**NEUROMUSCULAR PREDICTORS OF COMPETITION PERFORMANCE IN ADVANCED INTERNATIONAL FEMALE WEIGHTLIFTERS: A CROSS-SECTIONAL AND LONGITUDINAL ANALYSIS.**

**1,2Shaun A. Joffe** and 1Jamie Tallent

*1School of Sport, Health and Applied Sciences, St Mary’s University, Twickenham, United Kingdom, TW1 4SX*

*2British Weight Lifting, 1st Floor Office, St Ann's Mill, Kirkstall Road, Leeds, West Yorkshire, LS5 3AE*

Running Head: Predicting Weightlifting Performance

Word Count: 4313

**Address for correspondence:**

**Shaun A. Joffe**

St Mary’s University

Waldegrave Road

Twickenham

TW1 4SX

United Kingdom

Tel: +44 20 8240 4000

Fax: +44 20 8240 4255

E-mail: shaun.joffe@stmarys.ac.uk

Jamie Tallent E-mail: jamie.tallent@stmarys.ac.uk

**NEUROMUSCULAR PREDICTORS OF COMPETITION PERFORMANCE IN ADVANCED INTERNATIONAL FEMALE WEIGHTLIFTERS: A CROSS-SECTIONAL AND LONGITUDINAL ANALYSIS.**

**ABSTRACT**

The aim of this study was to investigate the physical determinants of weightlifting competition performance based on Isometric Mid-Thigh Pull (IMTP) and Countermovement Jump (CMJ) force-time variables, in a cross-sectional and longitudinal analysis. Ten British advanced international female weightlifters’ (age 23.4 ± 3.3 years, height 1.59 ± 0.06m, body mass 63.3 ± 8.82kg, training history 6.1 ± 3.2 years) competition results and neuromuscular assessment data collected as part of the British Weight Lifting World Class Programme were utilised for the purpose of this study. All data were averaged for two consecutive 1-year periods. The cross-sectional analysis utilised the second year of data, whereas the longitudinal analysis assessed the mean change between the two years. The cross-sectional analysis results reveal IMTP Net Isometric Peak Force (PF) and CMJ Peak Power (PP) predict 94.2%, 95.1% and 91.8% of the variance in Total, Snatch and Clean & Jerk competition performance respectively (*p* = <0.005). The longitudinal analysis results revealed that ∆IMTP PF was the only predicting factor of longitudinal change in weightlifting competition performance predicting 41.5%, 41.7% and 42.5% of ∆Total, ∆Snatch and ∆Clean & Jerk respectively (*p* = <0.005). The assessments and equations may be utilised by coaches or sports scientists to inform the prescription of training and help predict competition performance.

**KEY WORDS Weightlifting, performance, Isometric Mid-Thigh Pull, Countermovement Jump, Force, Power**

**INTRODUCTION**

Weightlifting competition performance is the summation of technical, physical and psychological factors (Dreschler, 1998; Gourgoulis, Aggeloussis, Garas, & Mavromatis, 2009; Storey & Smith, 2012), however the fundamental nature of the sport is to produce sufficient vertical impulse into the ground to displace the bar from the floor overhead in either a single movement in the Snatch, or two movements in the Clean & Jerk. The load lifted in the Snatch and Clean has been strongly correlated with greater peak vertical ground reaction forces (VGRF) (Baumann, Gross, Quade, Galbierz, & Schwirtz, 2016; Souza, Shimada, & Koontz, 2002) and greater knee extension torque in the second pull phase within collegiate to elite international weightlifters (Kipp, Redden, Sabick, & Harris, 2012; Liu, Yang, Sun, Mei, & Gu, 2018). The increasing momentum generated throughout the lifts coupled with their unique technical characteristics, results in a particularly time-limited second pull phase ranging between 0.15 - 0.19s in elite female and 0.12 - 0.16s in elite male weightlifters (Gourgoulis, Aggelousis, Mavromatis, & Garas, 2000; Gourgoulis et al., 2002; Gourgoulis, Aggeloussis, Kalivas, Antoniou, & Mavromatis, 2004; Harbili, 2012). The duration of this phase has also been shown to decrease with increasing percentage of 1RM (Hadi, Akkus, & Harbili, 2012). A distinct rapid rise in net force occurs during the second pull which partly explains why this phase exhibits the greatest barbell velocity and power outputs compared with all other phases of the movement (Akkus, 2012; Gourgoulis et al., 2009; Hadi et al., 2012; Korkmaz & Harbili, 2016). However, by virtue of the time-constraint, the principle of mechanical impulse dictates that to increase the load lifted in the snatch or clean, a greater magnitude of force must be attained via an increase in the rate of force development.

