PhD thesis

The planning, monitoring and training of elite weightlifting

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THE PLANNING, MONITORING AND TRAINING OF ELITE WEIGHTLIFTING

A thesis submitted in fulfillment of the requirements for the degree of doctor of philosophy

(Sports Science)

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ABSTRACTS

The journey of Olympic success can be attributed to the appropriate planning and monitoring of key information which can help inform the training process. Weightlifting has been studied over multiple decades, with the most prominent research coming from the Soviet Union in the 1980's. Since then, research on weightlifting has often been conducted within silo's relating to technique or physical surrogates. However, no research has been conducted with an attempt to understand the weights required to achieve international success and how physical attributes can change over time in conjunction with technical ability. Therefore, the primary aims of this thesis were to (i) develop a series of models to predict key performance zones for major international events, (ii) review the literature around methods of analysing and defining technique, (iii) explore the validity and reliability of a commercially available inertial sensor for measuring barbell mechanics, (iiii) evaluate alternative kinetic surrogate measures, and (iv) describe how the aforementioned has been used longitudinally in preparation for the Tokyo 2020 Olympic Games.

In study 1, the primary objective was to develop a set of predictive models to predict performance total (Ptot) for newly announced weight categories across five performance zones, rangin; 1st-3rd, 4-5th, 6-8th, 9-10th and 11-15th, for 3 major weightlifting competitions. On average, predicted Ptot displayed a difference from actual Ptot of 3.65±2.51% (12.46±9.16 kg), 0.78±3.29% (2.26±10.08 kg) and -1.13±3.46% (-4.32±11.10 kg) for the Olympics and World and European Championships, respectively. The results suggest that the predictive models may be a good indicator of future performances, however, the models may have greater efficacy in some weight categories and performance zones than others.

In study 2, a Scoping review was conducted using Medline, Web of Science, and PubMed in helping to identify themes in the analysis and definition of competitive weightlifting. A total of 47 articles were included for analysis. Two general themes were identified with biomechanical information being captured within competition or within laboratory environments. A large proportion of data capture utilised single or multi-camera systems utilising custom scripts of software. The most common method of phase identification used change in knee joint angle and barbell displacement, often when using multi-camera systems. The number of phases identified ranged from 2 to 6, with 5 and 6 being reported most

frequently, with the difference often being the rise from the catch position. The varying methods of capture and phase identification can impact the kinetic and kinematic outputs that are often reported within the research. More research is needed to identify valid, accessible, and discreet methods of monitoring weightlifting.

Study 3 aimed to fulfil the additional research identified from the scoping review (study 2), focusing on weightlifting technique. This study assessed the validity and reliability of the Enode, a commercial Inertial Measurement Unit (IMU) for measuring barbell kinematics and kinetics during the snatch. The Enode demonstrated good validity for most variables, particularly in measuring peak velocity. However, it tended to overestimate horizontal displacement, showing fixed or proportional bias. The within-session and between-session reliability of the Enode were generally good to excellent for variables such as velocity and vertical displacement. Horizontal displacement measures displayed large variability. Practical applications suggest that the Enode is a valid and reliable tool for monitoring weightlifting technique, particularly for assessing vertical velocity and vertical displacement. However, caution is advised when interpreting horizontal displacement data.

In study 4, the kinetics of the countermovement jump was assessed to identify which kinetic measures best associated with weightlifting performance. From a total of 15 metrics, 13 were deemed reliable, with propulsive impulse showing the greatest level of reliability. Correlational analysis showed *strong* to *very strong* ($r = 0.676 – 0.817$) relationships between all absolute measures of weightlifting performance and propulsive impulse for both women and men. This novel finding suggests that practitioners may wish to monitor propulsive impulse as it may provide more insight into changes of force capabilities following training.

Study 5 aimed to take the learnings from the previous studies and apply it to the longitudinal planning, monitoring, and training of an elite weightlifter in preparation for the Tokyo Olympic Games. The key findings showed performance increases in 2019, with concurrent improvements in force capacity and expression measured in the isometric mid-thigh pull (IMTP) and countermovement jump (CMJ). The COVID-19 disruption led to decreased training intensity and varied volume application, resulting in reduced performance and consistent monitoring. Post-Covid, training intensity increased significantly, particularly during the taper in preparation for Tokyo. Positive increases in peak barbell velocity occurred

during the end of the taper suggesting a potential increase in preparedness. Predicted competition performance differed by 5.89%, but the top 10 target was achieved.

Overall, the thesis integrates these studies to provide a cohesive understanding of elite weightlifting performance, offering practical insights for coaches, scientists, and practitioners in the field. It underscores the importance of considering technical, biomechanical, neuromuscular, and contextual factors in elite performance preparation and monitoring.

ACKNOWLEDGEMENTS

"The strength of the team is each individual member. The strength of each member is the team."

Phil Jackson

Personally, this is the most important page in my thesis. It highlights that my journey of learning and my successes, no matter how small or big are attributed to those I keep around me. No amount of words can express my gratitude, but I'll give it a try.

To my director of studies and friend, Professor Anthony Turner. You've not only been a phenomenal mentor throughout my time as a PhD student, but also throughout my career. You never fail to inspire me and you've helped me pave my own path to success, ensuring I stay grounded and connected to what really matters, the athletes.

To my supervisors, Professors Jason Lake and Paul Comfort. You both brought a fountain of knowledge and experience to this thesis of which I have greatly benefited from. Jason, your calls about statistics and biomechanics really helped me to develop my knowledge in understanding weightlifting to a deeper level. Paul, the opportunities you have afforded me in contributing to positions stands and round tables has really helped my visibility as coach and academic. A lot of my knowledge and successes wouldn't be possible without you both. Thank you!

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Finally, I dedicate this thesis to my mum and baa (my gran), whose unwavering belief in me and encouragement to follow my own path have been the cornerstone of my journey. Their tenacity, which I proudly inherit, has been instrumental in completing this thesis. Additionally, I extend heartfelt gratitude to Stephanie, the most patient, understanding, and loving person in the world. Sorry it took so long, but it’s done!

Congratulations everyone, we’ve finished.

PUBLICATIONS & KNOWLEDGE EXCHANGE

PEER-REVIEWED JOURNAL ARTICLES

1) **Chavda, S**., Comfort, P., Lake, J. P., Bishop, C., & Turner, A. N. (2023). Predicting weight category–specific performance zones for Olympic, World, and European Weightlifting Competitions. *The Journal of Strength & Conditioning Research*, *37*(10), 2038-2045. (Chapter 2)

2) **Chavda, S,** Swisher, A., Haff, GG., Hill, M., Martin, S and Turner AN. Weightlifting: An Applied Method of Technical Analysis *Strength and Conditioning Journal*, 43(4): 32-42, 2021. (Chapter 3)

3) **Chavda, S**., Lake, J. P., Comfort, P., Bishop, C., Joffe, S. A., & Turner, A. N. (2023). Relationship between kinetic and kinematic measures of the countermovement jump and national weightlifting performance. *Journal of Science in Sport and Exercise*, 1-13. (Chapter 5)

4) **Chavda, S**., Bromely, T., Jarvis, P., Williams, S., Bishop, C., Turner, AN., Lake, J., and Mundy, PD. Force-time Characteristics of The Countermovement Jump: Analysing the Curve In Excel. *Strength and Conditioning Journal*, 40(2): 67-77, 2018. (Chapter 5&6)

5) **Chavda S**., Williams S., Turner A N., Bishop C., Lake J., Comfort P., and Haff G G. A Practical Guide to Analysing the Force-Time Curve of Isometric Tasks in Excel. *Strength and Conditioning Journal*, 42(2): 26-37, 2020. (Chapter 6)

CO-AUTHORED PEER-REVIEWED JOURNAL ARTICLES OF RELEVANCE

1) Comfort, P., Haff, G.G., Suchomel, T.J., Soriano, M.A., Pierce, K.C., Hornsby, W.G., Haff, E.E., Sommerfield, L.M., **Chavda, S**., Morris, S.J. and Fry, A.C. (2022). National strength and conditioning association position statement on weightlifting for sports performance. *The Journal of Strength & Conditioning Research*, 10-1519.

2) Joffe, S. A., Price, P., **Chavda, S**., Shaw, J., & Tallent, J. (2023). The relationship of lower-body, multijoint, isometric and dynamic neuromuscular assessment variables with snatch, and clean and jerk performance in competitive weightlifters: A meta-analysis. *Strength & Conditioning Journal*, *45*(4), 411-428.

3) Sorensen, A. M., **Chavda, S**., Comfort, P., Lake, J., & Turner, A. N. (2022). Intra-and Interday Reliability of Weightlifting Variables and Correlation to Performance During Cleans. *Journal of strength and conditioning research*, *36*(11), 3008-3014.

CONFERENCE ABSTRACTS AND PRESENTATIONS

Abstracts

1) **Chavda, S**., Yao, X., Harecoff, J**.**, **Martin, S**., and Turner, AN. Barbell Kinetics and Kinematics of the Clean in Female National Weightlifters: A Comparison Between Medallists and Non-Medallists (NSCA, Las Vegas, 2020)
2) **Chavda, S**., Yao, X., Harecoff, J., **Martin, S**., and Turner, AN. Alternative Jump Variables as Surrogate Measures of Weightlifting Performance in National Weightlifters (UKSCA, Milton Keynes, 2019)

Presentations & Panels

1) Invitational Panel, Weightlifting for Sports Performance: Position Stand, Roundtable (NSCA, Las Vegas, 2023)
2) Podium Presentation: Middlesex RSCC (2022)
3) Key Note: Middlesex Strength and Conditioning Student Conference (2022, Online)
4) Invitational Panel, Weightlifting Roundtable (UKSCA, Online, 2020)
5) Podium Presentation**-** Training of a Weightlifter: A Scientific Approach (UKSCA, Milton Keynes, 2019)
6) British Weightlifting Performance Pathway Conference- Key Note (Loughborough, 2018 and Coventry, 2020)
7) Podcast – Key Performance Indicators and Technical Models (RICH Performance, 2019)

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CHAPTER 1: INTRODUCTION

1.1 A BRIEF HISTORY OF WEIGHTLIFTING

Weightlifting first found governance in December 1890 (https://www.iwf.net/weightlifting_/history/). The first appearance of weightlifting as a sport was contested in the 1896 Olympic Games, Athens, where it hosted the one-handed snatch and two-hand clean and jerk, to which the two-hand press was added under a decade later (1905). Initially, the barbell was not allowed to contact the lifter's legs during these lifts. However, by the mid-sixties the barbell "brushing" the thigh was accepted with full contact allowed from 1969. Over the decades, the one-handed variants of the snatch were abolished (1961), with the removal of the press following in 1973. This left weightlifting with the current movements contested today in the modern Olympic games, where competing athletes aim to achieve the greatest aggregate total of two lifts: the snatch and the clean and jerk. The snatch is characterised by the athlete lifting the barbell from floor directly overhead, whereas the clean and jerk is a two-part lift in which the athlete lifts the barbell from the floor to shoulder during the clean (the end position which sees the barbell positioned on the anterior deltoids), before displacing the barbell from the shoulder to directly overhead during the jerk. The lift must be executed within the confinement of the rules as governed by three referees positioned four meters directly in front of the competition platform (Ajan, 2020). Furthermore, a jury's table is also present to support or question the referee's outcome, with additional support of video technology playback where appropriate, with the latter introduced in 2015. Technical infringements are outlined in the International Weightlifting Federations (IWF) technical and competition rules and regulations (TCRR) handbook (Ajan, 2020). A missed lift is identified as a lift which exhibits a technical infringement which commonly manifests itself as the bar not reaching the shoulders or overhead. Understanding technical infringements and their potential causes may assist coaches in developing the optimal technique for their lifter(s) and highlights the importance of what coaches should be looking for on a day-to-day basis within training, thus informing the training process.

During competition, each athlete has three attempts at the snatch followed by three attempts at the clean and jerk. In both cases, the athlete aims to lift the heaviest load possible. The athlete who lifts the heaviest load first becomes the successor. If two athletes achieve the same load, the aforementioned still applies, whereas previously the lighter lifter would win via a coefficient total, where each bodyweight has an assigned coefficient based on most recent world records each Olympic year (Chavda & Everett, 2018) (Equation 1). The relevance of this is that it is now more critical for lifters to: 1) select the appropriate weights for the allocated attempts, 2) be able to lift heavier loads sooner to increase chances of success, and 3) understand what tactical, technical, and physical parameters help achieve increased performance. Collectively, the aforementioned points mean that coaches must be able to appropriately strategize to enhance the chance of success, whilst ensuring their training prescription and outcomes allows them to apply such strategies.

Equation 1 – The Sinclair Coefficient

$10^{AX^2}\ (x \leq b)$

$1\ (x > b)$

where $x = log_{10}\left(\frac{x}{b}\right)$

$x = athlete\ bodyweight\ (kg)$

	Men	Women
A	0.751945030	0.783497476
b	175.508 kg	153.655 kg

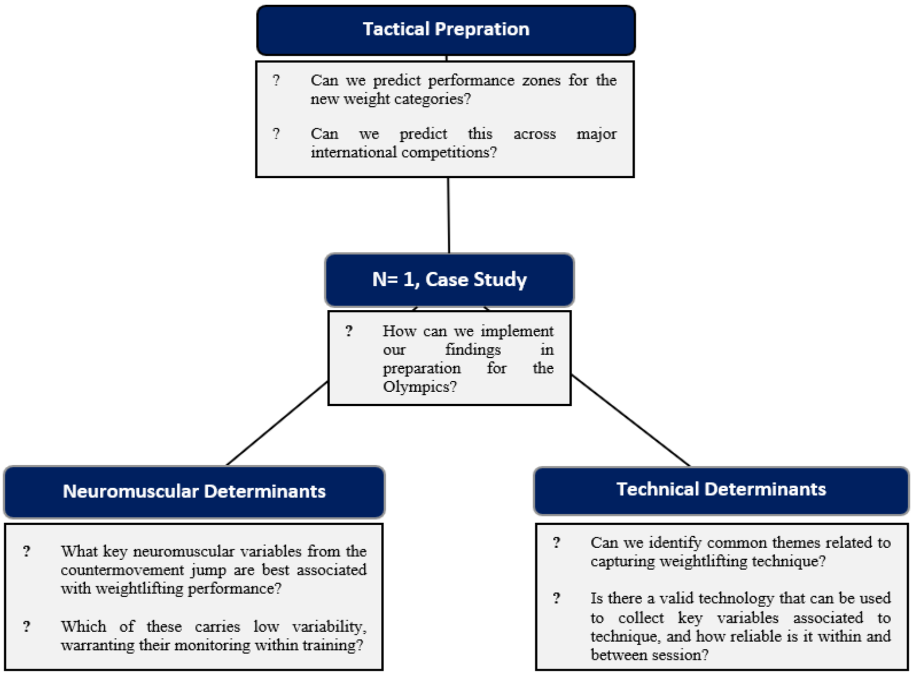
Another facet of weightlifting that must be considered are the weight classes within which each athlete competes. Over the last four decades the sport of weightlifting has seen multiple weight class changes with the most recent occurring in the summer of 2018 where it was announced that seven of the ten weight categories would be contested at the XXXII Olympiad, 2020 (Table 1.0). Unlike some previous years, where all weight classes were included, the decision by the international Olympic committee (IOC) and IWF may heavily impact the performances within the Olympic categories compared to the non-Olympic categories, with a likely increase in the former, and decrease in the latter. Additionally, as of December 2020, it was announced that a further reduction in athlete quotas for the Paris 2024 Olympics will be undertaken, thus lessening the number of weight-classes.

Table 1.0. Evolution of Senior Weight classes presented in kilograms (kg).

1920 – 1972	1973 – 1992§		1993 – 1997		1998 – 2018		2018 – Present	
Men	Men	Women	Men	Women	Men	Women	Men	Women
52	52	44	54*	46*	56	48	55	45
56	56	48	59*	50*	62	53	61*	49*
60*	60	52	64*	54*	69	58	67	55
67.5*	67.5	56	70*	59*	77	63	73*	59*
75*	85.25	60	76*	64*	85	69	81	64
82.5*	90	67.5	83*	70*	94	75	89*	71*
82.5+*	100	75	91*	76*	105	75+	96	76
90	110	82.5	99*	83*	105+		102**	81**
110	110+	82.5+	108*	83+*			109	87
110+			108+*				109+	87+

* denotes an Olympic weight class; § Women's weightlifting introduced in 1988; ** denotes an Olympic weight category with no top end weight limit (i.e. 102+ and 81+)

The relevance of the logistical and technical changes within the sport highlights that the strategies adopted to maximise performance must be multifaceted and holistic. Figure 1.1 depicts the approach adopted within this thesis, highlighting the key components and questions that underpin high performance weightlifting and how the monitoring and interactions of technique, neuromuscular ability, and strategy, must be used in unison to optimise performance for a single athlete. This figure will be presented prior to each chapter, highlighting the key area of focus.



Tactical Prepration

? Can we predict performance zones for the new weight categories?

? Can we predict this across major international competitions?

N= 1, Case Study

? How can we implement our findings in preparation for the Olympics?

Neuromuscular Determinants

? What key neuromuscular variables from the countermovement jump are best associated with weightlifting performance?

? Which of these carries low variability, warranting their monitoring within training?

Technical Determinants

? Can we identify common themes related to capturing weightlifting technique?

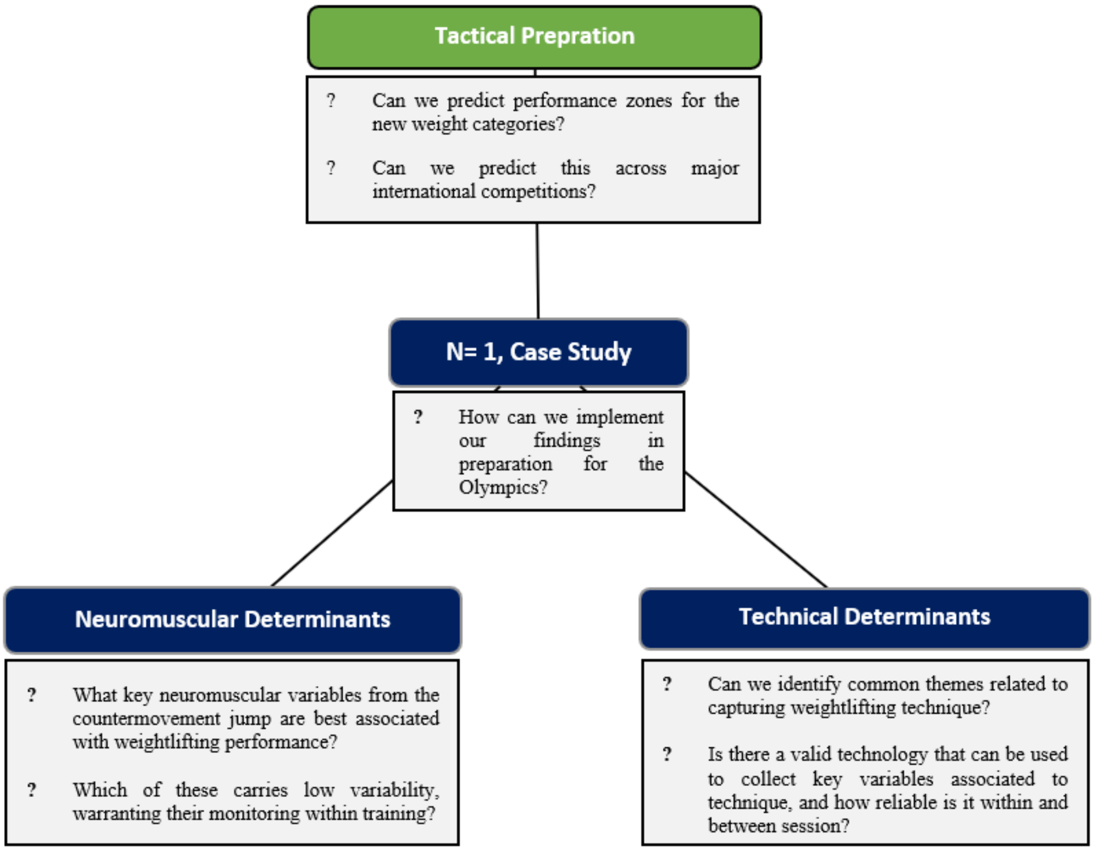
? Is there a valid technology that can be used to collect key variables associated to technique, and how reliable is it within and between session?

