a ($p < 0.05$). The reduced models revealed that the ITPP and ITPP_a were statistically significant predictors of Total and Total_a ($P < 0.05$), respectively. Furthermore, the reduced model for the IMTP revealed it was a significant predictor for Total, however the IMTP_a was not a significant predictor of Total_a. The LRT analysis of these reduced models showed that that omission of Time resulted in a significantly poorer model fit ($p < 0.05$).

< Table 2 here >

DISCUSSION

The aim of this study was to explore the longitudinal associations between isometric PF measured in the ISPP, ITPP, IMTP with competition Total in international-level female weightlifters. The ISPP emerged as the strongest longitudinal predictor of performance with ISPP and ISPP_a explaining 45% and 18% of the variance in Total and Total_a, respectively. These findings indicate that changes in ISPP PF are strongly and consistently associated with changes in Total over time, with a 10 N increase in ISPP PF corresponding to an approximate increase of 1.05 kg in Total (95% CI: 0.85 to 1.25 kg). Furthermore, visual inspection of individual longitudinal trajectories of percentage change in Total and ISPP PF revealed similar temporal patterns and comparable magnitudes and directions of change across most participants. The present study reinforces the emerging evidence that isometric force production in the start position has greater utility as a predictor of competition total compared with positions that resemble the transition and second pull phases^{11-13,16}.

Joffe et al.¹⁷ recently examined whether isometric PF measured in the same isometric test positions collectively contribute to the

explanation of Snatch and C&J performance. A single latent factor was identified, with all three measures equally weighted in the model, but further analysis indicated that only ISPP was significant, with no further explanation in the model provided by the ITPP and IMTP. This reinforces the greater predictive power of the ISPP and its importance in profiling for weightlifting performance. Similarly, in the present study, ITPP and IMTP PF were only significant in the reduced models and explained only 3-4% of the variance in Total. This reflected in visual inspection of individual longitudinal trajectories of the ITPP and IMTP alongside Total, showing limited agreement in temporal patterns, magnitudes and directions of change. These data indicate that improvements in Total do not consistently translate when temporal effects are accounted for. Furthermore, the IMTP_a reduced model indicated no association with Total_a, suggesting longitudinal changes in weightlifting performance are not related to these measures when allometrically scaled to body mass. Contrary to these findings, Joffe et al.³⁰ previously showed that the annual percentage change in IMTP PF across two consecutive years was in fact positively correlated ($r = 0.64$) with percentage change in Total in female weightlifters, illustrating a longitudinal association. Differences in the time resolution of data (annual vs. quarterly average), a greater number of data points per participant and the utilisation of LMM's over regression which account for individual variability, may explain the discrepancy in the longitudinal association between IMTP with weightlifting performance between studies. Collectively, these data emphasize the importance of maximal isometric force capacity across all key positions in the pull while, highlighting its greater importance in the earlier phases of the lifts. Multiple studies from different research groups have consistently reported greater correlations between ISPP PF with Total, compared with the IMTP^{11-13,15-17}, a relationship that has now been substantiated with longitudinal analyses. Practically, the ISPP appears to offer the greatest value for longitudinal monitoring of performance-relevant maximal isometric force. Nonetheless, ITPP and IMTP may still provide valid complementary insights for profiling (e.g., identifying phase-specific limitations) and should not be discounted based on the current longitudinal findings alone. More broadly, these results underscore the critical role of positional specificity in isometric assessment for accurately understanding how maximal isometric strength transfers to dynamic athletic performance. In a recent Meta-Analysis, James et al.³⁴ investigated the agreement and relationship between changes in lower-body maximal isometric strength and dynamic one-repetition maximum (1RM) performance following 6-12 weeks of lower-body resistance training in a mixed (non-weightlifting-specific) resistance trained population (recreational, collegiate and strong). They reported the concordance correlation coefficient

was 16%, indicating a poor agreement between changes in isometric and dynamic strength measures. This illustrates how these measures poorly correlate with each other over time, challenging the assumption that improvements in a specific isometric strength test are reflected in the corresponding dynamic strength exercise. Similarly, Saeterbakken et al.³⁵ conducted a Meta-Analysis investigating the effects of dynamic strength training on dynamic and isometric strength performance and reported significant pre-post improvements for both dynamic and non-trained isometric strength, with effect sizes approximately two-fold larger (SMD = 0.92 vs. 0.42, respectively) for dynamic outcomes.