The assessment of neuromuscular force generating characteristics is essential in supporting practitioners and coaches in predicting performance and informing the prescription of training. A breadth of research has explored the relationship between isometric (Beckham et al., 2013; Haff et al., 2005; Stone et al., 2005) and dynamic (Carlock et al., 2004; Haff et al., 2005; Kite & Spence, 2017; Vizcaya, Viana, Olmo, & Acero, 2009) measures of neuromuscular performance with weightlifting performance. Two of the most commonly employed assessment protocols are the Isometric Mid-thigh Pull (IMTP) (Beckham et al., 2013; Haff et al., 2005, 2008, 1997; Stone et al., 2005) and the Countermovement Jump (CMJ) (Carlock et al., 2004; Haff et al., 2005; Vizcaya et al., 2009). The IMTP was first described by Haff et al. (1997) and is intended to evaluate the expression of maximal force and rate of force development in a mechanically identical position to the start of the second pull phase of the Snatch and Clean lifts. This phase of the lift is of particular interest as it elicits the largest VGRF (Baumann et al., 2016), knee and hip joint moments (Kipp et al., 2012) and vertical barbell velocity (Gourgoulis et al., 2000). The IMTP isometric peak force (PF) is demonstrated to have high reliability (De Witt et al., 2016; Dos’Santos et al., 2016; James, Roberts, Haff, Kelly, & Beckman, 2017) and correlates strongly with weightlifting performances ranging from *r* = 0.75 to 0.84 in national and international level male and female weightlifters (Beckham et al., 2013; Haff et al., 2005; Stone et al., 2005). The assessment of IMTP maximal force, may not reflect the dynamic and ballistic nature of the muscular contraction characteristic of the Snatch and Clean & Jerk, despite it being a strong predictor of weightlifting performance. Due to the kinetic and kinematic biomechanical similarity between the Olympic lifts and jumping tasks (Canavan, Garrett, & Armstrong, 1996; MacKenzie, Lavers, & Wallace, 2014) numerous jump-based assessments have also been investigated in relation to weightlifting performance.

The breadth of jump assessments have included the standing long jump (Kite & Spence, 2017), squat jump (Fry et al., 2003; Haff et al., 2005; Vizcaya et al., 2009) and the CMJ (Carlock et al., 2004; Fry et al., 2003; Haff et al., 2005; Vizcaya et al., 2009). The CMJ is the more widely investigated jump assessment method in relation to weightlifting performance with most studies employing the use of a switch mat to examine jump height and an estimation of peak power based on flight time and body mass (Carlock et al., 2004; Fry et al., 2003; Haff et al., 2005; Sayers, Harackiewicz, Harman, Frykman, & Rosenstein, 1999; Vizcaya et al., 2009). Both jump height and peak power have demonstrated moderate to strong (*r* = 0.59 - 0.93) correlations with weightlifting performance (Carlock et al., 2004; Haff et al., 2005; Vizcaya et al., 2009), which illustrates the relationship with a dynamic and ballistic triple extension movement pattern of the lower body. However, this method of CMJ analysis is limited in its output of kinetic and kinematic variables which are of potential interest when trying to further understand the determinants of weightlifting performance. Force plate CMJ analysis is considered gold standard and is a more mechanically robust calculation of jump height and peak power output (Buckthorpe, Morris, & Folland, 2012; Hori et al., 2009), whilst offering the ability to obtain a greater breadth of kinetic and kinematic information (Chavda et al., 2018).

Force plate analysis of the CMJ has revealed a strong correlation between CMJ Peak Force with back squat (r = 0.79) and power clean (r = 0.84) 1RM performance (Nuzzo, Mcbride, Cormie, & Mccaulley, 2008) and the Peak Force attained in dynamic clean pulls with 60% (r = 0.80) and 90% (r = 0.94) of power clean 1RM (Kawamori et al., 2006) in different male collegiate athletes. In addition, the CMJ Peak Velocity obtained from force plate analysis of the CMJ has demonstrated strong positive correlations with relative back squat and power clean 1RM performance in male collegiate athletes (Nuzzo et al., 2008).These fundamental biomechanical CMJ variables (Peak Force and Peak Velocity) have not previously been investigated in relation to competitive weightlifting performance and yet may reveal further detail as to the force-velocity determinants of the Snatch and Clean & Jerk.

Despite the agreement in the literature advocating strong positive relationships between specific IMTP and CMJ variables with weightlifting performance, it is still unclear which variables are better predictors. Multi-variate regression analysis offers a predictive analysis using multiple independent variables. No study to date appears to have employed this statistical analysis method to examine this question. Furthermore, previous studies have been cross-sectional in their design and failed to examine any association between the longitudinal changes in neuromuscular performance variables with changes in weightlifting performance. It is therefore difficult to draw conclusion as to any cause and effect relationship between them. It is imperative to be able to determine whether a change in specific neuromuscular qualities leads to a change in weightlifting performance in order to objectively inform the prescription of training. Therefore, the purpose of this study is 1) to investigate which IMTP and CMJ variables best predict weightlifting competition performance (Total, Snatch and Clean & Jerk) and 2) to investigate which of these variables best predict the change in weightlifting performance between two consecutive years.

**METHODS**

Force-plate neuromuscular assessment and competition performance data, collected as part of the British Weight Lifting (BWL) World Class Programme routine sports science service, were used for the purpose of this study. Data was collected over a 3-year period (2015 – 2017), with the frequency of competitions varying between 2 - 5 times per year and neuromuscular assessment between 4 – 12 times per year between participants. The timing and frequency of competition and neuromuscular assessment data capture were influenced by several factors including injury status, availability, competition calendar and individual athlete objectives.

***Participants***

Ten British advanced international female weightlifters (Age 23.4 ± 3.3 years; Height 1.59 ± 0.06m; Body Mass 63.3 ± 8.82kg; Training Age 6.1 ± 3.2 years) were included for the purpose of this study. All athletes were part of the BWL World Class Programme or Talent Pathway between 2015 and 2017. Participants were included based on the criteria of having competed at an International Weightlifting Federation (IWF) sanctioned event during this period. Despite some participants moving between body weight categories during this period for strategic qualification reasons, the distribution of athletes across preferred weight categories in December 2017 were 1 x W48kg, 2 x W53kg, 2 x W58kg, 2 x W63kg 2 x W69kg 1 x W75kg. All data utilised in this study were collected as part of the routine sport science support service provided to each athlete as part of their membership of British Weight Lifting World Class Programme. Project approval was gained through St Mary’s University Ethics committee. Participants consented to the use of this data as part of standard practices.