Figure 1.1. Weightlifting performance triangle.

CHAPTER 2: STUDY 1 – DEFINING & PREDICTING PERFORMANCE ZONES

Chavda, S., Comfort, P., Lake, J. P., Bishop, C., & Turner, A. N. (2023). Predicting weight category–specific performance zones for Olympic, World, and European Weightlifting Competitions. *The Journal of Strength & Conditioning Research*, *37*(10), 2038-2045.

It becomes evident from chapter 1 that there have been a number of changes in the weight categories over time. This inherently makes it difficult to know what totals would need to be achieved to obtain a medal or a specific rank of interest. The focus of chapter 2, therefore, is to predict key performance zones for major international weightlifting events, such as the Olympics and World and European championships. Given the changes in weight categories, utilising historic performance data from previously contested weight categories, may allow performance scientists and coaches to identify areas of opportunities and influence selection policies based on predicted performances.



- ? Can we predict performance zones for the new weight categories?
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- ? How can we implement our findings in preparation for the Olympics?

- ? What key neuromuscular variables from the countermovement jump are best associated with weightlifting performance?
- ? Which of these carries low variability, warranting their monitoring within training?

- ? Can we identify common themes related to capturing weightlifting technique?
- ? Is there a valid technology that can be used to collect key variables associated to technique, and how reliable is it within and between session?

2.2. INTRODUCTION

Practitioners in high performance sport often look to gain a competitive advantage by better understanding trends in performance data which may help direct the development and selection of athletes at major sporting events. Furthermore, this information can help with tactical decisions to best position the athlete within the rankings of the sport, which is often associated to increased funding opportunities and other incentives provided by relevant governing bodies and key stake holders. One way of utilising trends is to use historic performance data to forecast future performances. While predicting medal zones is a primary objective for many performance teams working in Olympic sports, opportunities outside of this zone, such as 4th place and below may also provide valuable information in ensuring that the athletes selected to represent their nation will be those who bring the greatest chance of success. These can be termed performance zones, where the medal zone is 1st -3rd and all subsequent performance zones can be context specific to the sport.

The sport of weightlifting is contested across two lifts: the snatch (SN) and clean and jerk (CJ), of which the highest successful performance (load lifted) of each is totalled (Ptot). It is currently contested at the Olympic games (OG), as well as hosting its own World and European championships (WC and EC, respectively) by the International Weightlifting Federation (IWF), with these three competitions carrying the most importance, particularly for European competitors. Within these competitions, there can be up to 300+ athletes competing across 10+ weight categories for both men and women, therefore predicting performance zones based on competition type and weight category, may provide useful insights into what to expect at such competitions, enabling better tactical decisions to be made in the selection of athletes. Predicting performance zones particularly to the granularity of competition type and weight class, requires large quantities of historical data which are often publicly available and has been a preferred method for many investigations of this type (Bhanu *et al*., 2017; Delen *et al*., 2012; Huebner *et al*., 2019). This information can then be used to forecast future performances using regression analysis, which estimates the relationship between a dependent and an independent variable by presenting the proportionality of variance in which the dependent variable is explained by the independent variable. Prior use of regression analysis in weightlifting has helped to identify surrogate measures of weightlifting performance (Ince and Ulupinar, 2020; Joffe and Tallent, 2020; Khaled, 2013), helping performance scientists identify key physical indicators that underpin weightlifting success. For example, Joffe and Tallent (2020) found that isometric mid-thigh pull peak force (IMTP PF) and countermovement jump peak power (CMJ PP), could statistically significantly predict 94.2% of variance in Ptot in international female weightlifters through the use of stepwise multiple regression. Additionally, the authors also suggested that 91.8% and 95.1% of variance in the SN and CJ, respectively, could also be explained by IMTP PF and CMJ PP. While this information is highly valuable when collecting physical performance measures, a gap still exists in trying to predict which Ptot are required to achieve a specific rank at a specific competition, within a specific weight category, and therefore needs to be explored.

A unique issue that exists in trying to predict future weightlifting performances is that as of July 2018, the IWF announced 10 new weight categories for women and men, which consequently also changed the contested weight categories at the next Olympics (Tokyo 2020). Therefore, the data sample available for the newly contested weight categories would not be sufficient to develop a predictive model, and therefore utilising performance data from the old weight categories would need to be used in developing predictive models. Though one can try to predict future performances, a clear method of data organisation and analysis must be conducted to ensure the model best reflects the trend of the data in which the performance teams are interested in. An inherent issue with using historical data is that differences in performances between competition year and single athlete reoccurrence may affect predictive ability. These can present themselves as outliers thus affecting the fit of the model. Therefore prior to any regression analysis being made, one must account for this by exploring such differences and deciding whether the inclusion of outliers will be deleterious to the development of the predictive model at the expense of utilising data that truly represents the population. Once accounted for, this may help with; i) reducing the noise by being able to exclude specific data that may not be representative of the normal trend and ii) provide an opportunity to pool data to increase its utility within the predictive model. The aforementioned considerations help to ensure the model is not under or over fitted, thus presenting a trade-off between bias and variance. This allows for appropriate predictive ability, while also ensuring the generalizability of the model for future data sets (Briscoe and Feldman, 2011).

To the authors' knowledge, predicting future performances of major weightlifting competitions is yet to be explored within the published literature, particularly given the weight class changes in 2018, therefore presenting a novel challenge of predicting future performance zones of the new weight categories utilising the historic data of previous categories. The primary objective of this investigation, therefore, is to predict the Ptot required within specific performance zones in major weightlifting competitions within the newly adopted weight categories. A secondary objective of this investigation is to compare the predicted Ptot to current available performances achieved within the new weight categories.

2.3. METHODOLOGY

Experimental Approach

Men's performance totals of the OG, WC, and EC (referred to as competition type) from 1998 to 2021 were obtained from the IWF website. All data were organised by competition type, year, and rank, based on the Ptot of the top 15 athletes using the old weight category classifications (pre-November 2018). To ensure enough data was available to develop the predictive model, Ptot from each competition type across each year was pooled and averaged followed by a Hedges *g* effect size analysis to identify if any meaningful differences existed between competition year. The Ptot data was then split into five performance zones for each competition type. A second order Polynomial regression was conducted using the individual Ptot and bodyweights for each performance zone. The *y* intercept was used to extrapolate the predicted Ptot for each Performance Zone across each competition type for the new weight categories. The prediction was then compared to existing performance zones using percentage and absolute differences to provide insight into the efficacy of the models.

Sample

Men's Ptot data was obtained from the old weight categories, for a total of 7,037 samples from the official IWF webpage using a custom data scrapping script developed in Python (v3.8, Van Rossum, Amsterdam) (Appendix 2.1) accessed 27th May 2020. The data was organised so that only the top 15 athletes within each weight category across all competitions were considered. This range was selected as this was the maximum number of athletes contested at the 2020 OG, which is considered the pinnacle of the sport. Following the above reductions, a total of 4,011 samples from old weight category data was utilised to develop the performance zone predictive models. New weight category data was obtained manually between July and August 2021, following the 2020 Olympic games, providing an additional 639 samples. Ethics was granted via the London Sport Institute ethics committee (Appendix 2.2).

Statistical Analysis

Figure 1 outlines the sequence of analysis conducted.

Pooling of Data

A Hedges *g* effect size analysis was used to determine the magnitude of differences between each year within each competition type using a custom Microsoft Excel spreadsheet (Lakens, 2013; Turner *et al*., 2021). Descriptors for effect sizes were as follows; <0.2 '*Trivial'*, 0.21-0.5 '*Small'*, 0.51-0.8 '*Moderate'*, >0.8 '*Large'* (Cohen, 1988). All effect sizes were calculated with 95% confidence intervals (CI) (Nakagawa and Cuthill, 2007). Checking for year-to-year differences enabled the pooling of Ptot based on competition type, should no *moderate to large* differences be present. This provides a larger sample size in which the predictive model can be developed and would also enable the exclusion of specific competition years that are not representative of the typical trend, thus avoiding dilution of the data and is comparable to removing outliers within data sets.

As the second objective of the investigation was to compare the predictions to actual outcomes, all new weight categories that had been contested at the WC and EC from 2018 – 2021, had been pooled, of which the average of each performance zone ± SD was calculated. The exception to this was the OG, which only had one instance of which the new weight categories were contested (July-August 2021), compared to the two of the WC and EC (November 2018 and September 2019, and April 2019 and 2021, respectively).

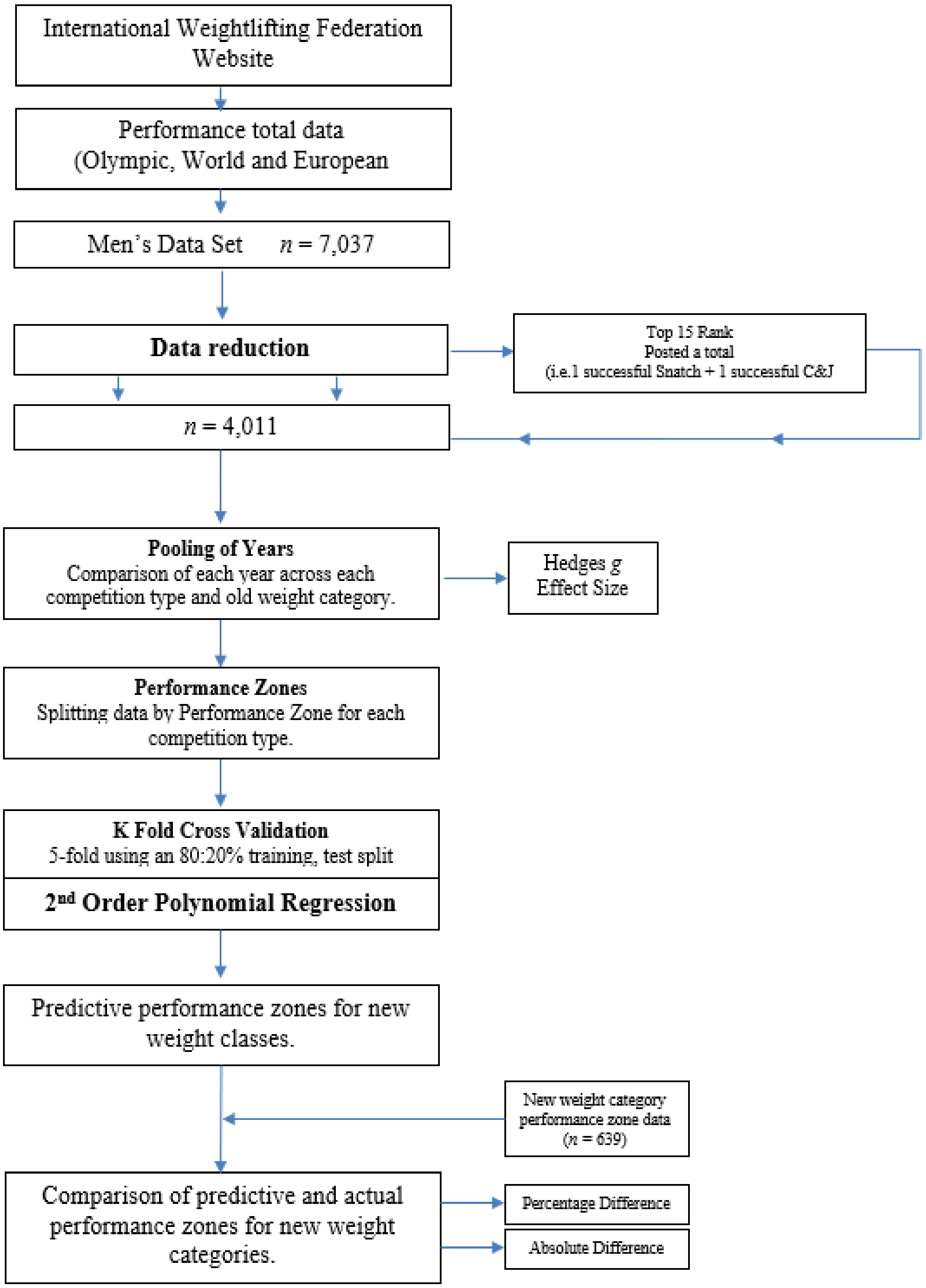


Figure 2.1. Schematic outlining the data collection, organisation and analysis processes.

Rank Zone Definitions

In phase 3, the data for each weight category and competition type was divided into five rank Zones: Medal Zone (1st - 3rd), Zone 2 (4th – 5th), Zone 3 (6th – 8th), Zone 4 (9th - 10th) and Zone 5 (11th – 15th). Although performance zone grouping can arguably be approached using many variations, these performance zones were chosen for the following reasons: The Medal Zone provides a Zone in which all athletes aspire to and is the pinnacle of performance, Zone 2 serves as an 'outside shot' of a medal opportunity as there is a likelihood of crossover due to the variation of Ptot achieved in the Medal Zone and Zone 2. Current qualification for the OG provides the top eight ranked athletes within a weight class to automatically gain a spot at the Olympics. Furthermore, Zone 3 provides the lower echelon of the minimum rank required (8th) to attain an Olympic diploma and is often associated with higher funding potential within national Olympic committees (NOC's). Like Zone 2, Zone 4 is an 'outside shot' of achieving atop 8 finish. Zone 5 is the lower echelon of the ranking system and is the maximum number of athletes within a given weight category at the OG.

Predictive Model

It has been well established that the relationship between strength and body size is nonlinear (Batterham and George, 1997; Cleather, 2006) specifically, a parabola relationship between weightlifting performance and bodyweight has previously been reported (Batterham and George, 1997; Briscoe and Feldman, 2011; Kauhanen *et al.*, 2002). It was therefore determined appropriate to use a second order Polynomial model of regression. The regression was used to predict Ptot at the newly contested weight classes using the equation $\hat{y}^{*} = ax^2 + bx + c$, where $\hat{y}^{*}$ is the prediction (Ptot), x is the known value of bodyweight, and a, b and c are the coefficients.

Confidence intervals of 95% were calculated using the equation $\hat{y}^{*} \pm \mathrm{t}a/2S_{\hat{y}*}$, where $\hat{y}^{*}$ is the predicted point estimate, ta is the t distribution given alpha, and $S_{\hat{y}*}$ is the estimated SD of the mean of $\hat{y}^{*}$. The calculation of $S_{\hat{y}*}$, was as follows:

$$\mathrm{S}_{\hat{y}*} = S * \sqrt{\frac{1}{n} + \frac{(x^{*} - \tilde{x})^2}{(n-1)S_x^2}}$$

Where S is the standard error of the regression model, n is the sample size, x is the known value of bodyweight and $\tilde{x}$ is the mean of all known x values. The 95% CI provides an upper and lower boundary in which one could expect that the populations line of best fit would likely fall between. Like the above, a 95% predictive interval (95% PI) was calculated as $\hat{y}^*$ ± t$a/2S_{Pred}$, with it's estimated SD calculated as:

$$S_{\hat{y}*} = S * \sqrt{1 + \frac{1}{n} + \frac{(x^* - \tilde{x})^2}{(n-1)S_{x}^{2}}}$$

The 95% PI provides a boundary in which 95% of future predictions (or Ptot) for a single value of x (bodyweight) would likely fall between. Prediction intervals must account for both the uncertainty in estimating the population mean, plus the random variation of the individual values and is therefore wider than a confidence interval (Kümmel *et al.,* 2018). Since the new weight categories had been contested during WC and EC from 2018, the mean bodyweight for each class was used to intercept the *y* slope. All polynomial analysis was conducted using a custom Matlab script (v.9.6.0, R2019a, Natick Massachusetts: The Mathworks Inc) (Appendix 2.3).

Predictive Model Validation

A 5-fold k-cross internal validation method was used to evaluate the quality of each performance zone model, using the Regression Learner application in Matlab (v.9.6.0, R2019a, Regression Learner, Natick Massachusetts: The Mathworks Inc). The old weight category data set was compartmentalised as 80% training data and 20% test data randomly assigned across 5 iterations. Root mean square error (RMSE), mean squared error (MSE) and mean absolute error (MAE) are presented in the supplementary material for each performance zone (Appendix 2.4). Although preferred (Abt *et al.*, 2022), utilising newly contested weight categories performances for external validation was not conducted as the sample size would not have been sufficient enough to use as a test model and was therefore the primary reason internal validation utilising the 80:20 split of the old weight category data was used.

2.4. RESULTS

Pooling of data

All Ptot data within each competition type displayed primarily *trivial* differences between years (Appendix 2.5 - 2.7) with only 36/224 (16%) observations showing small differences, therefore all Ptot's were pooled for each competition type. Performance total data was then subdivided into their respective performance zones in preparation for the regression analysis.

Predictive Model

The regression model outputs can be seen in Table 2.1. Differences between the predicted Ptot and actual Ptot outcome (±SD) can be seen in Table 2.2 – 2.4. Graphical data can be referred to in the supplementary material (Appendix 2.8 – 2.10).

2.5. DISCUSSION

The primary objective of this investigation was to predict performance zones of newly contested weight categories within major competitions using historic data. The findings from this investigation indicate that predicting performance zones for major weightlifting competitions can be achieved depending on the competition type, performance zone, and weight category. Data validation showed that the final model performance of each performance zone within each competition type carried low error rates (RMSE). This suggests that the models perform well on unseen data (Test data). However, what becomes apparent is that the error increases the lower down the performance zone (i.e. 11th -15th). This is evidenced and discussed further below within the context of performance zones and their practical interpretations.

2.5.1. Olympic Games

The performance zones for the OG displayed R^2 values ranging from 0.79 to 0.97 to suggesting a variance of 79 to 97% of the Ptot could be explained by the weight category. Average predictive ability of all the performance zones was 3.65 ± 2.51% (12.46 ± 9.16 kg). The predictions for the Medal Zones averaged a 2.15 ± 1.20% (8.10 ± 4.53 kg) difference from the Tokyo 2020 performances across all new weight categories. The best prediction occurred in the 73 kg weight category, which had a 0.16% (0 kg) difference to the actual Medal Zone (351 vs 351 kg). This can be deemed a perfect prediction, but it is important to state that the interpretation of this should consider that this prediction would provide a silver medal performance as it is an average of 1st, 2nd and 3rd.