These meta-analyses collectively highlight that isometric and dynamic maximal strength measures are not interchangeable as they may examine different neuromuscular qualities and respond uniquely to different strength training modalities³⁴⁻³⁶. However, A further point to consider when interpreting the findings of research comparing exercise-specific multi-joint isometric assessment in relation to dynamic strength assessment, is that observed inconsistencies could be attributed to the commonly adopted isometric test position. The IMTP is understood to be the strongest mechanical position of the clean pull and deadlift^{13,37}. Similarly, the isometric squat performed at knee joint angles between 90-140°, which also corresponds to the latter half of the concentric phase and the strongest region of the lift^{38,39}. However, numerous studies have reported that PF measured in isometric tests conducted in lift-specific positions corresponding with the weakest mechanical positions in the earlier portion of the concentric phase in the back squat^{38,39}, bench press⁴⁰, deadlift⁴⁰⁻⁴² and clean^{11-13,16} show higher correlations with dynamic strength performance (1RM) compared with the stronger mechanical positions. It is therefore plausible that isometric pull assessments performed at the start (weaker) position of the concentric phase provide a better representation of dynamic strength performance^{11,13,16,39} and are therefore conceivably more sensitive to monitor longitudinal changes in dynamic lift performance. This would explain the apparent lack of agreement between isometric and dynamic strength assessments³⁴ and supports the findings of the present study. Based on current evidence, the ISPP appears to be the preferred isometric measure for evaluating weightlifting-specific maximal force, supporting a practical shift away from reliance on the IMTP alone. The ITPP and IMTP may provide secondary profiling value (e.g., position-specific limitations) that may help to inform specific training, but further research is needed to determine whether they add meaningful information beyond the ISPP.

Although employing a longitudinal LMM analysis in this investigation provides insight into temporal links between strength and performance, the absence of experimental manipulation means causality cannot be confirmed. Furthermore, the limited sample of elite female weightlifters restricts the generalisability to males or less competitive athletes. Future research should use controlled experiments to assess training interventions and their effects on neuromuscular measures and weightlifting performance across sexes and competition levels.

PRACTICAL APPLICATIONS

The present study adds to the emerging evidence from both cross-sectional and longitudinal investigations, illustrating a strong association between ISPP PF and weightlifting performance. These findings offer several practical applications for both training and testing practices among weightlifters. As maximal isometric force in the first pull is a strong determinant of performance, it is logical that this phase should be developed accordingly to increase maximal force production. As the athlete–barbell system continues to accelerate throughout the lift, the late transition and second pull phases are increasingly influenced by the ability to rapidly generate force under high-velocity conditions, as the lifter must continue to apply impulse to the barbell. The capability to generate impulse in these phases is more reliant on dynamic and ballistic force production. Thus, utilising a specific exercise to target phase-specific strength qualities is recommended. Furthermore, the ISPP offers a valid and reliable method for evaluating the maximal force production characteristics pertaining to the pull. Given its strong cross-sectional and longitudinal associations with performance, the ISPP may serve as the most sensitive measure for monitoring temporal changes in weightlifting performance. However, we believe there is still value in the use of the ITPP and IMTP, as they provide deeper insights into force production characteristics specific to their respective phases of the pull.

CONCLUSIONS

In conclusion, the ISPP PF was the only measure to show a stable, meaningful longitudinal association with weightlifting performance, explaining a substantial proportion of variance in Total and tracking closely with individual performance trajectories. In contrast, the ITPP and IMTP PF showed limited and inconsistent relationships with performance. These findings reinforce the pre-eminence of ISPP PF as a determinant of long-term performance change and highlight the importance of positional specificity when profiling strength in weightlifters. Overall, the ISPP appears to be the most sensitive marker for monitoring performance-relevant strength adaptations.

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FIGURE CAPTIONS

Figure 1. Isometric assessment pull positions: (a) Isometric Start Position Pull (b) Isometric Transition Position Pull, and (c) Isometric Mid-Thigh Pull.

Figure 2. Individual longitudinal percentage change from baseline in Total (kg), ISPP, ITPP, and IMTP Peak Force (N) across the study period ($n = 7$). Quarter = an averaged three-month period (not aligned to calendar quarters). Total is depicted by a solid black line with filled circles; ISPP by a large-dotted black line with hollow triangles; ITPP by a moderate-dotted grey line with hollow squares; and IMTP by a small-dotted grey line with hollow circles. ISPP is emphasized in black to reflect its stronger predictive association with Total in the linear mixed-effects models. ISPP: isometric start position pull; ITPP: isometric transition position pull; IMTP: isometric mid-thigh pull.

TABLES

Table 1. Baseline Descriptive Isometric Assessment and Performance Data

Table 2. Summary of Mixed Model Results Predicting Longitudinal Total Performance from longitudinal in Isometric Pull Strength