***Competition Data Collection***

The competition data collected for this study included all British domestic national championships across all age groups (e.g. British Senior Championships), IWF sanctioned events (i.e. Olympic Games, World Senior Championships) and the European U23 Championships (a non IWF sanctioned event) between the 1st January 2015 and 31st December 2017. Two consecutive years of data were collected for each participant between 2015 to 2016 or 2016 to 2017. This was based on the greatest number of competitions within the selected time periods. Year two for each participant was used for the cross-sectional analysis. All competition data were obtained from sources in the public domain and included the BWL, IWF and the European Weightlifting Federation (EWF) websites (www.britishweightlifting.org; www.IWF.net; www.ewfed.com). Test-retest reliability of weightlifting performance in international female weightlifters has previously been reported as between 3.2-3.5% (McGuigan & Kane, 2004).

***Force-Plate Testing***

Both the IMTP and CMJ assessment protocols were performed using ForceDecks bilateral (2x 350mm x 750mm) force plate system (ForceDecks FD4000 Force Platforms, NMP Technologies, London UK) and analysis software (NMP Technologies, London UK). Sampling frequency was set to 1000 Hz. The IMTP and CMJ assessments took place between Monday to Friday at the beginning of either morning or afternoon squad training sessions. Warm-ups were individually standardised focusing towards preparing for heavy lifting (e.g. a series of technical drills, bar complexes and warm-up attempts) and all testing took place before the heaviest working sets of the first exercise.

*Isometric Mid-Thigh Pull*

The IMTP assessment was performed on the force plate and inside a customised rig with the bar set to an individually pre-determined height. The notches for each bar height setting were fixed at 2.5cm intervals and were numbered accordingly. Prior to any data collection, participants individual IMTP positions were set and recorded in accordance with previous literature (Comfort et al., 2019; Comfort, Jones, McMahon, & Newton, 2015; Dos’Santos, Thomas, Jones, McMahon, & Comfort, 2017). Knee and hip angle were set between 125-145° and 140-150° respectively and the bar held in a clean grip and the torso is oriented vertically to ensure correspondence to the start of the second pull. Weightlifting straps were used to eliminate the influence of grip strength and Weightlifting shoes were specified as a requirement for the test. Due to the participant’s familiarity with the movement, a single warm-up attempt was performed to practice. Before the test, participants were then instructed “pull as hard and fast as possible” and “keep pulling until you are signalled to release” (Comfort et al., 2019; Halperin, Williams, Kyle, Martin, David, & Chapman, Dale, 2016). The signal to cease the test was given 1 second after the force trace either plateaued or continued to decline. Each test typically lasted approximately 2-4 seconds. Three tests were performed for each athlete with 3 minutes rest in between attempts. The Net Peak Force (PF) was collected and the average value of all the three trials was used for the analysis. In house test-retest reliability for PF was ICC = 0.97, CV 2.76%, similar to previous reports (Haff et al., 2005; Stone et al., 2003, 2005).

*Countermovement Jump*

Participants performed three countermovement jumps in succession with approximately 1-minute rest between each attempt. The participant stood on the force plate and with feet positioned between hip and shoulder width apart with a dowel placed across the shoulders to eliminate the contribution of the arms during the jump. The CMJ was performed to a self-selected depth and the athlete was instructed to ‘jump as high as possible’. Once the data collection window had begun, a three second weighing phase was gathered for body weight calculation (McMahon, Suchomel, Lake, & Comfort, 2018). The athlete was then instructed to remain still while the administrator counted them into the jump with the command “3, 2, 1, Jump”. Concentric Peak Force (CPF), Peak Power (PP), Peak Velocity (PV) and Peak Displacement (PD) were obtained for each jump trial. The calculation of the specific phases of jump and the variables are in keeping with protocols described previously (Barker, Harry, & Mercer, 2018; Chavda et al., 2018; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; McMahon, Murphey, Rej, & Comfort, 2017; McMahon et al., 2018). The average across the three trials was used for analysis. In house test-retest reliability for CPF, PP, PV and PD were ICC = 0.98, CV = 2.73%, ICC = 0.99, CV = 1.20%, ICC = 0.91, CV = 2.40% and ICC = 0.90, CV = 5.41% respectively.

**Statistical Analysis**

All data were averaged for two successive 1-year periods. This was done to account for the time misalignment in the competition calendar, training phases and assessment data between participants across the training cycle. All data were tested for and confirmed to be normally distributed using the Shapiro-Wilks test. A paired-samples T-Test was used to assess the change in all strength assessment and weightlifting performance variables across the 2 time periods. The absolute changes between the two time periods were calculated with 95% confidence intervals and effect sizes. The effect sizes were interpreted consistent with recommendations presented by Rhea (2004) for strength training research of <0.25 = trivial, 0.25-0.5 = small, 0.5-1.0 = moderate, >1.0 = large. Alpha level was set at *P* < 0.05. Pearson’s Product Correlation Coefficient was used to examine the bivariate relationship between Snatch, Clean & Jerk and Total with IMTP PF, CMJ PP, CPF, PV, PD, plus the relationship between the magnitudes of change in each performance and neuromuscular assessment variable. Correlation coefficient were interpreted in accordance 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 (Hopkins, Marshall, Batterham, & Hanin, 2009). Further analysis involved a Stepwise Multiple Linear Regression Analysis to determine a) competition performance predicted by the neuromuscular performance variables from CMJ and IMTP b) change in the competition variables predicted by change in neuromuscular performance variables. Evaluation of the collinearity of the predictor variables was performed using a tolerance of < 0.10 (variance inflation factor). F was set at 0.05 for entry and 0.10 for removal from the model. All data were analysed using SPSS (version 22.0, Chicago, Illinois, USA) and data are presented as mean ± standard deviation (SD).