The men's 96 kg weight category displayed the biggest difference between the prediction and actual outcome, with a value of 3.71% (15 kg). The actual outcome achieved was 392 ± 9 kg, with the prediction being 407 kg. This over prediction would in fact achieve a gold medal, however, the LLPI of 380 kg encapsulates the actual outcome ± the SD (401 – 383 kg) and therefore it is suggested in this instance that performance teams aim for anything above the LLPI to increase medal potential. The Medal Zone for all other categories displayed prediction to actual outcome differences of between 1.17 – 3.71%. When analysing all other performance zones within the OG, it becomes apparent that the differences between the prediction to the actual outcome generally ascend down the performance zones, with the largest differences existing in Zone 5 (11th – 15th). This is likely due to multiple reasons, 1) this performance zone has the largest number of athletes within it, compared to the other performance zones which is likely to increase the variance of Ptot and 2) this Zone likely contains athletes who qualified outside of top 8 automatic qualification spots in the lead up to the OG.

Table 2.1. Polynomial regression outputs

	Zone	Equation	Coefficient 95% Confidence Interval			R^2
			Coefficient 1	*Coefficient 2*	*Intercept*	
OG	Medal Zone (1st-3rd)	$-0.019x^2 + 5.623x + 41.730$	[-0.021 - -0.017]	[5.217 - 6.028]	[22.290 - 61.180]	0.97
	Zone 2 (4-5th)	$-0.023x^2 + 6.448x + -7.257$	[-0.026 - -0.021]	[5.928 - 6.969]	[-31.910 - 17.390]	0.97
	Zone 3 (6-8th)	$-0.022x^2 + 6.250x + -6.446$	[-0.025 - -0.019]	[5.658 - 6.842]	[-33.940 - 21.050]	0.96
	Zone 4 (9-10th)	$-0.023x^2 + 6.293x + -15.190$	[-0.027 - -0.019]	[5.562 - 7.025]	[-50.180 - 19.790]	0.92
	Zone 5 (11-15th)	$-0.021x^2 + 5.811x + -6.373$	[-0.026 - -0.016]	[4.772 - 6.850]	[-54.460 - 41.720]	0.79
WC	Medal Zone (1st-3rd)	$-0.019x^2 + 5.599x + 37.060$	[-0.020 - -0.018]	[5.363 - 5.835]	[25.530 - 48.590]	0.96
	Zone 2 (4-5th)	$-0.022x^2 + 6.151x + 4.186$	[-0.023 - -0.021]	[5.869 - 6.432]	[-9.376 - 17.750]	0.96
	Zone 3 (6-8th)	$-0.024x^2 + 6.521x + -19.380$	[-0.025 - -0.023]	[6.232 - 6.810]	[-32.980 - -5.788]	0.95
	Zone 4 (9-10th)	$-0.025x^2 + 6.753x + -36.040$	[-0.027 - -0.023]	[6.350 - 7.156]	[-54.860 - -17.220]	0.94
	Zone 5 (11-15th)	$-0.026x^2 + 6.803x + -44.880$	[-0.028 - -0.024]	[6.444 - 7.162]	[-61.480 - -28.270]	0.90
EC	Medal Zone (1st-3rd)	$-0.020x^2 + 6.035x + -4.710$	[-0.022 - -0.019]	[5.690- 6.379]	[-21.570 - 12.150]	0.94
	Zone 2 (4-5th)	$-0.024x^2 + 6.625x + -40.230$	[-0.026 - -0.022]	[6.236 - 7.014]	[-58.420 - -22.040]	0.96
	Zone 3 (6-8th)	$-0.027x^2 + 7.091x + -67.680$	[-0.029 - -0.024]	[6.664 - 7.518]	[-87.690 - -47.670]	0.93
	Zone 4 (9-10th)	$-0.021x^2 + 5.834x + -18.340$	[-0.024 - -0.018]	[5.211 - 6.456]	[-48.210 - 11.530]	0.87
	Zone 5 (11-15th)	$-0.022x^2 + 5.968x + -32.620$	[-0.026 - -0.019]	[5.198 - 6.738]	[-69.150 - 3.898]	0.75

Table 2.2. Difference between predicted point estimate and actual outcome performances (±SD) with range presented in parenthesis for new men's weight categories contested at the Olympic Games.

		55 kg	61 kg	67 kg	73 kg	81 kg	89 kg	96 kg	102 kg	109 kg	109 kg
Medal Zone (1st – 3rd)	Predicted (kg)	294	314	333	351	373	391	407	418	431	462
	Actual ± SD (kg)	N/A	303 ± 10	328 ± 6	351 ± 12	369 ± 5	N/A	392 ± 9	N/A	421 ± 10	451 ± 33
	Difference (%)	N/A	3.65%	1.57%	0.16%	1.17%	N/A!	3.71%	N/A	2.30%	2.52%
	Abs. Difference (kg)	N/A	11	5	1	4	N/A	15	N/A	10	11
Zone 2 (4th – 5th)	Predicted (kg)	277	300	321	340	363	382	398	409	421	442
	Actual ± SD (kg)	N/A	290 ± 3	321 ± 1	340 ± 2	360 ± 1	N/A	384 ± 4	N/A	409 ± 1	414 ± 0
	Difference (%)	N/A	3.28%	0.04%	0.07%	0.79%	N/A	3.66%	N/A	3.07%	6.72%
	Abs. Difference (kg)	N/A	10	0	0	3	N/A	14	N/A	13	28
Zone 3 (6th – 8th)	Predicted (kg)	269	291	311	329	352	370	385	396	408	427
	Actual ± SD (kg)	N/A	282 ± 7	307 ± 5	334 ± 4	353 ± 6	N/A	365 ± 8	N/A	394 ± 6	400 ± 8
	Difference (%)	N/A	3.17%	1.31%	-1.46%	-0.34%	N/A	5.63%	N/A	3.59%	6.78%
	Abs. Difference (kg)	N/A	9	4	-5	-1	N/A	21	N/A	14	27
Zone 4 (9th – 10th)	Predicted (kg)	261	283	303	321	343	361	376	386	398	413
	Actual ± SD (kg)	N/A	267 ± 2	300 ± 2	324 ± 1	328 ± 15	N/A	355 ± 6	N/A	380 ± 12	386 ± 6
	Difference (%)	N/A	6.02%	1.11%	-0.90%	4.76%	N/A	6.00%	N/A	4.75%	7.17%
	Abs. Difference (kg)	N/A	16	3	-3	16	N/A	21	N/A	18	28
Zone 5 (11th – 15th)	Predicted (kg)	249	269	287	304	324	341	355	364	375	389
	Actual ± SD (kg)	N/A	252 ± 17	265 ± 28	299 ± 18	308 ± 11	N/A	321 ± 15	N/A	334 ± 6	380 ± 2
	Difference (%)	N/A	6.55%	8.39%	1.79%	5.50%	N/A	10.46%	N/A	12.17%	2.50%
	Abs. Difference (kg)	N/A	17	22	5	17	N/A	34	N/A	41	10

Note: negative values present an underestimation of the prediction relative to the actual performance outcome. Abs. = absolute. All values have been rounded up to the nearest 1 kg. N/A represents not applicable as no data was available at the time of data capture.

Table 2.3. Difference between predicted point estimate and actual outcome performances (±SD) with range presented in parenthesis for new men's weight categories contested at the World Championships.

		55 kg	61 kg	67 kg	73 kg	81 kg	89 kg	96 kg	102 kg	109 kg	>109 kg
Medal Zone (1st – 3rd)	Predicted (kg)	288	308	328	345	367	385	401	412	425	457
	Actual ± SD (kg)	270 ± 16	310 ± 6	330 ± 6	351 ± 8	373 ± 5	372 ± 2	403 ± 10	395 ± 2	422 ± 11	457 ± 20
	Difference (%)	6.91%	-0.59%	-0.54%	-1.64%	-1.53%	3.42%	-0.67%	4.25%	0.64%	-0.06%
	Abs. Difference (kg)	19	-2	-2	-6	-6	13	-3	17	3	0
Zone 2 (4th – 5th)	Predicted (kg)	276	297	317	335	358	376	391	402	413	434
	Actual ± SD (kg)	257 ± 7	298 ± 4	321 ± 5	339 ± 2	360 ± 3	369 ± 1	388 ± 4	388 ± 8	408 ± 9	431 ± 2
	Difference (%)	7.39%	-0.42%	-1.26%	-1.05%	-0.74%	1.71%	0.78%	3.57%	1.25%	0.75%
	Abs. Difference (kg)	19	-1	-4	-4	-3	6	3	14	5	3
Zone 3 (6th – 8th)	Predicted (kg)	266	288	309	328	350	368	383	394	405	419
	Actual ± SD (kg)	249 ± 11	291 ± 4	314 ± 3	337 ± 1	353 ± 5	365 ± 2	379 ± 5	372 ± 7	397 ± 6	425 ± 3
	Difference (%)	7.09%	-0.82%	-1.51%	-2.83%	-0.91%	0.79%	1.27%	5.93%	2.04%	-1.45%
	Abs. Difference (kg)	18	-2	-5	-10	-3	3	5	22	8	-6
Zone 4 (9th – 10th)	Predicted (kg)	258	281	302	321	344	362	377	387	398	408
	Actual ± SD (kg)	233 ± 11	283 ± 2	310 ± 3	334 ± 1	347 ± 2	361 ± 2	372 ± 6	365 ± 8	393 ± 1	415 ± 4
	Difference (%)	10.75%	-0.78%	-2.65%	-3.89%	-0.93%	0.41%	1.29%	6.24%	1.51%	-1.68%
	Abs. Difference (kg)	25	-2	-8	-13	-3	1	5	23	6	-7
Zone 5 (11th – 15th)	Predicted (kg)	251	273	294	312	334	351	366	375	385	390
	Actual ± SD (kg)	235 ± 0	278 ± 2	306 ± 5	328 ± 3	341 ± 4	353 ± 2	366 ± 6	349 ± 11	388 ± 2	400 ± 11
	Difference (%)	6.34%	-2.25%	-4.29%	-4.90%	-2.06%	-0.38%	0.08%	7.75%	-0.54%	-2.67%
	Abs. Difference (kg)	15	-6	-13	-16	-7	-1	0	27	-2	-11

Note: negative values present an underestimation of the prediction relative to the actual performance outcome. Abs. = absolute. All values have been rounded up to the nearest 1 kg.

Table 2.4. Difference between predicted point estimate and actual outcome performances (±SD) with range presented in parenthesis for new men's weight categories contested at the European Championships.

		55 kg	61 kg	67 kg	73 kg	81 kg	89 kg	96 kg	102 kg	109 kg	>109 kg
Medal Zone (1st – 3rd)	Predicted (kg)	266	287	308	327	351	371	387	399	413	446
	Actual ± SD (kg)	251 ± 9	287± 5	314± 5	339 ± 4	358 ± 9	369± 6	380 ± 15	381 ± 7	439 ± 34	455 ± 20
	Difference (%)	6.04%	-0.02%	-1.93%	-3.36%	-2.12%	0.55%	1.73%	4.66%	-6.02%	-2.03%
	Abs. Difference (kg)	15	0	-6	-11	-8	2	7	18	-26	-9
Zone 2 (4th – 5th)	Predicted (kg)	252	275	297	317	340	361	376	388	401	424
	Actual ± SD (kg)	246 ± 2	279 ± 6	302 ± 7	329 ± 5	348 ± 3	355 ± 6	367 ± 3	375 ± 4	414 ± 21	423 ± 1
	Difference (%)	2.66%	-1.54%	-1.80%	-3.84%	-2.11%	1.60%	2.41%	3.58%	-3.23%	0.42%
	Abs. Difference (kg)	7	-4	-5	-13	-7	6	9	13	-13	2
Zone 3 (6th – 8th)	Predicted (kg)	244	266	288	308	331	351	365	376	388	404
	Actual ± SD (kg)	229 ± 5	276 ± 5	298 ± 12	323 ± 7	340 ± 7	346 ± 2	361 ± 9	369 ± 6	403 ± 12	414 ± 4
	Difference (%)	6.49%	-3.62%	-3.45%	-4.73%	-2.67%	1.26%	1.06%	1.83%	-3.67%	-2.55%
	Abs. Difference (kg)	15	-10	-10	-15	-9	4	4	7	-15	-11
Zone 4 (9th – 10th)	Predicted (kg)	239	259	279	297	318	337	350	361	383	391
	Actual ± SD (kg)	219 ± 8	267 ± 5	283 ± 4	316 ± 12	343 ± 3	341 ± 8	354 ± 7	354 ± 13	395 ± 18	399 ± 8
	Difference (%)	10.55%	-2.24%	-0.79%	-5.92%	-7.23%	-1.25%	-1.22%	1.82%	-5.74%	-0.92%
	Abs. Difference (kg)	23	-6	-2	-19	-25	-4	-4	6	-23	-4
Zone 5 (11th – 15th)	Predicted (kg)	227	246	266	283	303	320	333	342	361	363
	Actual ± SD (kg)	N/A	257 ± 13	284 ± 18	295 ± 16	315 ± 20	318 ± 10	339 ± 14	330 ± 18	380 ± 20	371 ± 13
	Difference (%)	N/A	-4.05%	-6.38%	-4.26%	-3.73%	0.69%	-1.94%	3.39%	-7.65%	-2.20%
	Abs. Difference (kg)	N/A	-10	-18	-13	-12	2	-7	11	-29	-8

Note: negative values present an underestimation of the prediction relative to the actual performance outcome. Abs. = absolute. All values have been rounded up to the nearest 1 kg. N/A represents not applicable as no data was available at the time of data capture.

2.5.2. World Championship

The WC contested all 10 new weight categories. The R^2 values for the regression models ranged from 0.90 to 0.96, suggesting each model had the ability for bodyweight to strongly account for the variance of Ptot. The average predictive ability for the WC across all performance zones was 0.78 ± 3.29% (2.26 ± 10.08 kg). The average prediction for the Medal Zone was 1.02 ± 2.71% (3.28 ± 8.78 kg) across all new weight categories. The best predictive ability in the Medal Zone was the <109 kg weight category, with a near perfect prediction of -0.06% (0 kg) compared to the actual Medal Zone (457 vs 457 kg, respectively). Interestingly, the actual Ptot had a SD of 20 kg (457 ± 20 kg), suggesting that the Medal Zone is large. The likely reason behind this is that in both the 2018 and 2019 WC from which this data has been formulated, the differences between each medal zone ranged from 14-24 kg, averaging 20 kg. Although the absolute value of 20 kg may seem large, the SD as a percentage of the actual outcome is <5%. As the actual results could be between 437 kg and 477 kg, it is suggested that performance teams aim to achieve a Ptot close to or above the LLCI of 453 kg, as the LLPI of 426 kg may results in a rank outside of the Medal Zone.

The worse predictive model for the WC Medal Zone was the 55 kg weight category, displaying a 6.91% (19 kg) overprediction. Interestingly, this was followed by the 102 kg and 89 kg weight category which also showed overpredictions of 4.25% (17 kg) and 3.42% (13 kg), respectively. A likely reason for this is that the data used to analyse the WC was prior to the OG, in which the aforementioned weight categories were not contested. Therefore, it is likely that athletes moved to Olympic weight categories therefore affecting these, Medal Zones. All other Medal Zones had predictions ranging from -1.64-0.64% (-6 – 3 kg) relative to the actual Ptot. All other performance zones showed a range of predictive ability, with the best being Zone 5 in the 96 kg weight category showing a near perfect predictive Ptot with no difference (0.08% ,0 kg) to the actual Ptot (366 vs 366 kg). On average the predictive models for the 96 kg weight category showed a difference across performance zones of only 0.55 ± 0.75%, suggesting this model may be useful for those working with athletes preparing for the WC in this weight category.

2.5.3. European Championships

The EC predictive models displayed R^2 values ranging from 0.75 to 0.96, with the lowest variance observed for performance zone 5. The average predictive ability for the EC across all performance zones was -1.13±3.46% (-4.32±11.10 kg). The average prediction for the Medal

Zone across all new weight categories was -0.25 ± 3.47% (-1.93 ± 12.51 kg). The best predictive ability in the Medal Zone was the 61 kg weight category, with a -0.02% (0kg) prediction compared to the actual Medal Zone (287 vs 287 kg, respectively). The worst predictive model in the Medal Zone was for the 55 kg weight category, overpredicting the actual Ptot by 6.04% (15 kg). The actual Ptot had a SD of 9 kg (251 ± 9 kg), which means a 1st place finish would be a total of ~260 kg, which is 2 kg less than that of the LLCI (262 kg). Interestingly, the 2019 and 2021 EC 1st place finish achieved a total of 261 kg and 258 kg respectively, therefore, performance teams should consider aiming for the LLCI of 262 kg to increase their chance of a gold medal.

All other Medal Zones had varying under- and over- predictions ranging from -6.02% to 4.66% (-26.45 – 17.78 kg). Much like the WC, on average, the best predicted weight category was the 96 kg category with a small over prediction of Ptot by 0.41% (1.67 kg) across all performance zones. Suggesting this model may be useful for those working with athletes preparing for the EC in this weight category.

The primary objective of this investigation was to develop a set of predictive models for specific performance zones within the newly contested weight categories in the sport of weightlifting. While our findings suggest that some predictive models maybe able to better predict performance zones within specific weight categories than others, discussion around limitations that may have influenced the model development should be made, therefore enabling those who wish to replicate this study the ability to do so within their own context and environment whilst also understanding the constraints and philosophical decision around data analysis that may need to be made based on context.

2.5.4. Re-occurrences (same athlete data)

The old weight category data obtained from the IWF website spanned over a period of 20 years (1998 – 2018) across 3 major competitions. Data re-occurrences of individuals and their performances within these competitions must be considered. Although we acknowledge the concern of possible limiting of model generalisability arising from the use of recurring athletes, we believe that the methodologies used throughout this investigation maximise the generalisability of the models given the unique case of the sport weightlifting.

Firstly, individual performance totals were considered to be observed within the study design, as opposed to individual athletes. This is because performance can vary over time and across competitions which is important information that should be captured. Furthermore, selecting only one out of several performance totals could introduce the issue of selection bias. Additionally, this would significantly reduce the sample size for modelling which in turn would result in lower generalisability of predictions. For future analysis, using a larger database of athletes (which would naturally expand over time) would help to further tackle this potential issue.

2.5.5. Outliers (individuals)

Often, outliers within data sets can skew the dispersion around the mean. In high performance sport it is not uncommon to come across statistical outliers which may distort the calculated outcome (Aitken, 2004), in this case the predicted Ptot within performance zones. It is important to state that performance teams would need to consider whether they are willing to accept an increase in predictive variance keeping in known outliers, or removing outliers at the risk of not capturing performances reflective of what is actually achieved within competition. The practical ramifications of the latter can be explained when looking at medal zones. If an athlete who achieves a Gold medal Ptot considerably more than that of 2nd place was removed, the medal zone would reduce in both its mean and SD (as well as 95% CI and PI), telling us that the total required to achieved a medal is artificially lower than it would be having kept in the outlier. As this practical example shows, given the consequences of underprediction and by extension incorrectly classifying an athlete as a potential medallist or OG qualifier (i.e false positive) it is clear that we would be willing to accept overprediction if this ensures we minimise the number of false positives.

2.5.6. Performance Zone grouping

The performance zones utilised in this investigation were based on current processes and requirements for qualifying for the Olympic games (top 8) and/or predicting outside opportunities for medals (zone 2 4-5th) across major competitions. While this may carry ecological utility, some issues may exist in developing the predictive model given that some performance zones are so closely grouped together (i.e. zone 2, 4-5th). This reduces the sample size and consequently may lead to models with low bias and higher levels of variance. This potential of overfitting is one we have attempted to address through the use of lower model complexity alongside K-Fold Cross validation. Future analysis using an expanding database over time will further help address the issue of low samples within performance zones.

2.5.7. Doping

At the time of data extraction from the IWF database all athletes who had Anti-Doping rule violations (ADRVS) were marked as “DNF” (did not finish) and were therefore excluded from the analysis. However, many bans within weightlifting occur retrospectively following re-analysis of samples collected during major competitions. For example, Kollari-Turner *et al.* (2021) reported that a total of 61 weightlifters were identified to have adverse analytical findings of prohibited substances during the 2008 and 2012 OG. From this sample a total of 34 of them were medallists. The relevance of this within the present study is that it highlights the need to update the data used in developing the predictive models as and when doping violations are announced to ensure higher levels of efficacy.

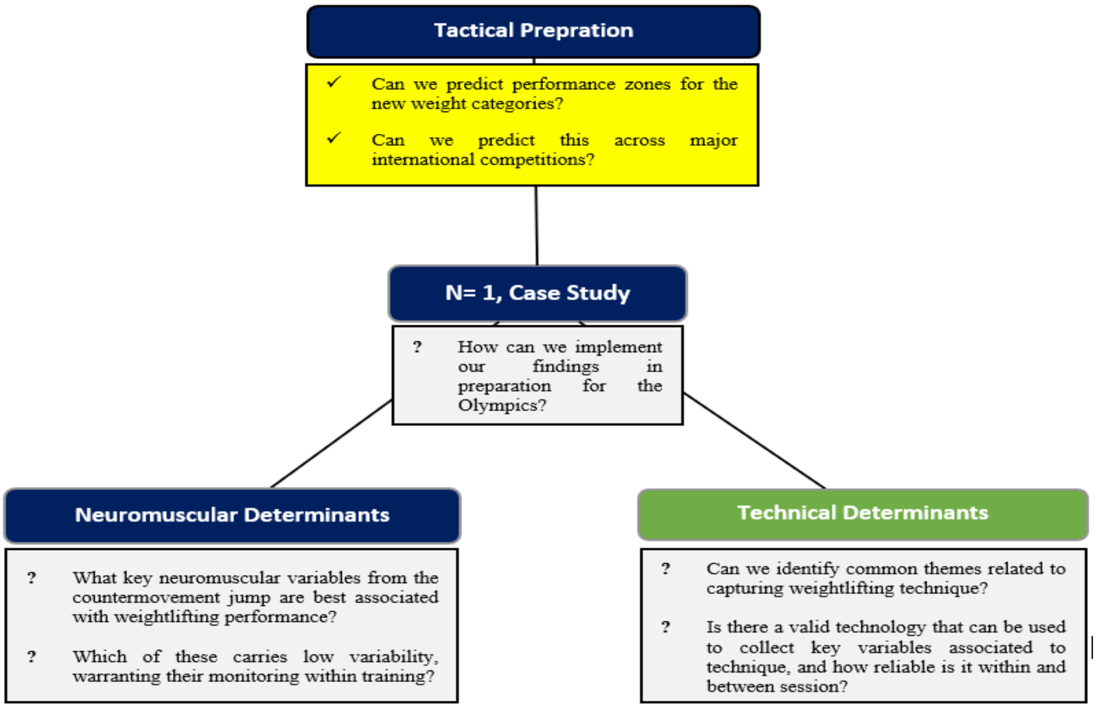
2.6. PRACTICAL APPLICATION

This study provides outcomes for predictive models for major competitions in the sport of weightlifting. The tables provided in this manuscript can be used by performance teams to aid in the long- and short- term preparation for the Olympic Games and World and European Championships. Furthermore, the results from this study may also provide a more objective selection process for the analysed competition types to enhance the chance of achieving the highest possible rank. While the predictive models generally carried low percentage differences relative to the actual Ptot, some consideration around interpretation and utility must be considered. It is evident that the predictive models carried variation throughout each competition type and performance zone. Given that there were both over and underpredictions throughout the models, it is suggested that performance teams manage expectation and use these predictions in conjunction with a coach’s intuition and knowledge of the field of play. It is also worth highlighting that crossover between performance zones will be likely, and therefore should be explored further. Future investigation should also look to apply this as a proof of concept within women’s weightlifting, which was introduced to the Olympics and the World Championships at later time points than the men, thus having less data over the years. Additionally, since the primary aim of this paper was to develop a predictive model for the new weight categories utilising historic performance data, it was important to try and ensure that new data could be directly applied to the model, to future proof against potential weight class changes. Given the homogeneity of the group, any additional data would likely incur some changes in the regression coefficient within the 95% CI presented and therefore, would simply require the user of the model to select the specified x value (weight category) of interest. Furthermore, the authors present K fold cross validation to train the model on unseen data. Results from this suggest that the models display low levels of error as presented in table 2.1. As for immediate utility, coaches or performance teams can use the equations provided to identify specific Ptot within specific weight categories and performance zones. Furthermore, with the freely available Ptot data, performance teams may also repeat the proposed methodology for other weightlifting demographics (i.e. women, junior and youth), for different performance zones they deem relevant and also for the individual lifts of the snatch and jerk, given medals opportunities are available for each of these at WC and EC.

CHAPTER 3: STUDY 2 - A SYTEMATIC SCOPING REVIEW ON THE BIOMECHANICAL ANALYSIS OF WEIGHTLIFTING PERFORMANCE

Chavda, S, Swisher, A., Haff, GG., Hill, M., Martin, S and Turner AN. Weightlifting: An Applied Method of Technical Analysis *Strength and Conditioning Journal*, 43(4): 32-42, 2021. (Chapter 3)

From chapter 2, it is now possible to predict the loads required to achieve specific ranks at major international competitions. Understanding how these loads can be achieved through a knowledge of how to measure and then optimise technique can help coaches appropriately structure and deliver relevant technical training. Chapter 3 will begin to focus on the current literature available in understanding what methods have been used to identify key technical commonalities and differences in competitive weightlifters. This may provide insight into the monitoring and coaching of technique. Additionally, chapter 4 will then aim to add to the body of research by investigating the validity of a commercially available inertial measurement unit and the within and between session reliability of commonly presented measures associated to technique. This will provide performance scientists and coaches information on what could be worth monitoring when looking to enhance technique.



3.1. INTRODUCTION

How a weightlifter executes the competitive lifts is of great use to coaches and sport scientists because it enables them to better understand what phase of the lift can be optimised to increase its mechanical efficiency and therefore success. Weightlifting technique is rooted in placing the body in positions of strength and stability, where leverage is optimized and the body is capable of producing high levels of force, thus allowing it to apply mechanical work to the barbell (Garhammer, 1980). As coaches, it is important to understand that a lifter's ability to effectively move the barbell from the floor to over-head (snatch or jerk) or to the shoulders (clean) is dependent on specific, key positions being met. Energy transference from skeletal muscle through the skeletal lever system will aid in the ideal organisation of movement and therefore the trajectory of the barbell (Garhammer, 1982). Given the high technical requirements of weightlifting, its foundations should be based on, and further quantified by, biomechanical principles, which allows for further insight in to how to maximise performance (Lees, 1999). Since success is determined by the load lifted, investigations into the biomechanics of weightlifting within the competitive field of play or at maximal loads can help provide important insights to coaches by providing them with a greater understanding of the interaction of the body and barbell and the consequential processes and outcomes that determined performance.

Given that weightlifting is a closed-skill sport, the capture of data has typically been focused on the kinematics and kinetics of the barbell and joints (Ammar *et al*., 2017; Ammar *et al*., 2020; Baumann *et al*., 1988; Enoka, 1979; Kauhanen *et al*., 1984). This has allowed researchers to explore discriminatory factors that may exist in different level athletes (Burdett, 1982; Grabe & Widule, 1988; Kauhanen *et al*., 1984; Liu *et al*., 2018; Ono *et al*., 1969) and successful versus unsuccessful lifts (Gourgoulis *et al*., 2009; Mastalerz *et al*., 2019; Nagao *et al*., 2019; Nagao *et al*., 2023; Stone *et al*., 1998). Additionally, it also allows researchers to provide characteristic information on some of the highest-performing weightlifters (Cunnan *et al*., 2021; Baumann *et al*., 1988; Garhammer, 1980). While the current body of research provides coaches and sport scientists with valuable information, differences around methods of data capture which consequently influence how phases of the lift are defined become apparent. In order to accurately monitor weightlifting technique, key phases of the lift must be defined in a way which is highly repeatable and objective. Given that competition and laboratory or training-based environments may present different constraints, a scoping review of the literature is warranted to help better identify key characteristics reported within the research around data capture, phase identification and associated kinetics and kinematics (Munn *et al.*, 2018).

The aim of this review was to provide clarity around key method utilised in the analysis of weightlifting as well as identify key characteristics used to define the phases of the lift. Specifically, we will discuss the methods in which data is obtained and how this influences various kinematic and kinetic measures of the body and barbell. Furthermore, we will comprehensively evaluate the existing body of literature to help identify key definitions of the phases. A “Directions for Future Research” section is provided offering guidelines on what needs to be explored further to better understand the measures that warrant monitoring, which may aid coaches in the development and prescription of appropriate training strategies.

3.2. METHODS

3.2.1. Protocol and registration

This scoping review has been developed using the guidelines presented by Levac, Colquhoun and O’Brien (2010) and the preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) checklist (Tricco *et al.*, 2018).

3.2.2. Eligibility criteria and definitions

The term *Weightlifting* in the context of this scoping review, refers to the competitive sport of weightlifting. This includes the snatch and clean, by athletes whose primary sport is weightlifting. To be included in this scoping review, research articles needed to measure a combination of kinetics and, or kinematics of the body or barbell in competitive weightlifters at loads conducted at 100% of one repetition maximum (1RM) within competition. The articles were required to be written in English, full text, and peer reviewed. Abstracts and non-peer reviewed articles were not considered. Articles were excluded if they utilised non-weightlifting athletes, used computational models to simulate kinetics and kinematics, or utilised derivative weightlifting movements (i.e. pulls and, or power variants). The jerk was also excluded from this scoping review as to only focus on the snatch and clean.

3.2.3. Information sources and search strategy

A search of electronic databases was conducted during December 2023 to identify all publications on *weightlifting kinetics and kinematics* using Medline, Web of Science and PubMed databases, with no restriction of dates. Key search terms of 'weightlift*' and 'Olympic weightlift*' were combined by Boolean logic and truncation (AND, OR) with 'snatch', 'clean', 'barbell', 'joint', 'kinetic*' and 'kinematic*'. To avoid a large number of irrelevant articles displaying during the search, the key search terms had to be present in the title. Figure 1 displays a PRISMA-ScR flow chart of the search methodology. Further literature was obtained from an electronic 'related articles' search within Google scholar by manually screening the reference lists of all included studies conducted up to September 2023 as to stay current with relevant literature.

3.2.4. Data charting and synthesis

Data-charting was developed by the principle investigator to determine the information to be extracted. The charting tool was further assessed by an additional co-author to determine robustness and ensure key information would be captured to help identify common methods used to capture performance and define phases of the lift. Participant descriptive' s (sex, level, sample size, bodyweight), primary aim of the article, methods (lift analysed, equipment used, method of phase determination) and variables reported (kinetic and, or kinematic) were extracted during data charting. A comprehensive study breakdown is available in table 3.1 and 3.2.

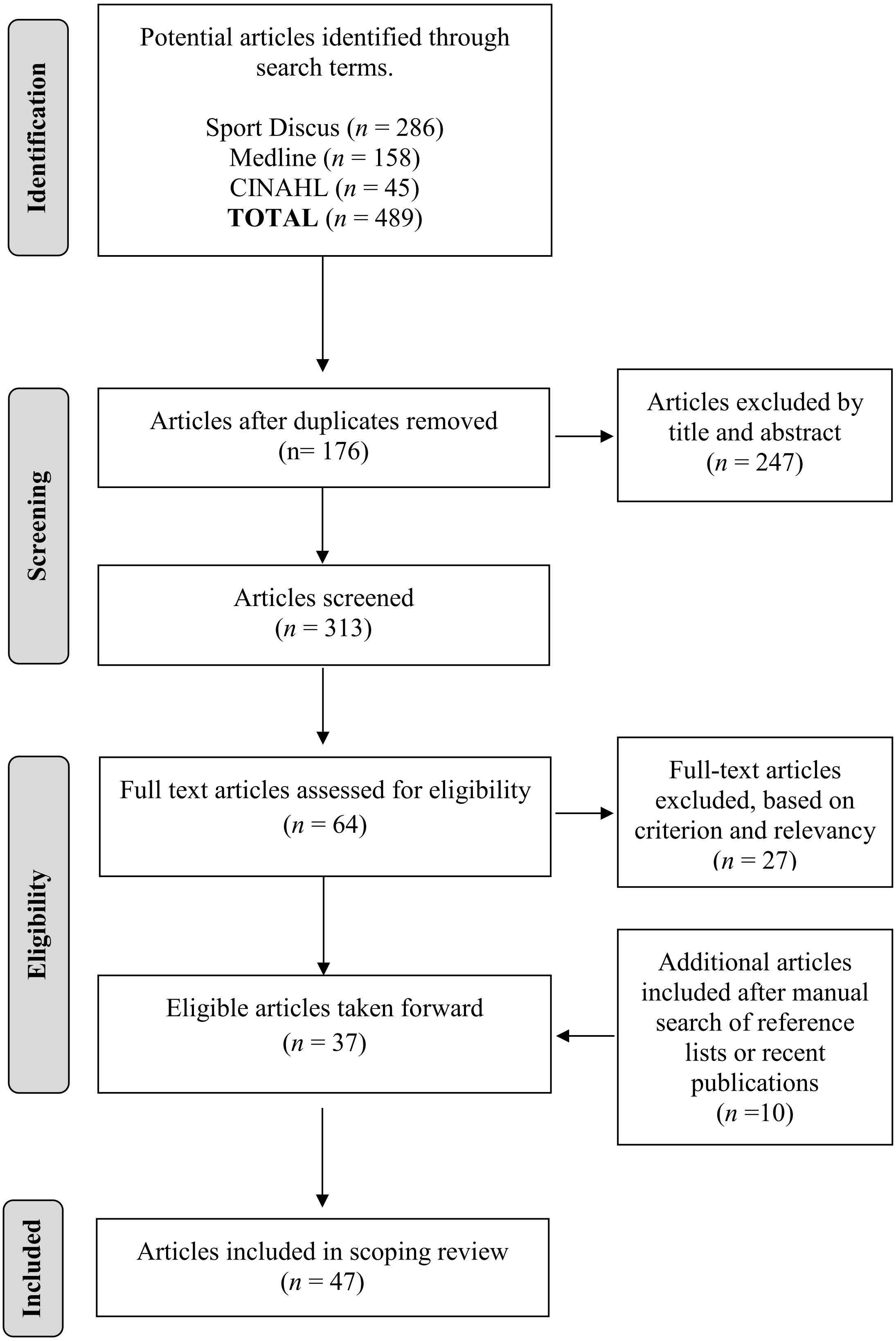


Figure 3.1. PRISMA-ScR flow chart of extracted, included and excluded studies.

3.2.5. Critical appraisal of articles and quality assessment

Currently there is little consensus on the appropriate method in assessing the quality of an article. This raises concern for the risk of bias when deciding which articles are appropriate for inclusion and further analysis, and therefore requires consideration. Hindle *et al.* (2019) utilised a checklist from similar systematic reviews investigating biomechanical research, which has more recently been used by Soriano *et al*. (2023). The scoring system used by Soriano has been further adapted in this review to help more effectively identify methodological rigour and application in weightlifting (Appendix 3.1). This adapted method is further warranted by the fact that some quality assessment criteria will unintentionally bias more recent investigations which are bound by differing criteria based on where they are published and to conform to what is currently acceptable in sport science research. Furthermore, given the scope of this review, investigations into characterising or describing performance qualities possessed by weightlifters will likely score low in their statistical methods and results due to their study design. Therefore, while other systematic reviews (traditional or scoping) have provided a cut-off percentage, the authors of the current review have decided that following the inclusion-exclusion process, all articles will be included and appropriately graded based on the quality scoring criteria with no percentage cut-off.

The process of quality evaluation was initially undertaken by one researcher, with two additional evaluators then utilised to grade the articles independently. The quality scores were finally collated by a fourth researcher to ensure there was a consensus between scores. Those articles failing to meet consensus from the four independent scorers were discussed to provide a definitive score. The achieved score was divided by the total achievable score of 14 and multiplied by 100 to obtain a percentage. Quality assessment scores can be seen in table 3.3.

Table 3.1. Summary of data extraction for in competition data capture and analysis.

Quality Score (%)	Reference	Subject Details	Competition	Aim	Methods	Variables
93	Akkus (2012)	*Sex*: Female *Level*: Elite professional $n = 7$ *BW*: 77.1 ± 19.6 kg	2010 World Championship	Comparison of barbell and joint kinetics and kinematics between maximal and sub maximal loads.	Lift: Snatch Unit(s): 4 Cameras Frequency: 50 fps Filter: Low pass 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch, rising)	*Average Load* 114.71 ± 18.81 kg *Kinematics* Duration of phases Bar Vert and Horz s Bar Vert v Bar Vert P AKH Joint ∠ AKH Joint v
50	Antoniuk, Pavlyuk, Chopyk and Pavlyuk (2016)	*Sex:* Female *Level*: Elite $n = 137$ *BW*: only weight classes presented (48 – 75+ kg)	2 European Championships 2 World Championships	Determine barbell trajectory type within female weight categories.	Lift: Snatch Unit(s): Weightlifting analyser 3.0 Frequency: N/D Filter: N/D Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* N/D *Other* Barbell trajectory type; A, B and C.