**RESULTS**

The average competition performances for all participants were 76.8 ± 15.1kg, 96.4 ± 18.3kg and Total 174.0 ± 33.1kg for the Snatch, Clean & Jerk and Total respectively. No significant differences were demonstrated between the two time periods for all competition lifts (Snatch 0.75 ± 4.8kg; t(9) = -0.398; CI -0.40 to 2.80; *P* = 0.70, ES = 0.04, Clean & Jerk 0.70 ± 3.6kg; t(9) = -0.537: CI -3.12 to 1.92; *P* = 0.60, ES = 0.03, Total 2.86kg ± 7.4kg; t(9) = 1.168; CI -8.22 to 2.62;*P* = 0.27, ES = 0.08) (Figure 1). Of the force plate assessment variables, IMTP PF (287.8 ± 185N, t(9) = -4.918; CI -420.3 to 155.4; *P* = 0.001, ES = 0.60) and CMJ CPF (135.3N ± 162.5N, t(9) = -2.63; CI -251.5 to -19.05; *P* = 0.027, ES = 0.38) demonstrated a significant positive change between the two time periods (Figure 2). All other force plate assessment variables did not reach statistical significance.

*<<< Insert Figure 1 >>>*

*<<< Insert Figure 2 >>>*

For the cross-sectional analysis, correlation analysis was conducted for all competition performance, IMTP and CMJ variables. IMTP PF and CMJ PP demonstrated significant strong positive correlations with the Snatch, Clean & Jerk and Total (*r* = 0.76 - 0.90; *P = <* 0.05) (Figure 3). CMJ PV, PD and CPF showed no significant correlation with any weightlifting performance variables (*P =* > 0.05). For the longitudinal analysis, correlation analysis was conducted for all competition performance, IMTP and CMJ variables. Only ∆IMTP PF demonstrated a significant correlation with ∆Snatch, ∆Clean & Jerk and ∆Total (*r =* 0.64-0.65; *P* = < 0.05) (Figure 4).

*<<< Insert Figure 3 >>>*

*<<< Insert Figure 4 >>>*

 Stepwise multiple regression analysis revealed that IMTP PF and CMJ PP significantly predicted 94.2% (*R2* = 0.94; SEE = 9.05kg, *P* = < 0.005) of variance in Total yielding the equation;

Total = -33.873 + (0.040 x IMTP PF) + (0.032 x CMJ PP) (1)

Additionally, both IMTP PF and CMJ PP variables revealed a similar statistically significant prediction of variance in the Snatch and Clean & Jerk with 95.1% (*R2* = 0.951; SEE = 3.79kg; *P* < 0.005) and 91.8% (*R2* = 0.951; SEE = 5.99kg; *P* = < 0.005) respectively, yielding the equations;

Snatch = -20.231 + (0.017 x CMJ PP) + (0.015 x IMTP PF) (2)

Clean & Jerk = -14.236 + (0.024 x IMTP PF) + (0.014 x CMJ PP) (3)

 The coefficient of determination revealed that the IMTP PF explained the majority of variance in the Total (75.5%) and Clean & Jerk (80.8%), whereas CMJ PP explained most of the variance in the Snatch (77.1%). Stepwise multiple regression analysis revealed that only the ΔIMTP PF significantly predict 41.5% of change in ΔTotal (*R2* = 0.415; SEE = 0.43kg; *P* = < 0.05) yielding the equation;

∆Total = -0.038 + (0.443 x ∆IMTP PF) (4)

Analysis further revealed that 41.7% of ΔSnatch (*R2* = 0.417; SEE = 0.063kg; *P* = < 0.05) and 42.5% of ∆Clean & Jerk (*R2* = 0.425; SEE = 0.035kg; *P* = < 0.05) are explained by ∆IMTP PF yielding the equations;

ΔSnatch = -0.071 + (0.655 x ∆IMTP PF) (5)

∆Clean & Jerk = -0.038 + (0.369 x ∆IMTP PF) (6)

**DISCUSSION**

The purpose of this study was to determine which IMTP and CMJ force-time variables predict weightlifting competition performance in a cross-sectional and longitudinal analysis. The main findings of the study were two-fold; 1) IMTP PF and CMJ PP explained 94.2%, 95.1% and 91.8% of variance for the Total, Snatch and Clean & Jerk respectively. 2) ΔIMTP PF explained 41.5%, 41.7% and 42.5% of the variance for the ΔTotal, ΔSnatch and ∆Clean & Jerk respectively. To the best our knowledge, this is the first study where multiple force-time assessment variables from advanced international female weightlifters have been used to predict weightlifting performance. Furthermore, this is the first study to statistically show a causative relationship between changes in specific neuromuscular qualities and changes in weightlifting performance.