50	Antoniuk *et al.* (2017)	*Sex:* Female *Level*: Elite $n = 140$ *BW*: only weight classes presented (48 – 75+ kg)		Determine barbell trajectory type within female weight categories.	Lift: Snatch Unit(s): Weightlifting analyser 3.0 Frequency: N/D Filter: N/D Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* N/D *Other* Barbell trajectory type; A, B and C.
79	Baumann *et al.* (1988)	*Sex*: Male *Level*: World-class $n = 7$ *BW*: 110.71 ± 33.06 kg	1985 World Championship	Describe the kinetics of the snatch technique and compare them between groups and weight categories.	Lift: Snatch Unit(s): 4 cameras + 2 force plates Frequency: 50 Hz and 100 Hz Filter: N/D Phase Determination: ΔK∠ Number of Phases Defined: 2 (first pull and second pull)	*Average Load* 167.21 ± 20.93 kg *Kinematics* Duration Bar Vert and Horz s Bar Vert v Bar Vert P AKH Joint ∠ AKH Joint v *Kinetics* vGRF hGRF yGRF RFD AKH Muscle moments
86	Burdett (1982)	*Sex*: N/D	1975 International Competition	Comparison of highly skilled weightlifters to	Lift: Snatch Unit(s): 1 camera	*Average Load* N/D

		Level: World-class $n = 36$ (10 highly skilled, 26 skilled) *BW*: N/D	1974 American Collegiate Championship	skilled weightlifters during the snatch.	Frequency: 50 fps Filter: N/D Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 4 (1,2,3 and 4).	*Kinematics* Duration Bar Vert s AKH Joint ∠ CoG Vert s
100	Campos *et al.* (2006)	*Sex*: Male (Jnr) *Level*: Elite $n = 33$ (17 + 16) *BW*: A = 58.92 ± 1.65 kg B = 91.54 ± 1.78 kg	2003 European Junior Championship	Compare technical execution of the snatch between different weight categories.	Lift: Snatch Unit(s): 2 cameras Frequency: 50 fps Filter: N/D Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull, transition, second pull, turnover, catch, absorption)	*Average Load* A = 108.38 ± 11.82 kg B = 153.59 ± 10.08 kg *Kinematics* Duration Bar Vert s Bar Vert acc Bar Vert v AKH Joint ∠ AKH Joint rad
100	Chiu, Wang and Cheng (2010)	*Sex*: Male *Level*: National Taiwanese team	2006 Asian Games	Characterise barbell trajectory to identify if there is a standard patten for each lifter.	Lift: Snatch Unit(s): 2 cameras Frequency: 120Hz	*Average Load* 124.04 ± 15.08 kg *Kinematics* Bar Vert s Bar Horz s Bar Vert v

		n = 19 *BW*: 83.9 ± 16.8 kg			Filter: 4th Order Butterworth low pass filter, 6 Hz cut off. Phase Determination: bar Vert s, position of bar relative to knee, and manual detection of hip extension. Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	
100	Cunanan *et al.* (2020)	*Sex*: Male and Female *Level*: International n = <u>World Championship</u> 77 females 82 Males <u>Pan-American</u> 75 females 85 males *BW*: <u>World Championship</u>	2015 World Championships 2017 Pan-American Championships	A descriptive study on the trajectory and kinematics of successful snatch attempts during 2 international weightlifting competitions.	Lift: Snatch Unit(s): 1 Camera Frequency: 240 fps Filter: 20-point moving average. Phase Determination: N/A Number of Phases Defined: N/A	*Average Load* <u>World Championships</u> 104 ± 16 kg (Female) 164 ± 22 kg (Male) <u>Pan American</u> 90 ± 15 kg (Female) 136 ± 25 kg (Male) *Kinematics* Bar Vert and Horz s Bar Vert and Horz v Angle relative to vertical intercept from start. *Other*

		67.77 ± 21.64 kg (female) 88.76 ± 29.02 kg (male) <u>Pan-American</u> 69.25 ± 20.07 kg (female) 81.83 ± 24.47 kg (male)				Bar Trajectory type frequency (A, B or C)
50	Garhammer (1979)	*Sex*: N/D (Male) *Level*: N/D *n* = 9, only 6 lifters analysed. *BW*: 88.78 ± 38.78 kg	1975 U.S Senior National Championship	Evaluate barbell performance of weightlifting using an efficiency ratio of vertical work done vs. total work done.	Lift: Snatch Unit(s): N/D Frequency: N/D Filter: N/D Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* 127 ± 27.6 kg *Kinematics* Vert and Horz ME
79	Garhammer (1980)	*Sex*: Male *Level*: Superior lifters *n* = 7 *BW*: 87.96 ± 30.83 kg		Support previous methods of power calculation in weightlifting. Determine power output during different phases of weightlifting.	Lift: Snatch (Sn) + Clean and Jerk (CJ) Unit(s): 1 Camera Frequency: 50 fps Filter: 5 point moving arc Phase Determination: manual determination using	*Average Load* N/D *Kinematics* Duration Bar Vert and Horz ME CoM Vert and Horz ME Bar Vert and Horz P CoM Vert and Horz P

					ΔK joint. Number of Phases Defined: 5 (Snatch, Clean and Jerk)	
57	Garhammer (1982)	*Sex*: N/D (Male) *Level*: World-calibre $n = 8$ *BW*: 79.06 ± 11.25 kg	1975 U.S Senior National Championship 1978 World Championship	Provide information as to which dominant muscle groups make major energy contributions during the snatch and clean	Lift: Snatch (Sn) + Clean and Jerk (CJ) Unit(s): 1 Camera Frequency: 50 fps Filter: 5 point moving arc Phase Determination: N/D Number of Phases Defined: 3 (lift-off, start of knee rebend, top pull)	*Average Load* Sn: 150.26 ± 17.33 kg CJ: 186.06 ± 8.82 kg *Kinematics* Bar Vert v Joint ME Segment v CoM P *Kinetics* Joint F
86	Garhammer (1985)	*Sex*: Male *Level*: Olympians $n = 5 + 2$ for repeat measures *BW*: 89.56 ± 31.24 kg	1978 World Championships 1984 Olympic Games	Contribute additional data on world-class weightlifters at the Olympic games.	Lift: Snatch (Sn) + Clean and Jerk (CJ) Unit(s): 2 Cameras Frequency: 100 fps reduced to 50 fps Filter: 5 point moving arc Phase Determination: Observation of knee joint.	*Average Load* Sn: 152.80 ± 20.36 kg CJ: 198.80 ± 34.60 kg *Kinematic* Duration Bar Vert s Bar Vert v Bar Vert and Horz ME ME Efficiency Bar Vert P

					Number of Phases Defined: 3 (lif-off, second pull, move under bar)	
79	Garhammer (1991)	*Sex*: Female *Level*: Elite *n* = 9 *BW*: 62.33 ± 14.45 kg	1987 Women's World Championship	Determine power output by women weightlifting athletes and compare the to male power outputs.	Lift: Snatch (Sn) + Clean and Jerk (CJ) Unit(s): 1 Camera Frequency: 50 fps Filter: 5 point moving arc Phase Determination: Bar Vert *v* and observation of knee joint. Number of Phases Defined: N/A	*Average Load* Sn: 79.44 ± 9.74 kg CJ: 101.94 ± 17.31 kg *Kinematics* Duration Bar Vert *v* Bar Vert s Bar Vert and Horz ME CoM Vert ME Bar Vert P
93	Gourgoulis, Aggelousis, Mavromatis and Garas (2000)	*Sex*: Male *Level*: Elite *n* = 12 *BW*: 82.34 ± 16.63 kg	1998 International Memorial Competition	Determine linear kinematics and change in energy of the barbell along with angular kinematics as indicators of technique.	Lift: Snatch Unit(s): 2 Cameras Frequency: 60 Hz Filter: Low pass Butterworth filter, 4 Hz cut-off. Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull,	*Average Load* 145.92 ± 14.74 kg *Kinematics* Duration Bar Vert and Horz s Bar Vert *v* Bar Vert acc Bar Vert and Horz ME AKH Joint ∠ AKH Joint *v*

					transition, second pull, turnover, catch, rising)	
79	Gourgoulis, Aggelousis, Garas and Mavromatis (2009)	*Sex*: Male *Level*: High-level *n* = 7 *BW*: N/D	Greek National Competitions.	Determine kinematic characteristics between successful and unsuccessful snatch attempts.	Lift: Snatch Unit(s): 2 Cameras Frequency: 60 Hz Filter: Low pass digital filter, 4 Hz cut-off. Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* N/D *Kinematics* Duration Bar Vert and Horz s Bar Vert *v* Bar Vert and Horz acc Bar vector Bar Vert ME AKH Joint ∠ AKH Joint *v* Position of foot, knee and shoulder in references to bar.
93	Harbili (2012)	*Sex*: Male and Female *Level*: Elite *n* = 18 (9+9) *BW* = 68.64 ± 0.23 kg (m) 67.85 ± 1.20 kg (f)	2010 World Championship	Compare kinetic and kinematic differences in snatch performance between 69 kg male and female weightlifters.	Lift: Snatch Unit(s): 2 Cameras Frequency: 50 fps Filter: 4th order Butterworth low pass digital filter, cut-off 4Hz. Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull,	*Average Load* M = 148.00 ± 8.20 kg F = 105.80 ± 6.60 kg *Kinematics* Bar Vert and Horz s Bar Vert and Horz *v* AKH Joint ∠ AKH Joint *v* Bar Vert ME Bar Vert P

					transition, second pull, turnover, catch, rising)	
79	Harbili, Harbili and Alptekin (2017)	*Sex*: Male *Level*: Elite *n* = 7 *BW* = 77.43 ± 17.20 kg		Compare kinematic differences of the barbell between the first and second pull of the snatch.	Lift: Snatch Unit(s): 2 Cameras Frequency: 50 fps Filter: Low pass digital filter, cut-off 4 Hz. Phase Determination: N/D Number of Phases Defined: 2 (first pull and second pull)	*Average Load* 166.29 ± 21.29 kg *Kinematics* Bar Vert s Bar Vert *v* Bar Vert ME Bar Vert P
50	Hirunrat and Raktawee (2013)	*Sex*: Female *Level*: National Thai *n* = 6 *BW* = 61.26 ± 27.74 kg	2010 Youth Olympic Games	Describe the kinematics of the snatch technique during maximum lifting.	Lift: Snatch Unit(s): 1 Camera Frequency: 50 Hz Filter: N/D Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* N/D *Kinematic* Bar Vert and Horz s Bar Vert *v* Bar Vert acc
93	Hoover, Carlson, Christensen and Zebas (2006)	*Sex*: Female *Level*: National U.S	1999 U.S National Championship	Characterise the horizontal displacement of female weightlifters. Describe the drop under time, vertical barbell drop	Lift: Snatch Unit(s): 1 Camera system Frequency: 60 fps	*Average Load* 79.68 ± 12.83 kg *Kinematic* Duration

		$n = 10$ *BW* = N/D (69 kg *BW* class)		and maximal vertical velocity. Calculate and compare power output for the first second and total pull during the snatch.	Filter: 4th Order zero lag Butterworth digital filter. Phase Determination: bar Vert s, position of bar relative to knee, and manual detection of hip extension. Number of Phases Defined: 3 (first pull, second pull and total pull)	Bar Vert and Horz s Bar Vert v Bar Vert P CoM P
86	Ikeda *et al.* (2012)	*Sex*: Female *Level*: International $n = 10$ (5+5) *BW* = Grp: 61.08 ± 10.28 kg JAP: 61.00 ± 10.94 kg BL: 63.80 ± 8.10 kg	2008 Asian Championship	Characterize the barbell kinematics and kinetics for international and Japanese weightlifters. Characterise lifting motion. Look at the motion to exert force during the second pull during the snatch.	Lift: Snatch Unit(s): 3 Cameras Frequency: 2 x 250 Hz, 1 x 50 Hz Filter: low-pass fourth order Butterworth digital filter, cut-off 4 Hz. Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* Grp: 94.50 ± 15.83 kg JAP: 84.60 ± 10.11 kg BL: 105.90 ± 12.76 kg *Kinematic* Duration Bar Vert and Horz s Bar Vert and Horz v Bar Vert and Horz acc Bar acc vector KH Joint ∠ Trunk ∠ KH Join v *Kinetic* Bar Vert and Horz F

86	Isaka, Okada and Funato (1996)	*Sex*: Male *Level*: Elite *n* = 6 *BW* = 94.83 ± 17.87 kg	1993 Japan International Friendship Tournament	Describe kinematic barbell characteristics of the snatch.	Lift: Snatch Unit(s): 1 Video tracker system Frequency: 60 fps Filter: 2nd Order Butterworth filter, cut - off 3.6 Hz. Phase Determination: N/D Number of Phases Defined: 6 (Start, first pull, transition, second pull, catch, finish)	*Average Load* 152.50 ± 10 kg *Kinematic* Duration Bar Vert and Horz s Bar Vert and Horz *v* Bar Vert and Horz acc Bar acc vector
79	Kipp and Harris (2015)	*Sex*: Male *Level*: Competitive regional *n* = 6 *BW:* 97.7 ± 5.5 kg	U.S Regional Competition	To determine the association between vertical barbell acceleration patterns during the snatch.	Lift: Snatch Unit(s): 6 Motion Capture Cameras Frequency: 250 Hz Filter: 4th order low-pass Butterworth filter, cut-off 6 Hz. Phase Determination: N/D	*Average Load* 97.1 ± 5.5 kg *Kinematics* Bar Vert acc

					Number of Phases Defined: N/D	
93	Liu *et al.* (2018)	*Sex*: Male *Level*: Top-elite Sub-elite *n* = 12 (6+6) *BW*: E = 68.83 ± 0.15 kg SE = 68.62 ± 0.17 kg	2015 Chinese National Championship 2016 Chinese Olympic Trials	Highlight differences of technical characteristics between top-elite and sub-elite weightlifters.	Lift: Snatch Unit(s): 2 Cameras Frequency: 50 Hz Filter: Low pass digital filer, cut off 4 Hz. Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull, transition, second pull, turnover, catch, rising)	*Average Load* E = 155.83 ± 2.14 kg SE = 146.00 ± 4.10 kg *Kinematics* Duration Bar Vert s Bar Vert *v* Bar Vert acc AKH Joint ∠ Hip Joint *v* CoG Vert and Horz s
79	Mastalerz *et al.* (2019)	*Sex*: Female *Level*: Elite *n* = 14 *BW*: 62.19 ± 12.38 kg	2013 World Championship	Identify biomechanical factors affecting successful and unsuccessful attempts during competition.	Lift: Snatch Unit(s): 2 Cameras Frequency: 50 fps Filter: Low pass digital filter, cut off 4 Hz. Phase Determination: N/D Number of Phases Defined: 4 (first pull, second pull, turnover, catch)	*Average Load* 99.86 ± 14.78 kg *Kinematics* Duration Bar Vert s Bar Vert *v* CoG Vert s CoG Vert *v* Knee and Hip Joint ∠

79	Musser *et al.* (2014)	*Sex*: Male *Level*: Elite $n = 36$ *BW*: 59.30 ± 9.50 kg	2009 Pan American Championship	Examine the relationship between anthropometry and horizontal barbell displacement during the pull phase of a snatch.	Lift: Snatch + Clean and Jerk Unit(s): 1 Camera Frequency: 60 Hz Filter: Cubic spline function using a smoothing parameter of 0.2. Phase Determination: Δ in Horz position of barbell. Number of Phases Defined: 2 (first pull and second pull)	*Average Load* Sn: 84.14 ± 11.90 kg CJ: 105.82 ± 15.42 kg *Kinematics* Bar Horz s *Other* Upper limb length Lower limb length Trunk length Thigh length Shank length
93	Nagao *et al.* (2019)	*Sex*: Male *Level*: Elite $n = 61$ *BW*: 83.2 ± 21.7 kg	2017 World Championship 2017 Junior World Championship	Investigate success factors of the snatch based on barbell trajectory.	Lift: Snatch Unit(s): 1 Camera Frequency: 60 Hz Filter: 4th order Butterworth low pass digital filter, cut off 4 Hz. Phase Determination: Δ bar kinematics (s, v) Number of Phases Defined: 4 (first pull,	*Average Load* 142 ± 21.2 kg *Kinematics* Bar Vert and Horz s Bar Vert and Horz v Bar Vert P Trunk-Arm, Trunk, Hip, Knee and Ankle Joint ∠ Hip, Knee and Ankle Joint v *Kinetics* Bar Vert and Horz F

					second pull, turnover, catch)	
93	Nagao, Huang and Kubo (2023)	*Sex*: Male *n* = 22 *Level*: World-Class Elite *BW*: 83.8 ± 32.4 kg (all cases)	2015 World Weightlifting Championships	Clarify the success factor of the snatch based on barbell and lifter motion.	Lift: Snatch Unit(s): 2 Cameras Frequency: 60 Hz Filter: 4th order Butterworth low pass digital filter, cut off 6 Hz. Phase Determination: Δ bar kinematics (s, *v*) and ΔK∠ Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* 154.5 ± 27.0 kg (All cases) *Kinematics* Bar Vert and Horz *s* Bar Vert and Horz *v* CoM Vert and Horz *s* CoM Vert and Horz *v* *Kinetics* Bar Vert and Horz F
71	Ono, Kabuto and Kato (1969)	*Sex*: Male *Level*: Top class players *n* = 23 *BW*: OL: 77.10 ± 24.52 kg HS: 62.79 ± 9.04 kg Snr: 68.28 ± 12.04 kg	1964 Olympic Games 20th Annual Athletic Meeting	Analyse barbell and joint kinematics during the snatch, clean and press	Lift: Snatch + Clean and Jerk Unit(s): 1 x 16 mm Camera Frequency: 64fps Filter: N/D Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* Sn OL: 129.00 ± 16.6 kg HS: 95.94 ± 11.03 kg Snr: 112.66 ± 13.95 kg CJ OL: 166.6 ± 21.80 kg HS: 123.28 ± 15.91 kg Snr: 142.81 ± 19.10 kg *Kinematics* Lifter Horz s

						Bar Vert s Bar Vert *v* Knee Joint ∠ Trunk and lower limb ∠ Trunk and floor ∠
93	Sandau, Chaabene and Granacher (2021)	*Sex*: Male *Level*: Elite weightlifters *n* = 30 *BW*: 88.9 ± 28.6 kg	2018 World Weightlifting Championships.	Examine the agreement of computing mean vertical barbell force using work-energy approach compared with inverse dynamic approach.	Lift: Snatch Unit(s): Re-analyzer custom system. Frequency: 50 fps Filter: N/D Phase Determination: Qualitative observation of changes in knee joint angle and bar vertical *v.* Number of Phases Defined: 4 (lift off, first pull, transition, second pull).	*Average Load* Sn: N/D *Kinematics* Bar Vert s Bar Vert *v* Kinetics Bar vertical force
93	Schilling *et al.* (2002)	*Sex*: Male *Level*: *n* = 25 *BW*:	1998 U.S Collegiate National Championships	Quantify foot displacement during a snatch and its relationship to performance.	Lift: Snatch Unit(s): 1 Camera Frequency: 60 Hz Filter: N/D	*Average Load* 1.17 ± 0.22 of BW *Kinematics* Lifter Horz s

		85.96 ± 19.00 kg			Phase Determination: N/D Number of Phases Defined: N/A	
50	Shalamanov *et al.* (2015)	*Sex*: Male *n* = 184 *Level*: National *BW*: 56 = 55.7 ± 0.027 kg 62 = 61.1 ± 1.76 kg 69 = 68.3 ± 0.88 kg 77 = 76.1 ± 0.92 kg 85 = 84.3 ± 0.14 kg 94 = 92.8 ± 1.4 kg 105 = 103.1 ± 2.0 kg 105+ = 133.3 ± 17.0 kg	Cup of Russia Russian Championship XXVII World Summer Universiade 2012 – 2014	Assessment of athlete's technique.	Lift: Snatch Unit(s): 1 Camera Frequency: 50 fps Filter: N/D Phase Determination: N/D Number of Phases Defined: 4 (first pull, amortization, second pull, fixation)	*Average Load* 56 = 101.2 ± 8.3 kg 62 = 118.6 ± 11.6 kg 69 = 137.1 ± 7.7 kg 77 = 139.7 ± 12.4 kg 85 = 150.3 ± 12.4 kg 94 = 161.3 ± 12.6 kg 105 = 169.4 ± 15.1 kg 105+ = 178.7 ± 18.4 kg *Kinematics* Duration Bar Vert s Bar Vert *v* Bar Vert P
79	Stone *et al.* (1998)	*Sex*: Male *Level*: Elite *n* = 43	1996 U.S National Championship North American, Central American and Caribbean Island Championship	Identify markers of successful snatch technique and to compare U.S and non U.S lifters to see what constitutes as successful technique.	Lift: Snatch Unit(s): 1 V-Scope Frequency: N/D Filter: N/D	*Average Load* N/D *Kinematics* Duration Bar Vert and Horz s Bar Vert P

		BW: N/D			Phase Determination: N/D Number of Phases Defined: N/D	*Kinetics* Bar peak F
43	Szyska and Mastalerz (2015)	*Sex*: Male *Level*: World *n* = 14 *BW*: 67.48 ± 22.21 kg	2013 World Championship	Present the variation of biomechanical indicators depending on sporting level and parameters that differentiate best and worst lifters.	Lift: Snatch Unit(s): 2 Cameras Frequency: 50 Hz Filter: N/D Phase Determination: 1 (suspension) – knees straighten, 2 (pick up) – lifter aligns body with hip and 3 (non-resistant) – lifter squats under bar and bar is raised. Number of Phases Defined: 3 (phase1 ,2 and 3)	*Average Load* 95.35 ± 24.61 kg *Kinematics* Bar Vert and Horz s Bar Vert *v*
14	Viorel *et al.* (2013)	*Sex*: Male (Jnr) *Level*: European finalists *n* = 7 *BW*: 55.88 ± 0.14 kg	2011 European Junior Championships	Highlight the kinematic and dynamic characteristics of movement phases of the snatch.	Lift: Snatch Unit(s): N/D (1 Camera?) Frequency: N/D Filter: N/D Phase Determination: N/D	*Average Load* 109.14 ± .42 kg *Kinematics* Duration Bar Vert and Horz s Bar Vert and Horz *v* *Kinetics* Bar Vert and Horz F

					Number of Phases Defined: 5 (start, straightening, flipping, getting under and catching)	
14	Viorel *et al.* (2014)	*Sex*: Male (Jnr) *Level*: European finalists *n* = 7 *BW*: 55.88 ± 0.14 kg		Highlight the kinematics and dynamic characteristics of movement phases of jerk style.	Lift: Clean and Jerk Unit(s): N/D Frequency: 30 fps Filter: N/D Phase Determination: N/D Number of Phases Defined: 5 (clean) – Phase 1 (start, straightening, flipping, high pull, lifting) 3 (jerk) – Phase 2 (semi squat, the drive and overhead locking)	*Average Load* 134.43 ± 7.27 kg *Kinematics* Duration Bar Vert and Horz s Hip Vert and Horz s Hip Vert and Horz *v* *Kinetics* Hip Vert and Horz F
64	Viorel and Potop (2017)	*Sex*: Male (Jnr) *Level*: European finalists *n* = 7 *BW*: 55.88 ± 0.14 kg		Highlight synchronisation of the kinematic and dynamic indicators of key elements of the clean and jerk technique.	Lift: Clean and Jerk Unit(s): N/D Frequency: 30 fps Filter: N/D Phase Determination: N/D	*Average Load* 134.43 ± 7.27 kg *Kinematics* Duration Bar Vert and Horz s Bar Vert and Horz *v* Bar resultant s

					Number of Phases Defined: 5 (clean) – Phase 1 (start, straightening, flipping, high pull, lifting) 3 (jerk) – Phase 2 (semi squat, the drive and overhead locking)	*Kinetics* Bar Vert and Horz F Bar ME
79	Whitehead *et al.* (2014)	*Sex*: Male *Level*: National U.S n = 24 *BW*: 83.2 ± 21.7 kg	1999 U.S Senior National Championship	Examine body position and to determine the prevalence of rearward displacement.	Lift: Snatch Unit(s): 1 Camera Frequency: collected at 30 fps and deinterlaced at 60 fps Filter: Low-pass Butterworth filter, cut-off 5 Hz. Phase Determination: N/D Number of Phases Defined: N/D	*Average Load* *Kinematics* Duration Bar Vert s Bar Vert v CoM Horz s CoM Vert v Hip ∠ Shoulder and Hip distance

Where: n is the sample size, *BW* = Bodyweight, fps = frames per second, Hz = hertz, Δ = change in, ∠ = angle, AKH = ankle, knee, and hip, ΔK∠ = change in knee angle, N/D = not defined, N/A = not applicable, Vert = vertical, Horz = horizontal, s = displacement, v = velocity (m/s), acc = acceleration (m/s^{-2}), CoM = centre of mass, CoG = centre of gravity, P = power, ME = mechanical energy, F = force.

Table 3.2. Summary of data extraction for laboratory based data capture and analysis.

Quality Score (%)	Reference	Subject Details	Aim	Methods	Variables
93	Ammar *et al.* (2017)	*Sex*: Male *Level*: Elite *n* = 9 *BW*: 77.1 ± 19.6 kg	Compare kinematic and kinetic characteristics during clean movement across sub maximal to maximal loads.	Lift: Clean Unit(s): 4 Digital cameras + 1 force plate Frequency: 200 Hz and 1000 Hz Filter: Kinematic = 6 Hz Kinetic = 25 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull, transition, second pull, turnover, catch and recovery)	*Average Load* 170 ± 15 kg *Kinematics* Duration of phases Bar Vert and Horz s Bar Vert *v* Bar Vert acceleration Bar Vert power Time to max *v* Time to max Vert s Time to Peak Power *Kinetics* Time to Peak vGRF Time to Peak RFD vPower vWork vRFD
93	Ammar *et al.* (2020)	*Sex*: Male *Level*: Elite *n* = 9 *BW*: 77.2 ± 7.1 kg	Effect of 2- vs. 3- minute rest period on clean kinetics and kinematics.	Lift: Clean Unit(s): 4 Digital cameras + 1 force plate Frequency: 200 Hz and 1000 Hz Filter: Kinematic = 6 Hz Kinetic = 25 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined:	*Average Load* 170 ± 5 kg *Kinematics* Bar Vert and Horz s Bar Vert power *Kinetics* vGRF vPeak Power *Other* RPE

				4 (first pull, second pull, turnover, catch)	
79	Enoka (1979)	*Sex*: Male *Level*: ‘Experienced’ *n* = 5 *BW*: 84.4 ± 13.5 kg	Examine the influence of externally applied force on barbell displacement, to help determine the significance of the second knee bend.	Lift: Clean Unit(s): 1 cinefilm camera + Force Oscillator Frequency: 59.2 fps and N/D Filter: Kinematic = N/D Kinetic = N/D Phase Determination: vGRF Number of Phases Defined: 3 (weighting 1, unweighting and weighting 2).	*Average Load* 1RM: 145 ± 34.45 kg D1RM: 113 ± 21.40 kg *Kinematics* Bar Vert s Bar Vert *a* Bar Vert *v* Knee and trunk angle *Kinetics* vGRF Bar F Resultant Muscle F
93	Gourgoulis *et al.* (2002)	*Sex*: Male and Female *Level*: Elite *n* = 12 (6 male and 6 female) *BW*: M = 74.4 ± 13.19 kg F = 60.73 ± 13.08 kg	Compare snatch kinematics between male and female weightlifters.	Lift: Snatch Unit(s): 2 Digital cameras Frequency: 60 fps Filter: 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull, transition, second pull, turnover, catch, rising)	*Average Load* M = 141.33 ± 17.53 kg F = 73.33 ± 13.57 kg *Kinematics* Duration of phases AKH Joint ∠ AKH Joint *v* Bar Vert and Horz s Bar Vert *v* Bar Work Bar Power
93	Gourgoulis *et al*, (2004)	*Sex*: Adult and Adolescent *Level*: Elite	Compare snatch kinematics between adults and adolescent weightlifters.	Lift: Snatch Unit(s): 2 Digital cameras Frequency: 60 fps	*Average Load (kg)* Adults =137.28 ± 12.95 kg Adolescents = 113.36 ± 19.24 kg *Kinematics* Duration of phases

		n = 23 (9 Adults and 14 Adolescents) *BW*: Adults = 75.6 ± 12.43 kg Adolescents = 75.49 ± 12.28 kg		Filter: 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 6 (first pull, transition, second pull, turnover, catch, rising)	AKH Joint ∠ AKH Joint *v* Bar Vert and Horz s Bar Vert *v* Bar Work Bar Power
86	Hadi, Akkuş and Harbili (2012)	*Sex*: Male *Level*: Elite professional *n* = 7 *BW*: 77.1 ± 19.6 kg**	Kinematic analysis of snatch technique with ascending load.	Lift: Snatch Unit(s): 4 Digital cameras Frequency: 50 fps Filter: Low pass 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* 134.28 ± 19.88 kg** *Kinematics* Duration of phases Bar Vert and Horz s Bar Vert *v* Bar Work Bar Power CoG *s* CoG *v* CoG Vert Work Efficiency
93	Harbilli and Alptekin (2014)	*Sex*: Male *Level*: Elite Adolescent *n* = 9 *BW*: 73.76 ± 16.77 kg	Compare barbell and joint kinematics during the snatch in elite adolescent weightlifters.	Lift: Snatch Unit(s): 2 Digital cameras Frequency: 50 fps Filter: Low pass 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* 127.11 ± 17.12 kg *Kinematics* Duration of phases AKH Joint ∠ AKH Joint *v* Bar Vert and Horz s Bar Vert *v* Bar Work Bar Power

79	Kauhanen, Häkkinen and Komi (1984)	*Sex*: Male *Level*: National and District n = 13 (7 National and 6 District) *BW*: National = 76 ± 17.3 kg District = 76.3 ± 13.2 kg	Compare performance characteristics of national and district level weightlifters in the snatch and clean and jerk.	Lift: Snatch and C&J Unit(s): 1 video camera 1 force plate Frequency: 40fps Filter: N/D Phase Determination: ΔK∠ Number of Phases Defined: 5 (Preparatory, first pull, second pull, third pull, drop under)	*Average Load* National Snatch: 117.9 ± 22.1 kg C&J: 147.9 ± 29.7 kg District Snatch: 91.5 ± 16.2 kg C&J: 114.3 ± 25.3 kg *Kinematics* Duration of phases K Joint v Bar Vert and Horz s Bar Vert v *Kinetics* vGRF as % of BW vGRF Impulse *Other* Anthropometrics Body composition sEMG Position of shoulder relative to bar
93	Korkmaz and Harbili (2015)	*Sex*: Female *Level*: Elite junior n = 10 *BW*: 61.24 ± 12.28 kg	Investigate three-dimensional kinematics of the snatch.	Lift: Snatch Unit(s): 2 Digital cameras Frequency: 50 fps Filter: Low pass 4 Hz Phase Determination: ΔK∠ and bar Vert s Number of Phases Defined:	*Average Load* 61.24 ± 12.28 kg *Kinematics* Duration of phases AKH Joint ∠ AKH Joint v Bar Vert and Horz s Bar Vert v Bar Work Bar Power

				6 (first pull, transition, second pull, turnover, catch, rising)	
100	Sandau, Langen and Nitzsche (2023)	*Sex*: Male *Level*: Elite weightlifters *n* = 7 *BW*: 92.4 ± 23.9 kg	Investigate the intra-session variability of time series barbell kinematics in sub- and maximal loads for the snatch and clean and jerk.	Lift: Snatch, clean and jerk Unit(s): Re-analyzer custom system. Frequency: 50 fps Filter: N/D Phase Determination: Qualitative observation of changes in knee joint angle and bar vertical *v*. Number of Phases Defined: 5 (first pull, transition, second pull, turnover, catch)	*Average Load* Sn: 146.4 ± 19.9 kg CJ: 179.7 ± 20.3 kg *Kinematics* Bar Vert and Horz s Bar Vert *v* Bar Vert acc

Where: *n* is the sample size, *BW* = Bodyweight, fps = frames per second, Hz = hertz, Δ = change in, ∠ = angle, AKH = ankle, knee, and hip, ΔK∠ = change in knee angle, N/D = not defined, N/A = not applicable, Vert = vertical, Horz = horizontal, s = displacement, *v* = velocity (m/s), acc = acceleration (m/s^{-2}), CoM = centre of mass, CoG = centre of gravity, P = power, ME = mechanical energy, F = force.

Table 3.3. Quality assessment scores.

Reference	1) Sample description	2) Procedures	3) Instrumentation and Methods	4) Dependent Variable Defined	5) Statistical analysis	6) Results	7) Conclusion	Total (%)
Campos *et al.* (2006)	2	2	2	2	2	2	2	14 (100%)
Chiu, Wang and Cheng (2010)	2	2	2	2	2	2	2	14 (100%)
Cunan *et al.* (2020)	2	2	2	2	2	2	2	14 (100%)
Sandau, Langen and Nitzsche (2023)	2	2	2	2	2	2	2	14 (100%)
Akkus (2012)	2	2	2	2	1	2	2	13 (93%)
Ammar *et al.* (2017)	2	2	2	2	1	2	2	13 (93%)
Ammar *et al.* (2020)	2	2	2	2	1	2	2	13 (93%)
Gourgoulis, Aggelousis, Mavromatis and Garas (2000)	2	2	2	2	2	2	1	13 (93%)
Gourgoulis *et al.* (2002)	2	2	2	2	1	2	2	13 (93%)
Gourgoulis *et al.* (2004)	2	2	2	2	1	2	2	13 (93%)
Harbili (2012)	2	2	2	2	2	2	1	13 (93%)
Harbilli and Alptekin (2014)	2	2	2	2	2	2	1	13 (93%)
Hoover, Carlson, Christensen and Zebas (2006)	1	2	2	2	2	2	2	13 (93%)
Korkmaz and Harbili (2015)	2	2	2	2	1	2	2	13 (93%)
Liu *et al.* (2018)	2	2	2	2	1	2	2	13 (93%)
Nagao *et al.* (2019)	2	2	2	2	1	2	2	13 (93%)
Schilling *et al.* (2002)	2	2	2	2	1	2	2	13 (93%)
Nagao, Huang and Kubo (2023)	2	2	2	2	2	2	1	13 (93%)
Sandau, Chaabene and Granacher (2021)	2	1	2	2	2	2	2	13 (93%)
Burdett (1982)	2	2	2	2	1	2	1	12 (86%)
Garhammer (1985)	2	2	2	2	1	1	2	12 (86%)
Hadi, Akkuş and Harbili (2012)	2	2	2	1	1	2	2	12 (86%)
Ikeda *et al.* (2012)	2	2	2	2	1	2	1	12 (86%)
Isaka, Okada and Funato (1996)	2	2	2	2	1	2	1	12 (86%)
Baumann *et al.* (1988)	1	2	2	2	1	1	2	11 (79%)
Enoka (1979)	2	2	2	2	1	1	1	11 (79%)
Garhammer (1980)	1	2	2	2	1	1	2	11 (79%)

Garhammer (1991)	2	2	2	2	1	1	1	11 (79%)
Gourgoulis, Aggelousis, Garas and Mavromatis (2009)	1	1	2	2	1	2	2	11 (79%)
Harbili, Harbili and Alptekin (2017)	2	2	2	1	2	2	0	11 (79%)
Kauhanen, Häkkinen and Komi (1984)	2	2	2	1	1	2	1	11 (79%)
Kipp and Harris (2015)	1	2	2	1	2	2	1	11 (79%)
Mastalerz *et al.* (2019)	2	2	2	1	1	2	1	11 (79%)
Musser *et al.* (2014)	2	1	2	2	1	2	1	11 (79%)
Stone *et al.* (1998)	1	2	1	2	1	2	2	11 (79%)
Whitehead *et al.* (2014)	1	2	2	1	1	2	2	11 (79%)
Ono, Kabuto and Kato (1969)	2	2	1	2	1	1	1	10 (71%)
Viorel and Vladmir (2017)	2	1	1	1	2	2	0	9 (64%)
Garhammer (1982)	1	2	1	2	1	0	1	8 (57%)
Antoniuk, Pavlyuk, Chopyk and Pavlyuk (2016)	1	2	0	1	1	1	1	7 (50%)
Antoniuk *et al.* (2017)	1	2	0	1	1	1	1	7 (50%)
Garhammer (1979)	2	2	0	2	0	0	1	7 (50%)

3.3. RESULTS

3.3.1. Selection of sources of evidence

The initial search yielded 489 articles. Following the removal of duplicates this was reduced to 313. Following brief review of the 313 articles, 64 full text articles were reviewed. A total of 27 articles were excluded based on the eligibility criteria outlined in section 2.2. Thirty-seven articles were reviewed in depth, with a further 10 added following manual screening of the reference lists, thus making a total of 47 articles included in this scoping review.

3.3.2. Synthesis of results

Research conducted into weightlifting performance ranged from 1979 to 2023. Seventy-nine percent (79%) of studies investigated in-competition biomechanical analysis across Olympic (12%), world (43%), continental (19%), national (24%) and regional (2%) events. The primary method of data capture utilised a single-camera system (49%), with 8% of total studies using custom made systems not available on the market. The utilisation of multi-camera systems made up 40% of total studies, with the remaining 11% not specifying equipment explicitly within their methods. In comparison, 21% of studies were conducted under laboratory environments. All studies included explicitly stated the methods of data capture, with 70% using multi-camera systems, 20% utilising single-camera systems and a single study (10%) utilising a custom system.

The determination of the phases was dependent on the primary aim of the study. In some instances, characterisation of barbell kinetics and/or kinematics may not require such segmentation of the lifts. From the 37 competition studies analysed, 19% did not require segmentation of the lifts as it would not have provided any further insight into their original aims. A further 19% did not explicitly state the methods of phase determination, but did go on to refer to specific phases. The primary method of phase determination utilised either visual or objective inspection of change in knee joint angle and barbell kinematics (38%). The remaining 24% used either knee joint or barbell kinematic in isolation. Laboratory studies showed some similarities with competition-based studies in that the use of the knee joint angle and barbell kinematics was the primary method used to identify phases of the lift (80%). One study utilised a force plate (10%) and another utilised knee joint only.

Lastly, the number of phases identified varied between 2 and 6 across all 47 studies. Five phases were the most common (30%) with 6 phases accounting for 17% of all studies. The phases presented typically referred to first pull, transition, second pull, turnover and catch, with the rising phase generally following the catch to make the 6th phase.