Previously it has been shown that maximal isometric force of the leg extensors and back extensors, in addition to body weight, predict Snatch and Jerk performance (64% and 76% variance respectively) (Shetty, 1990). These findings are consistent with that of the present study as it illustrates the predictive capacity of measures of maximal strength for weightlifting performance. The larger variance explained in the present study, may be attributed to the higher competitive standard of our participants compared with that of Shetty et al. (1990). A greater transfer of maximal strength to performance has been observed in superior weightlifters (Lucero, Fry, LeRoux, & Hermes, 2019), supporting the notion that maximum strength is a greater predictor of performance in the more elite population. However, the lower variance explained by Shetty (1990) may further be attributed to the limited dynamic correspondence of the single-joint strength tests employed compared with multi-joint strength tests utilised in the present study (Anderson et al., 1991; Haff et al., 2005, 1997; Nuzzo et al., 2008). Alternatively, this may reflect the lack of inclusion of a dynamic and ballistic test such as the CMJ to reflect the rapid high-force neuromuscular qualities of the Snatch and Clean & Jerk.

This is not the only study to show strong positive correlations between IMTP PF and CMJ PP with weightlifting performance (Beckham et al., 2013; Carlock et al., 2004; Haff et al., 2005; Stone et al., 2005). In particular, Beckham et al., (2013), Haff et al., (2005) and Stone et al., (2005) reported strong positive correlations between IMTP PF and the Snatch(*r =* 0.83-0.93), Clean & Jerk(*r* = 0.83-0.89) andTotal (*r* = 0.80-0.84)in sub-elite to elite male and female weightlifters. The association between maximal strength and weightlifting performance is further corroborated by reports showing very strong relationship with front squat 1RM (*r* = 0.92-0.94) and Back Squat 1RM (*r =* 0.79 – 0.95) (Carlock et al., 2004; Lucero et al., 2019; Stone et al., 2005). It is reasonable to infer from these findings that given the time constraint dictated by technique, the greater capacity to express high maximal forces via an increase in the rate of force development, underpins the ability to express large vertical impulse, and therefore lift a heavier weight. This is further supported with a multitude of studies which demonstrate that the load lifted in the Snatch or the Clean is almost directly proportionate to the peak VGRF applied during the lift, particularly the second pull phase (Baumann et al., 2016; Enoka, 1979; Souza et al., 2002).

The second variable included in the predictive model of Total, Snatch and Clean & Jerk was CMJ PP. Several studies are in support of the findings which demonstrated strong positive correlations between CMJ PP and Snatch (*r =* 0.75 – 0.93), Clean & Jerk (*r =* 0.79 – 0.90) and Total (*r =* 0.75 - 0.78) (Carlock et al., 2004; Haff et al., 2005) and are similar to those reported in the bivariate analysis in the present study (Snatch *r =* 0.88, Clean & Jerk *r =* 0.76 and Total *r =* 0.83). A potential explanation for the inclusion of this variable in the model may relate to the similar ballistic and high rate of force development expressed the second pull phase of the Snatch and Clean movements (Enoka, 1979; Kawamori et al., 2006; Souza et al., 2002). Interestingly, for the Snatch regression model, the coefficient of determination revealed that the CMJ PP was the stronger predictor of the 2 variables (77.1% of 91.8% of the variance explained) whereas CMJ PP explained less of the variance in the Clean & Jerk (11% of 91.8% of the variance explained). This may be interpreted as an illustration of how the Snatch and Clean & Jerk lifts are potentially influenced in different proportions by both lower body maximal force and power output. This hypothesis is supported by performance results and biomechanical data which illustrate that Clean & Jerk is a more force dependant lift attaining greater loads compared with the Snatch, whereas the Snatch lift comparatively attains greater vertical velocity and power outputs (Garhammer, 1980; Gourgoulis et al., 2004; Korkmaz & Harbili, 2016). These findings imply that the Snatch and Clean & Jerk may be targeted through specific load-velocity based Snatch and Clean derivative training strategies as discussed by Suchomel, Comfort, & Lake (2017).

Within the current study it was observed that solely the ΔIMTP PF explained 41.5% to 42.5% of the variance for the change in weightlifting performance variables between the two consecutive 1 year periods. Previous research has reported a similar trend showing an association between changes in IMTP PF and isometric leg extensor peak force with change in weightlifting performance measures over training periods ranging between 5 months to two years, however no statistical tests were used to evaluate these relationships (Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Hakkinen, Kauhanen, & Taisto, 1987; Hornsby et al., 2017). Shorter duration studies of 11 weeks in elite female lifters appear to provide no indication of a relationship between the ΔIMTP PF and change in weightlifting performance (Haff et al., 2005). This potentially indicates either an insufficient time to increase maximal strength due to the highly-trained status of the participants (Peterson, Rhea, & Alvar, 2005) or a lag in the development of maximal strength and its carryover to an improvement in weightlifting performance. Regardless, these findings collectively reaffirm the importance for the continued development of maximal force capacity for the improvement of weightlifting performance.

On the contrary, ΔCMJ PP demonstrated no association with any change in weightlifting performance variables, which is consistent with previous reports (Hornsby et al., 2017). Interestingly, when performing CMJ’s with external loads ranging between 10-140kg, several studies have shown the change in CMJ PP and Average Concentric Power Index (Body Weight + load) x Jump / Body Weight) show strong correlations (*r* = 0.51 – 0.64) and visible trends with the change in weightlifting performance across periods of 5 months to two years (Hakkinen et al., 1988; Keijo. Hakkinen et al., 1987; Hornsby et al., 2017; Kauhanen, Hakkinen, & Komi, 1988). Again, not all these relationships were evaluated with statistical tests. These findings indicate a highly specific adaptation toward the high force region of the force-velocity curve (Cormie, McGuigan, & Newton, 2010; Haff & Nimphius, 2012) and therefore potentially advocate the use of a loaded ballistic movements such as a loaded CMJ to reveal the specific neuromuscular characteristics associated with an improvement in weightlifting performance. Lastly, this finding adds support to the literature which advocates the use of CMJ PP as a talent identification tool to evaluate potential for Weightlifting (Carlock et al., 2004). Despite the lack of association between ΔCMJ PP and change in weightlifting performance variables, CMJ PP still discriminates performance standards between weightlifters irrespective of long-term improvement in this muscular quality.