It is evident from the results of the search that a majority of research has been conducted within a competitive environment, with the remaining conducted in laboratory settings. These findings suggest that much of the available literature on competitive weightlifters has good ecological validity based on the task being measured in an environment that determines the success of the athlete and is therefore a better representation of the execution of the lift under investigation. This said it also becomes evident that there are some major inconsistencies in how phases of the lifts are determined which would consequently affect some of the information available to the weightlifting community. This makes it difficult for sport scientists and coaches to know what to monitor with accuracy. Therefore, the following discussion will look to summarise key concepts extrapolated from the synthesis of our results. These will focus on; methods of data capture, the effect of methods on variable derivation and definition of phases.

3.4. DISCUSSION

3.4.1. Methods of data capture

Given the logistical and ethical constraints that may be associated with in competition data capture, it is unsurprising that a majority of the literature utilise camera systems which are relatively unobtrusive. Where single cameras were used, they were placed perpendicular to the sagittal plane to optimise the capture of barbell trajectory. However, 5 studies where a single camera was used, also analysed joint kinematics or used changes in knee angle to determine different lift phases (Burdett, 1982; Garhammer, 1982; Grabe and Widule, 1988; Ono *et al.*, 1969; Whitehead *et al.*, 2014). Such a method raises the issue of joint centre occlusion of the knee caused by the weight plate during the lift of interest, with the exception of the jerk, where joint centre occlusion of the shoulder becomes prevalent (Grabe and Widule, 1988). It is well documented that the phases of the lift can be categorised using both knee joint angle and barbell displacement (discussed below) when utilising multi-camera set ups, however, the validity of knee joint angle as a marker of phase identification becomes questionable when using single camera methods from the sagittal plane. This is highlighted from the findings of Baumann *et al.* (1988) who reported a 15° difference between 2D and 3D knee joint angle at full flexion, which becomes relevant if comparing absolute knee angle. Furthermore, these remain the only data to compare the two.

It is for the above reasons that multi camera systems using between two and six cameras have been utilised. The typical set up of the 2-camera system creates an axis of 90° between the cameras, which are angled at 45° to either the centre of the platform or the competitor (Figure 3.2). Additional cameras provide a greater capture area for both the barbell and joint centres, thus avoiding occlusion of the points of interest (e.g. knee joint centre), and thereby providing more opportunity to digitise the points of interest with greater accuracy. Therefore, it is suggested that researchers investigating joint kinematics, or using these to identify phases based on knee joint angle, should implement a minimum of 2 synchronised cameras as shown in Figure 3.2. Furthermore, where this may not be possible, a single camera set up may be viable if only investigating barbell kinematics. The applicability of single camera video analysis within weightlifting has previously been discussed by Garhammer and Newton (2013), where the authors discuss the use of open-source software, therefore making it accessible. Additionally, barbell kinematic data can also be collected using specialised weightlifting analysers as used by Stone *et al.* (1998) and Antoniuk *et al.* (2016 and 2017), which provide instantaneous data. However, these kinds of systems have been discontinued and are therefore hard to attain. In addition to such technology, linear position transducers (LPT) have also been utilised where multiple units have been used to attain both the *x* and *y* axis of the barbell displacement (Cormie *et al.*, 2007). More recently, alternative technologies, such as accelerometers and smart phone applications that can simultaneously provide trajectory and video have gained popularity. Balsalobre-Fernández *et al.* (2020) investigated the concurrent validity of a smartphone-based barbell tracking application against a 14-camera 3D motion capture set up with results suggesting trivial to small differences between the criterion (3D motion capture) and the smart phone application on peak horizontal and vertical displacements as well as peak velocity. This could provide coaches with a cost-effective method if wanting to quantitatively analyse barbell trajectory for the aforementioned variables. What should be noted is that irrespective of utilising 2 or 3-D methods of barbell analysis, deformation of the barbell at high loads may affect the outcome measures derived from displacement which is difficult to account for. As this is a likely occurrence, acceptance of such uncontrollable issues must be considered if utilising lateral points on either end of the barbell. Additionally, rotation along the horizontal axis may also impact how barbell trajectory is perceived.

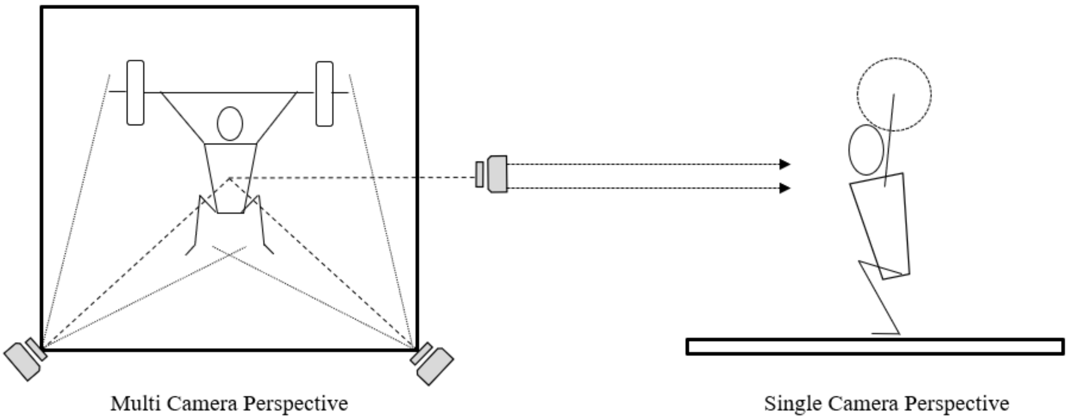


Figure 3.2. Typical multi and single camera set up perspective.

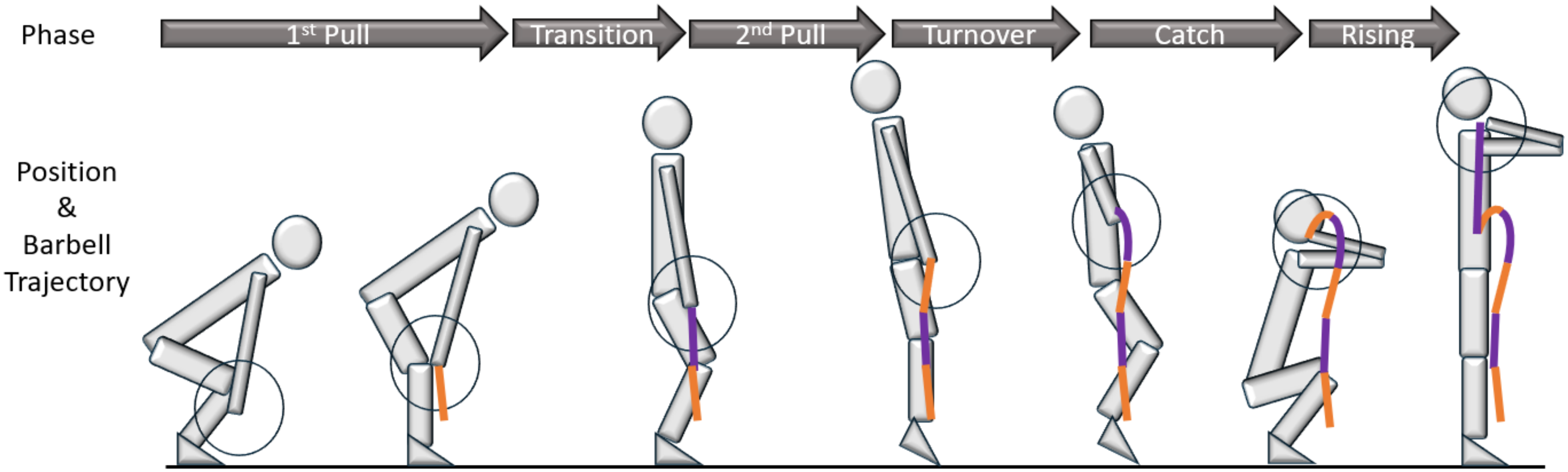
3.4.2. Variable Derivation and Filtering

The accuracy of kinematic and kinetic data within the studies analysed will largely be governed by the hardware used to collect the data. Given the date range of of included studies spanned from 1979 to 2023, a brief discussion is warranted around sampling frequency given technological advancements over the decades. While both competition and laboratory-based studies have used a range of camera set ups, the sampling frequency, can impact the quality of kinematic data. The barbell and joint angular velocity often reported in weightlifting are relatively slow compared to other sporting movements such as sprinting, and therefore it has been suggested that 50 to 100 frames per second (fps) is sufficient to obtain kinematic data (Garhammer and Newton, 2013). From the available literature, we have identified a range of 30 fps to 250 Hz frequencies across both competitive and laboratory-based investigations with a majority utilising 50 or 60 fps. While these large ranges in capture frequency have been used, lower frequencies maybe suitable for barbell trajectory analysis, but may pose problems when trying to obtain acceleration and velocity.

Once video footage is digitised, the change in position (displacement) and the rate of this change (velocity) can be calculated. With a majority of studies using camera systems or equivalent the method of collection and how these variables are calculated can affect the outcome and is therefore an important consideration. Since the co-ordinate of a marker in the calibrated space will provide a distance travelled, velocity and acceleration can be derived by differentiating displacement-time data. Velocity is calculated from the rate of change of displacement by time (Soriano *et al*., 2023), whereas acceleration is the product of double differentiation of displacement-time data, where velocity-time data is differentiated (Soriano *et al*., 2023). While these methods of deriving velocity and acceleration are acceptable, they are susceptible to increased signal noise, thus compromising data accuracy. Therefore, to obtain data that most accurately represents the performance, signal noise must be filtered out to improve the velocity and acceleration outputs. This issue is typically approached by *filtering* the displacement-time data and removing some of the noise associated with the movement and data collection methods (Robertson *et al*., 2014). Within this review of literature, 40% (19/47) of total studies did not report any filtering process, with the remaining studies using low pass filtering methods with cut-off frequencies between 3.6 and 6 Hz (Akkus, 2012; Ammar *et al*., 2017; Ammar *et al*., 2020; Chiu *et al*., 2010; Gourgoulis *et al*., 2000; Gourgoulis *et al*., 2002; Gourgoulis *et al*., 2004; Gourgoulis *et al*., 2009; Hadi *et al*., 2012; Harbili, 2012; Harbili and Alptekin, 2014; Harbili *et al*., 2017; Ikeda *et al*., 2012; Isaka *et al*., 1996; Kipp and Harris, 2015; Korkmaz and Harbili, 2015; Liu *et al*., 2018; Mastalerz *et al*., 2019; Nagao *et al*., 2019; Nagao *et al*., 2023; Whitehead *et al*., 2014). However, some researchers have used other methods like 5 point moving arc (Garhammer, 1985; Garhammer, 1980; Garhammer, 1982; Garhammer, 1991), 20 point moving average (Cunanan *et al*., 2020) and cubic spline (Musser *et al*., 2014). While there is no agreed method, the filtering will depend on several factors such as instrumentation noise, environment, and the variables of interest. Upon reviewing the literature, it is apparent that a 4th order Butterworth filter with a cut off frequency between 3.6 to 6 Hz is a popular choice amongst the research when filtering data. Utilising a residual analysis to identify an appropriate cut off frequency will help ensure that values relating to commonly presented peak measures, such as displacement, velocity, and power, will not be under or overestimated by the signal noise. Additionally, some filtering methods can also cause drift in the time related data, therefore shifting key markers which have previously been used to identify the start or end of a phase.

3.4.3. Definition of Phases

Appropriately defining the phases of a lift is important to standardise the terminology used between coaches and sport scientists. A determining factor of this will be governed by what data are collected. It has been highlighted that a range of methods have been utilised when identifying the phases of the lift with a total of 22 studies utilising changes in knee joint angle in conjunction with barbell kinematics, typically vertical barbell displacement. However, barbell and knee kinematics have also been used in isolation, which identifies two issues: 1) there is currently no standardised method of identifying weightlifting phases and 2) the most popular method to identify weightlifting phases (combining change in knee joint angle and vertical barbell displacement) requires a multi-camera set up to avoid joint occlusion. Issues surrounding these two points have been further confused with the use of inconsistent terminology to refer to the phases as well as the number of phases defined. If we are to optimise the transfer of weightlifting research to weightlifting practice the issue of standardising this element of weightlifting research must be resolved. Interestingly, laboratory-based investigations have shown a more uniform method of phase detection with 80% combining the change in knee joint angle and barbell vertical displacement. The disparity between the number of phases reported is also far less in laboratory-based investigation, with 40% defining 6 phases and 40% defining 5, but with the 6th phase referring to the rise up from the squat position. Figure 3.3 outlines the 6 main phases and the methods in which they are identified throughout the literature.



Position Definition	Lift off	Bar at knee	Power Position	Maximal Extension	Turnover	Catch	Rising from squat
Knee kinematics		1st peak knee extension	1st peak knee flexion	2nd max knee extension		2nd maximal knee flexion.	Knee at 3rd maximum extension.
Barbell kinematics	Vertical v exceeds 0.05 ms^{-1}	1st peak vertical v	1st peak horizontal displacement.	Peak vertical v.	Peak vertical displacement.		Vertical v = 0 ms^{-1}
Other	1st frame bottom of plate breaks off floor					Bottom of squat position.	

Figure 3.3. Phase definitions

The aforementioned highlights the issue that phase information in the literature cannot be compared making it difficult for sport scientists and coaches to make informed decisions, since the method that data are collected will govern how phases are defined. A primary consideration would therefore be to ensure that the phase start or end is defined by a distinct objective event that occurs regardless of the lifter's ability, gender, age, and load lifted. For example, Isaka, Okada and Funato (1996) used barbell acceleration to identify lift phases. They observed three acceleration peaks which, they explained, corresponded to the first pull, transition, and second pull. However, while this was observed in most of their participants, one of their participants did not produce a definitive second peak (transition). This suggests that three peak barbell acceleration model should not be used to identify lift phases. As the athlete gets stronger and more technically efficient and can apply more force to the barbell, this will alter the acceleration, velocity and positional-time curve. Therefore, if utilising acceleration to define phases for monitoring purposes it may yield incomparable results from previously collected data, particularly within the same loads, therefore further warranting its exclusion as a method of phase detection. In addition to the aforementioned, and as previously discussed in the *Variable Derivation and Filtering* section, barbell acceleration is obtained through double differentiation of displacement data when captured via video, therefore it is susceptible to increase noise which maybe exacerbated not only by the method of calculation from displacement and capture frequency, but also environmental noise such as camera distortion/movement caused by dropping the barbell.

It is important to understand that the key phases often utilised within the coaching models of the snatch and clean cannot be used across all methods and the standardisation of terminology used and the definitions of the start and end of these phases are important to ensure consistency across future research and application. Furthermore, utilising objective measures to identify phases is critical to enable appropriate monitoring over time. Where in most cases the day-to-day coach may not have access to such technologies to conduct objective analysis, the author refers to the work of Chavda *et al*. (2021) who discussed subjective video-based analysis methods.

3.4.4. Barbell Kinematics and Kinetics

Weightlifting performance measures are typically obtained from barbell motion, likely because it is relatively easy to capture and the importance of barbell position relative to body position, particularly the barbell's trajectory (its vertical displacement plotted against its horizontal displacement). Early literature from the Soviet Union reported three trajectory types; Type 1, 2, and 3 (Vorobyev, 1978) of which a fourth trajectory (4) was added by (Hiskia, 1997) (Figure 3.4). From our review of the literature, the frequency of trajectory type has been established across competition, ranking, gender and weight category (Antoniuk *et al.*, 2016; Antoniuk *et al.*, 2017; Cunanan *et al.*, 2020; Musser *et al.*, 2014). An investigation during the 2009 Pan American Championships showed a greater frequency of type 2 trajectories in 36 women weightlifters during the snatch lift. This was further supported by findings from Antoniuk *et al.* (2016) who found that type 2 trajectories accounted for 44.53% of the 238 successful snatch lifts from the women's categories during two European and two World Championships. Following this study, Antoniuk *et al.* (2017) added 66 lifts to their total (304 total). Contrary to their previous findings, the addition of the data from the 66 lifts changed the highest occurring trajectory to type 1, which now represented 42.9% of all lifts. More recently, a comprehensive study conducted by Cunanan *et al.* (2020) determined the trajectory type of 319 successful snatch attempts from two major championships: the 2017 Pan American and the 2015 World Championships. The authors investigated A session weightlifters, classified as those that post the highest opening total relative to others in their weight class. The findings demonstrate that the most common trajectory was type 3 across both competitions. This highlights the conflicting findings from each study and therefore, it becomes evident that the general barbell trajectory displayed by international weightlifters display variance. Furthermore, this variance in trajectory type is also evident within weight classes, with no obvious agreement between the investigations, other than heavier weightclass men and women displaying a higher frequency of type 3 trajectories (Antoniuk *et al.*, 2016; Antoniuk *et al.*, 2017; Cunanan *et al.*, 2020). This variance between weightclasses may be due to anthropometry and has been investigated by Musser *et al.* (2014). They found that weightlifters who produced a type 1 trajectory had significantly shorter trunk lengths than those presenting a type 2 or 3 trajectory. Interestingly, they went on to explain that the type 1 trajectory was more prevalent in the lightest women's class of 48 kg, which agrees with Antoniuk *et al.* (2017) but not with other research into 48 kg weight class athletes (Antoniuk *et al.*, 2016; Cunanan *et al.*, 2020).

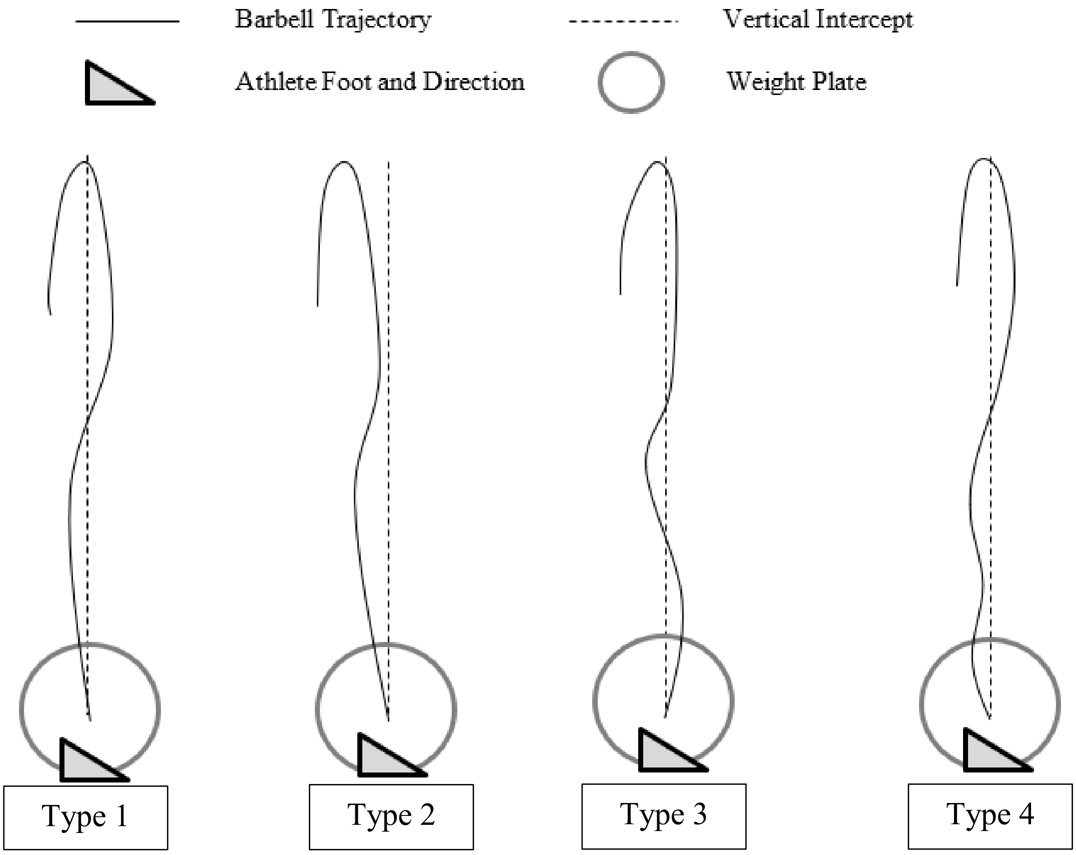


Figure 3.4. Barbell trajectory type determined by horizontal displacement and crossing of vertical reference line. Adapted from Vorobyev (1979) and Hiskia (1997).