Whilst this study has presented some novel findings which demonstrate the role of specific neuromuscular strength qualities for weightlifting, it is necessary to acknowledge the importance of proficient technique which ultimately limits the carry-over of strength to performance. The complex interdependence of these two factors must be considered when organising and prescribing training for different phases of the competition cycle and for different standards of athlete. It is logical to suggest that based on these finding, advanced and technically proficient weightlifters may allocate longer or more concentrated periods of their annual training cycle to the development of maximal strength as it is a key determinant of performance. This however may not be an optimal periodised strategy for novice or less proficient lifters who may require a greater emphasis on technical development. Future research in this area may wish to consider examining measures of technical proficiency in addition to neuromuscular characteristics to explain some of the remaining variance in performance. It is also important to acknowledge that whilst this study provides novel insight to the predictors of weightlifting performance, the nature of Weightlifting competitions will not always enable a competitor to attain a performance truly representative of their maximum capacity. For example, the order and progression of a competition may unfold so that a competitor does not need to lift near their maximum in order to secure their desired ranking position. This may explain a portion of the variance unaccounted for in the equations of the present study.

**CONCLUSION**

In conclusion the present study demonstrated that a high proportion of variance in weightlifting performance can be explained from IMTP PF and CMJ PP in advanced international female weightlifters. However, when examining the mean change in weightlifting performance across 2 consecutive years, only ∆IMTP PF explained a portion of the variance, eliminating all the CMJ force-time variables. These findings have potentially valuable implications and applications for Sports Scientists and Coaches working with competitive Weightlifters. Firstly, the regression models may help to predict weightlifting performance and therefore inform the training process leading into competition, and appropriate selection of attempts for competition. Secondly, the longitudinal analysis data suggests increases in maximal strength is a primary driving factor for the enhancement of weightlifting performance. Lastly, the cross-sectional but non-causative association between CMJ PP and weightlifting performance, implies that this variable may be a valuable talent identification metric as it still discriminates performance standards between athletes irrespective of long-term improvement in this muscular quality. Future research should focus on trying to identify the remaining variance in the prediction in change in weightlifting performance.

**REFERENCES**

Akkus, H. (2012). Kinematic Analysis of the snatch lift with elite female weightlifters during the 2010 world weightlifting championship. *Journal of Strength and Conditioning Research*, *26*(4), 897–905.

Anderson, M. A., Gieck, J. H., Perrin, D., Weltman, A., Rutt, R., & Denegar, C. (1991). The relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *Journal of Orthopaedic and Sports Physical Therapy*, *14*(3), 114–120.

Barker, L. A., Harry, J. R., & Mercer, J. A. (2018). Relationships Between Countermovmeent Jump Ground Reaction Forces and Jump Height Reactive Strength Index and Jump Time. *Journal of Strength and Conditioning Research*, *32*(1), 248–254.

Baumann, W., Gross, V., Quade, K., Galbierz, P., & Schwirtz, A. (2016). The Snatch Technique of World Class Weightlifters at the 1985 World Championships. *International Journal of Sport Biomechanics*, *4*(1), 68–89.

Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., … Stone, M. (2013). Relationships of isometric mid-thigh pull variables to weightlifting performance. *Journal of Sports Medicine and Physical Fitness*, *53*(5), 573–581.

Buckthorpe, M., Morris, J., & Folland, J. P. (2012). Validity of vertical jump measurement devices. *Journal of Sports Sciences*, *30*(1), 63–69.

Canavan, P. K., Garrett, G. E., & Armstrong, L. E. (1996). Kinematic and Kinetic Relationships between an Olympic-Style Lift and the Vertical Jump. *Journal of Strength and Conditioning Research*, *10*(2), 127–130.

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., … Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: A field-test approach. *Journal of Strength and Conditioning Research*, *18*(3), 534–539.

Chavda, S., Bromley, T., Jarvis, P., Williams, S., Bishop, C., Turner, A. N., … Mundy, P. D. (2018). Force-time characteristics of the countermovement jump: Analyzing the curve in excel. *Strength and Conditioning Journal*, *40*(2), 67–77.

Comfort, P., DosʼSantos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., & Haff, G. G. (2019). Standardization and Methodological Considerations for the Isometric Midthigh Pull. *Strength and Conditioning Journal*, *41*(2), 57–79.

Comfort, P., Jones, P. A., McMahon, J. J., & Newton, R. (2015). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test-retest reliability. *International Journal of Sports Physiology and Performance*, *10*(1), 58–63.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise*, *42*(8), 1582–1598.

De Witt, J. K., English, K. L., Crowell, J. B., Kalogera, K. L., Guilliams, M. E., Nieschwitz, B. E., … Ploutz-Snyder, L. L. (2016). Isometric Mid-Thigh Pull Reliability and Relationship to Deadlift 1RM. *Journal of Strength and Conditioning Research*, 1.

Dos’Santos, T., Jones, P. A., Kelly, J., McMahon, J. J., Comfort, P., & Thomas, C. (2016). Effect of sampling frequency on isometric midthigh-pull kinetics. *International Journal of Sports Physiology and Performance*, *14*(4), 525–530.

Dos’Santos, T., Thomas, C., Jones, P. A., McMahon, J. J., & Comfort, P. (2017). The effect of hip joint angle on isometric midthigh pull kinetics. *Journal of Strength and Conditioning Research*, *31*(10), 2748–2757.

Dreschler, A. (1998). *The Weightlifting Encyclopedia: A Guide to World Class Performance*. A is A Communications,U.S.

Enoka, R. M. (1979). The pull in olympic weightlifting. *Medicine and Science in Sports*, *11*(2), 131–137.

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003). Muscle Fiber Characteristics and Performance Correlates of Male Olympic-Style Weightlifters. *Journal of Strength and Conditioning Research*, *17*(4), 746–754.

Garhammer, J. (1980). Power production by olympic weightlifters. *Medicine and Science in Sports and Exercise*, *12*(1), 54–80.

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology and Performance*, *10*(1), 84–92.

Gourgoulis, V., Aggelousis, N., Mavromatis, G., & Garas, A. (2000). Three-dimensional kinematic analysis of the snatch of elite Greek weightlifters. *Journal of Sports Sciences*, *18*(8), 643–652.

Gourgoulis, V., Aggeloussis, N., Antoniou, P., Christoforidis, C., Mavromatis, G., & Garas, A. (2002). Comparative 3-dimensional kinematic analysis of the snatch technique in elite male and female greek weightlifters. *Journal of Strength and Conditioning Research*, *16*(3), 359–366.

Gourgoulis, V., Aggeloussis, N., Garas, A., & Mavromatis, G. (2009). Unsuccessful vs. successful performance in snatch lifts: A kinematic approach. *Journal of Strength and Conditioning Research*, *23*(2), 486–494.

Gourgoulis, V., Aggeloussis, N., Kalivas, V., Antoniou, P., & Mavromatis, G. (2004). Snatch lift kinematics and bar energetics in male adolescent and adult weightlifters. *Journal of Sports Medicine and Physical Fitness*, *44*(2), 126–131.

Hadi, G., Akkus, H., & Harbili, E. (2012). Three-dimensional kinematic analysis of the snatch technique for lifting different barbell weights. *Journal of Strength and Conditioning Research*, *26*(6), 1568–1576.

Haff, G. G., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Kawamori, N., Jackson, J. R., … Stone, M. H. (2005). Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *Journal of Strength and Conditioning Research*, *19*(4), 741–748.

Haff, G. G., Jackson, J. R., Kawamori, N., Carlock, J. M., Hartman, M. J., Kilgore, J. L., … Stone, M. H. (2008). Force-time curve characteristics and hormonal alterations during an eleven-week training period in elite women weightlifters. *Journal of Strength and Conditioning Research*, *22*(2), 433–446.

Haff, G. G., & Nimphius, S. (2012). Training principles for power. *Strength and Conditioning Journal*, *34*(6), 2–12.

Haff, G. G., Stone, M., O’Bryant, H. S., Harman, E., Dinan, C., Johnson, R., & Han, K. H. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength and Conditioning Research*, *11*(4), 269–272.

Hakkinen, K., Kauhanen, H., & Taisto, K. (1987). Neural, muscular and hormonal adaptations, changes in muscle strength and weightlifting results with respect to variation in training during one year period follow-up period of Finnish elite weightlifters. *World Weightlifting*, *87*(3), 1–10.

Hakkinen, K., Pakarinen, A., Alen, M., Kauhanen, H., & Komi, P. V. (1988). Neuromuscular and hormonal adaptations in athletes to strength training in two years. *Journal of Applied Physiology*, *65*(6), 2406–2412.

Halperin, I., Williams, Kyle, J., Martin, David, T., & Chapman, Dale, W. (2016). The Effects of Attentional Focusing Instructions on Force Production During the Isometric Midthigh Pull. *Journal of Strength*, *30*(4), 919–923.

Harbili, E. (2012). A gender-based kinematic and kinetic analysis of the snatch lift in elite weightlifters in 69-kg category. *Journal of Sports Science and Medicine*, *11*(1), 162–169.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–12.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of Performance Measurements Derived from Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency. *Journal of Strength and Conditioning Research*, *23*(3), 874–882.

Hornsby, G. W., Gentles, J., MacDonald, C., Mizuguchi, S., Ramsey, M., & Stone, M. (2017). Maximum Strength, Rate of Force Development, Jump Height, and Peak Power Alterations in Weightlifters across Five Months of Training. *Sports*, *5*(4), 78.

James, L. P., Roberts, L. A., Haff, G. G., Kelly, V. G., & Beckman, E. M. (2017). Validity and reliability of a portable isometric mid-thigh clean pull. *Journal of Strength and Conditioning Research*, *31*(5), 1378–1386.

Kauhanen, H., Haekkinen, K., & Komi, P. V. (1988). Changes in biomechanics of weightlifting and neuromuscular performance during one year training of elite weightlifters. *Biomechanics XI-B, International Series on Biomechanics*, 895–900.

Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O’Bryant, H. S., … Haff, G. G. (2006). Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength and Conditioning Research*, *20*(3), 483–491.

Kipp, K., Redden, J., Sabick, M., & Harris, C. (2012). Kinematic and kinetic synergies of the lower extremities during the pull in olympic weightlifting. *Journal of Applied Biomechanics*, *28*(3), 271–278.

Kite, R., & Spence, A. (2017). Horizontal Jump Predicts Weightlifting Performance. *EWF Scientific Magazine*, *8*(September), 5–16.

Korkmaz, S., & Harbili, E. (2016). Biomechanical analysis of the snatch technique in junior elite female weightlifters. *Journal of Sports Sciences*, *34*(11), 1088–1093.

Liu, G., Yang, H., Sun, D., Mei, Q., & Gu, Y. (2018). Comparative 3-dimensional kinematic analysis of snatch technique between top-elite and sub-elite male weightlifters in 69-kg category. *Helyion*, *4*(December 2017), 1–17.

Lucero, R. A. J., Fry, A. C., LeRoux, C. D., & Hermes, M. J. (2019). Relationships between barbell squat strength and weightlifting performance. *International Journal of Sports Science and Coaching*, *0*(0), 1–7.

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat. *Journal of Sports Sciences*, *32*(16), 1576–1585.

McGuigan, M. R., & Kane, M. K. (2004). Reliability of Performance of Elite Olympic Weightlifters. *Journal of Strength and Conditioning Research*, *18*(September 2000), 650–653.

McMahon, J. J., Murphey, S., Rej, S. J. E., & Comfort, P. (2017). Countermovement-Jump-Phase Characteristics of Senior and Academy Rugby League Players. *International Journal of Sports Physiology and Performance*, *12*(6), 803–811.

McMahon, J. J., Suchomel, T. J., Lake, J. P., & Comfort, P. (2018). Understanding the Key Phases of the Countermovement Jump Force-Time Curve. *Strength and Conditioning Journal*, *40*(4), 1.

Nuzzo, J. L., Mcbride, J. M., Cormie, P., & Mccaulley, G. O. (2008). Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *Journal of Strength and Conditioning Research*, *22*(3), 699–707.

Peterson, M. D., Rhea, M. R., & Alvar, B. A. (2005). Applications of the Dose-Response for Muscular Strength Development: A review of Meta-Analytic Efficacy and Reliability for Designing Training Prescription. *Journal of Strength and Conditioning Research*, *19*(4), 950–958.

Rhea, M. R. (2004). Determining the magnitude of treatment effects in strength training research through the use of the effect size. *Journal of Strength and Conditioning Research*, *18*(4), 918–920.

Sayers, S. P., Harackiewicz, D. V., Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross-validation of three jump power equations. *Medicine and Science in Sports and Exercise*, *31*(4), 572–577.

Shetty, A. B. (1990). Quantification of Selected Segmental Strength in Weightlifting. *Journal of Applied Sports Science Research*, *4*(1), 37–41.

Souza, A. L., Shimada, S. D., & Koontz, A. (2002). Ground reaction forces during the power clean. *Journal of Strength and Conditioning Research*, *16*(3), 423–427.

Stone, M. H., Sanborn, K., O’Bryant, H. S., Hartman, M., Stone, M. E., Proulx, C., … Hruby, J. (2003). Maximum Strength-Power-Performance Relationships in Collegiate Throwers. *Journal of Strength and Conditioning Research*, *17*(4), 739–745.

Stone, M. H., Sands, W. A., Pierce, K. C., Carlock, J., Cardinale, M., & Newton, R. U. (2005). Relationship of maximum strength to weightlifting performance. *Medicine and Science in Sports and Exercise*, *37*(6), 1037–1043.

Storey, A., & Smith, H. K. (2012). Unique aspects of competitive weightlifting: Performance, training and physiology. *Sports Medicine*.

Suchomel, T. J., Comfort, P., & Lake, J. P. (2017). Enhancing the force-velocity profile of athletes using weightlifting derivatives. *Strength and Conditioning Journal*, *39*(1), 10–20.

Vizcaya, F. J., Viana, O., Olmo, M. F. Del, & Acero, R. M. (2009). Could the deep squat jump predict weightlifting performance? *Journal of Strength and Conditioning Research*, *23*(3), 729–734.

****

**Figure 1.** Average and individual annual change in competition performance variables across two consecutive years. **(A)** Snatch **(B)** Clean & Jerk **(C)** Total.

****

**Figure 2.** Average and individual annual change in IMTP PKF and CMJ CPF across two consecutive years. **(A)** CMJ CPF **(B)** IMTP PKF. IMTP PF = Isometric Mid-Thigh Pull Peak Force, CMJ CPF = Countermovement Jump Peak Concentric Force. \* = P < 0.05.

******

**Figure 3.** Correlations between force-plate variables and weightlifting performance with 95% confidence intervals. **(A)** IMTP PF (N) and Snatch (Kg) **(B)** CMJ PP (W) and Snatch (Kg) **(C)** IMTP PF (N) and Clean & Jerk **(D)** CMJ PP (W) and Clean & Jerk **(E)** IMTP PF (N) and Total (Kg) **(F)** CMJ PP (W) and Total (Kg). IMTP PF = Isometric Mid-Thigh Pull Peak Force, CMJ PP = Countermovement Jump Peak Power.

******

**Figure 2.** Correlations between the percentage change in force-plate variables and weightlifting performance with 95% confidence intervals. **(A)** ΔIMTP PF (N) and ΔSnatch (Kg) **(D)** ΔIMTP PF (N) and ΔClean & Jerk **(C)** ΔIMTP PF (N) and ΔTotal (Kg). ΔIMTP PF = Change in Isometric Mid-Thigh Pull Peak Force