While variation in the display of trajectory type has been reported, an important factor to understand is the trajectory displayed by the top performing weightlifters that may help provide coaches with an understanding of discriminatory factors relative to lower performing weightlifters. Cunanan *et al.* (2020) reported that within the medal zones, the greatest frequency of barbell trajectory was type 3, but this was more prevalent in men than in women (30% vs 54% during World Championship and 43% vs 54% during the Pan American Championship). What was further extrapolated from this was that medal winning women displayed a type 2 trajectory, suggesting this may be a characteristic displayed by high performing female weightlifters. It becomes evident that the spread of frequency of trajectory types across weightclass and sex will vary. For example, the top performing women across all weight categories during the 2015 World Championships had a frequency of at least one type 2 with the remaining being either a type 1, 3 or 4, with 3 being more common than 1 and 4. Equivocally, men presented a similar pattern but with men's heavy weight classes (105 and 105+ kg) displaying type 3 trajectories only, which is likely due to longer trunk lengths as outlined by Musser *et al.* (2014). Additionally, Musser *et al.* (2014) also showed that none of the weightlifters who demonstrated a type 1 trajectory medalled across all categories during the 2009 Pan American Championship, with 68% displaying a type 2 and the remainder a type 3. Lastly, another contributing factor to trajectory type that must be considered is the weightlifter's nationality (Stone *et al.*, 1998). The reason for this is likely because of differences in coaching and teaching strategies which they believe will optimise weightlifting performance, however, research is warranted to quantify this.

Cunanan *et al.* (2020) presented the distribution of trajectory type across continents with North America, South America, Asia, Europe and Africa displaying a relative frequency of type 3 trajectories ranging between 46 and 65% at the 2015 World Championships and 2017 Pan American Championship. Although not presented, readers should be made aware that the distribution of continents within each weightclass would vary and therefore may skew the results, as well as the number of athletes per weightclass. To summarise, a range of barbell trajectory types may be observed in international weightlifters, and therefore further exploration into optimising performance maybe found within quantitative measures beyond barbell trajectory.

Characterising and quantifying barbell trajectory has received much investigation with a large proportion of studies reported in this scoping review presenting some sort of information relating to horizontal or vertical displacement. One reason for such interest in the displacement of the barbell is that it may provide quantitative measures which can help differentiate between success and failure. The first study to report discriminate factors relating to barbell displacement between successful and unsuccessful snatch lifts was Stone *et al.* (1998), who concluded that no one variable significantly distinguished between successful and unsuccessful lifts. This is further supported by findings from Mastalerz *et al.* (2019) and Gourgoulis *et al.* (2009) who also reported no significant differences in barbell displacement values between successful and unsuccessful snatch lifts. Although statistically no differences have been reported, observations among the literature provide some indication of differences that may help coaches identify flaws in technique. For example, Stone *et al.* (1998) noted that from the pooled attempts of all snatches analysed, 85% of misses occurred when the barbell was caught > 20 cm behind the initial start (vertical intercept) and that if 'looping', defined as the most forward position following the 2nd pull to the catch, was greater than the net backward horizontal displacement, then 65% of lifts were missed. Furthermore, Stone *et al.* (1998)

observed that from 6 successful re-attempts, lifters presented a combination of a greater rearward position of the barbell during the start of the 2nd pull (>2 cm), less 'loop' (3 cm), and the horizontal position of peak bar height was less than that of the miss (12.5 vs 16.0 cm). This highlights that horizontal displacement relative to the vertical intercept at the start, the position away from the lifter following the 2nd pull, and the position in which the peak barbell height is achieved, may affect snatch success, which is further supported by the findings from Cunanan *et al.* (2020). Additionally, Mastalerz *et al.* (2019) observed that peak barbell height in successful snatch lifts was, on average, 0.86 cm higher than unsuccessful lifts. The underpinning mechanism that explains this would be due to the interaction of the vertical force applied on the barbell and the time in which it is applied (impulse). Higher values of peak velocity, peak power and peak vertical force of the barbell have been shown to be greater in successful attempts (Stone *et al.*, 1998), therefore warranting a discussion around vertical velocity and acceleration profiles.

Barbell vertical velocity profiles in weightlifters have been shown to present a bi-modal curve, with the first peak relating to the first pull and the second relating to the end of the second pull (Garhammer, 1985) (Figure 3.5). The decrement between the two has been associated with the transition phase, where velocity decreases as the athlete repositions their knees under the bar. This decrement in barbell velocity has been observed to be less in higher performing weightlifters and may not always be present. Decreases in barbell velocity could be considered as mechanically inefficient because the lifter will have to re-establish the necessary velocity, which subsequently would require greater muscular effort when executing the second pull. The second peak in this bimodal curve represents peak vertical velocity and provides information that the lifter can move the load fast enough to displace it to a height which enables them to effectively turnover and receive. The large ranges of velocity reported in the literature can likely be explained by multiple factors previously discussed in this article, relating to measurement methodology and data filtering. Additionally, it is worth noting that the consensus on whether barbell velocity can differentiate athlete level, attempt success, age or nationality, is unclear. Early research from Ono, Kubota, and Kato (1969) found that high ranked adults had greater barbell velocities during the snatch than high school weightlifters. This discriminatory factor is also highlighted by Liu *et al.* (2018) who found significantly lower peak barbell velocity in sub- elite Chinese weightlifters compared to elite weightlifters ($1.44 \pm 0.28\ \text{m}\cdot\text{s}^{-1}$ vs $1.74 \pm 0.10\ \text{m}\cdot\text{s}^{-1}$, $p < 0.05$). Although this conceptually opposes the inverse relationship between load and velocity, the authors attributed this to sub-elite weightlifters not having the necessary strength qualities to move these loads as fast as their counterparts, and it highlights how critical the application of force to the barbell is, with the temporal confinement of the lifting technique. Contrary to these findings, Baumann *et al.* (1988), Campos *et al.* (2006) and Cunanan *et al.* (2020) found that higher performing weightlifters displayed lower peak vertical velocities, which is likely due to the heavier loads being lifted. Considering that the findings of Liu *et al.* (2018) indicate that higher performing weightlifters displayed higher velocities, this may highlight that the population used may not have lifted loads close enough to their maximal performance capability and therefore presented higher peak velocities. Additionally, they document that the elite group consisted of World and Olympic gold medallists across the previous four Olympic games (16 years) who achieved an average snatch of 155.83 kg, which corresponds to approximately 2 – 7 kg less than that lifted during the four Olympic games by Chinese weightlifters, and 155 kg being, on average, the first or second attempt. Given that strength has been suggested to potentially explain the higher velocities observed in higher performing weightlifters, an investigation by Chiu, Wang, and Cheng (2010) reported that stronger weightlifters (defined as those lifting > 1.63 kg/kg relative to body mass [RBM]) displayed lower (although not significantly [$p > 0.05$]) peak vertical velocities than their weaker (<1.28 RBM) counterparts, with mid-strength weightlifters (1.63 – 1.28 RBM) displaying the lowest values. Therefore, given the information reported from the aforementioned studies and the inverse relationship of load and velocity, it seems logical that higher performing weightlifters displaying higher vertical velocities than their counterparts are able to do so because they are likely not lifting maximal loads relative to their maximal capability for that specific lift.

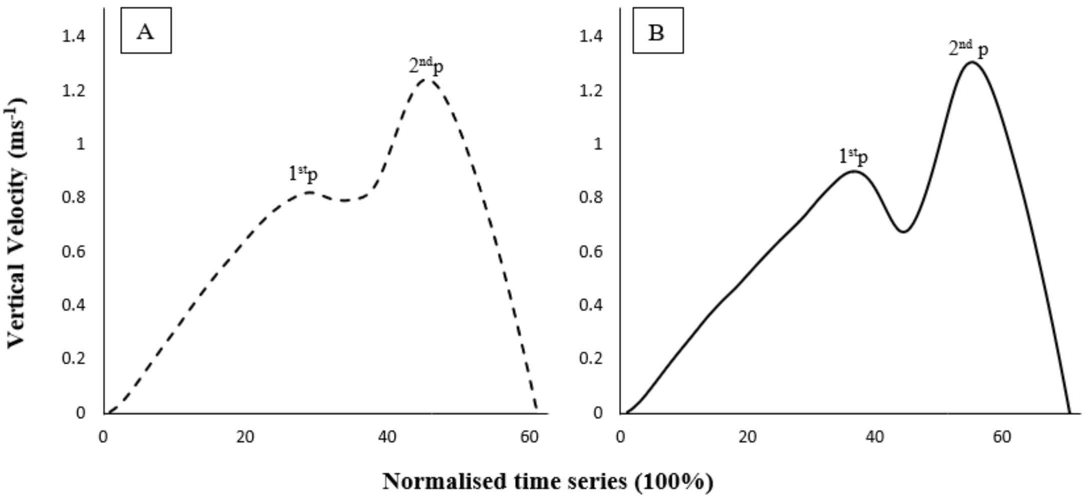


Figure 3.5. Vertical barbell velocity of two lifters A and B. Lifter A displays a better velocity profile based on a lower decrement in velocity between the first (1^{st}p) and second (2^{nd}p) peak. Time normalisation cropped to pull only.

In weightlifting, mechanical barbell power has been studied extensively. Mechanical power is defined as the rate at which work is performed (Garhammer, 1979). Mechanical work is the scalar product of absolute force being applied to the barbell, which would vary its displacement, thus work is equal to force multiplied by displacement (Equation 2a). Given that barbell trajectory has been measured using video capture technology in all of the studies we reviewed, the calculation of work and power has been determined using the sum of kinetic and potential energy, which is then divided by the difference in time between each frame of the video or the total duration of the phase of interest to obtain power (Equation 2 b,c and d, respectively) (Garhammer, 1993).

Equation 2 – Calculation of work and power on the barbell:

a) $W = \Delta KE$
b) Kinetic energy (KE) = $\frac{1}{2}\, m \cdot v^2$, where $v = s/t$
c) Potential Energy (PE) = $m \cdot g \cdot \Delta h$
d) Power = KE + PE / t

Early literature from Garhammer (Garhammer, 1979) used barbell work to help determine the efficiency of weightlifters in performing vertical work relative to total work (vertical plus horizontal). His results indicated that better performing weightlifters displayed a greater vertical to horizontal work ratio, across varying weight classes. These ratios enable comparison between those with differing heights and those lifting larger loads. It should also be discussed that the work performed would refer to the pull, or constituent parts of the pull. The variance within the literature when reporting power output is evident from the fact that the end of the pull has been defined in several ways, once again highlighting the issues around how phases are identified. Lots of studies have either used the second maximal knee extension (Akkus, 2012; Gourgoulis *et al*., 2000; Gourgoulis *et al*., 2002; Gourgoulis *et al*., 2004; Gourgoulis *et al*., 2009; Hadi *et al*., 2012; Harbili, 2012; Harbili and Alptekin, 2014; Korkmaz and Harbili, 2015), barbell peak vertical velocity (Garhammer, 1985; Garhammer, 1991), peak barbell height (Baumann *et al*., 1988; Hoover *et al*., 2006) or colloquial terms such as 'top pull' (Garhammer, 1980). Within the research conducted, several authors reported average power output of the first, second and/or total pull (Garhammer, 1985; Garhammer, 1980; Garhammer, 1991; Gourgoulis *et al*., 2000; Gourgoulis *et al*., 2002; Gourgoulis *et al*., 2004; Gourgoulis *et al*., 2009; Hadi *et al*., 2012; Harbili, 2012; Harbili and Alptekin, 2014; Hoover *et al*., 2006; Korkmaz and Harbili, 2015) by dividing the mechanical work done on the barbell during each phase by its duration, while others had reported instantaneous peak power (IPP) (Nagao *et al*., 2019; Nagao *et al*., 2023; Shalmanov *et al*., 2015; Stone *et al*., 1998), defined as the maximal power achieved through the entire movement. Given the discrepancies within the literature in defining the end of the second pull, the outcome observed for average power would be dependent on the definition used (i.e., peak velocity or peak knee extension). This would be due to the time in which mechanical work is divided as they would differ between methods, and therefore requires further investigation. When analysing average power during the second pull, it is advised that second maximal knee extension should be used as this, by common definition, is the end of the second pull. However, in the instance where knee joint kinematics are not obtainable, peak vertical velocity of the barbell is a viable option, provided the two power outputs are not used interchangeably or compared within or between weightlifters. Utilising IPP is less common within the weightlifting research, as it presents the power achieved at a singular point in time, which can be heavily influenced by the data collection methods, for example the capture frequency. Additionally, it provides little insight into the entirety of the phase under investigation and therefore may not reflect any potential changes in technique which may manifest itself within changes occurring to the barbell's displacement, time taken to execute the phase and thus the velocity at which it is executed. Furthermore, if peak velocity is the method used to define the end of the second pull and this has increased, this would infer an increase in IPP. Further to this, as power is a product of force and velocity, it is not the intention of the athlete to move the bar as fast as possible, but instead to increase the load lifted, while producing an optimal threshold velocity that allows the athlete to displace the bar to catch it. Based on the demands and KPI of the sport (to lift the heaviest load possible), it is suggested that coaches and scientists investigate individual's optimal minimum velocity threshold attained at maximal loads.

In addition to barbell vertical velocity, barbell acceleration has also been investigated. It was first presented from Enoka (1979) who examined the influence of externally applied force on barbell displacement when investigating the significance of the second knee bend. Additionally, barbell acceleration has also been presented from competitive data collected by Isaka, Okada and Funato (1996) whereby the authors used vertical acceleration of the barbell to highlight specific events relating to the pull. As alluded to in the *Definition of Phases* section, this has some drawbacks, such as individuals not presenting 3 distinct peaks, thus making it difficult to apply this method of phase definition to all individuals. In addition, Isaka and colleagues (Isaka *et al.*, 1996) also investigated the angle of resultant acceleration (ARA), calculated as the angle of direction of the resultant acceleration vector of the vertical and horizontal acceleration of the barbell. This information highlighted that most of the acceleration of the barbell during the first pull and transition was vertical and slightly toward the lifter, with the end of the second pull creating an anterior acceleration away from the lifter. The use of the acceleration profile is somewhat similar to that of the efficiency ratio presented by Garhammer (1979), who used the total work. Ikeda *et al.* (2012) also used ARA to compare Japanese weightlifters to the best performing weightlifters in their respective weightclass at the 2008 Asian games. Their results indicated that the ARA during the second pull did not discriminate between the two groups, however peak vertical force was significantly greater in the best weightlifters (1686.2 ± 225.1 N vs. 1328.6 ± 179.3 N, $p < 0.05$) with significantly lower forward horizontal velocity (-0.38 ± 0.14 m·s^{-1} vs. -0.63 ± 0.17 m·s^{-1}, $p < 0.05$). This suggests that the ARA between lifters could be similar with a determining factor being the magnitudes of vertical force applied to the barbell. Therefore, the acceleration profile may provide information about the angle the barbell is being lifted relative to the sagittal plane during the pull and therefore may provide additional objective measures of technique refinement and correction but may not be able to differentiate groups of competitive weightlifters.

The utilisation of acceleration time curves has been further explored and associated with heavier loads being lifted during the snatch when a smaller deceleration is observed between the end of the first pull and the transition, with a concurrent higher magnitude of acceleration during the second pull (Kipp and Harris, 2015), highlighting our previous discussion around minimising velocity decrement during the transition. This agrees with the findings from Ikeda *et al*. (2012) and reinforces that the magnitude and rate of force applied to the barbell in the vertical direction is a determining factor of weightlifting success and could be quantified with acceleration given that this should be directly proportional to the vertical force that's applied to the system. Additionally, Gourgoulis *et al*. (2009) reported that the mean angle of the first pull relative to the vertical axis was smaller in successful compared to unsuccessful snatch lifts (9.41 ± 6.32 vs 17.47 ± 4.97°, respectively) suggesting a rearward application of force on the bar toward the lifter may positively affect the outcome. While acceleration may provide some useful information on ARA and force applied to the barbell, it must be considered that investigations into weightlifting have primarily used displacement, of which acceleration is a second derivative. This therefore increases the noise to signal ratio and is highlighted in a study by Sandau, Chaabene and Granacher (2021) when calculating barbell force. The authors compared work energy approach (equation 2c) against the inverse dynamics approach which utilised barbell mass and instantaneous acceleration. The authors concluded no mean differences between the two methods ($p < 0.05$, $d = -0.04$), but due to the differentiation of displacement data, acceleration time series used in the inverse dynamics approach displayed an error of 8.2%, leading the authors to conclude the use of the work-energy method when calculating barbell force.

While kinematic barbell data has been heavily investigated many of the studies ignore its potential utility for monitoring. A recent study by Sandau and colleagues (Sandau, Langen and Nitzsche, 2023) investigated the intra-session variability of time series barbell kinematic in elite male German weightlifters between submaximal and maximal loads (85% vs 97% 1RM). Their results suggested that at higher measurement error occurred when analysing time series data (between the phases), but discrete values of displacement (vertical and horizontal), vertical acceleration and vertical velocity were generally lower, particularly for acceleration and velocity. What is also evident, is that horizontal displacement error shows large standard deviations relative to the means presented. Given that horizontal displacement is so small during the snatch and clean, the SD as a percentage would suggest that a large variability exists within horizontal measures. For example, the authors present a horizontal displacement standard error of measure of 0.004 ± 0.002 m, which is 50% of the mean SEM. This is an important point, as we have already discussed some of the seminal research that highlight the importance of minimising horizontal displacement and how it can be a differentiator between a successful and unsuccessful lift. This means the measure between lift is highly erroneous and must be used with caution. Practically, this would mean for a coach to confidently determine meaningful change around horizontal displacement, a change outside of that error must occur. While this is the first study to date to investigate the variability in commonly presented measures relating to barbell kinetics and kinematics, inter-session variability should also be investigated as a way to allow coaches to identify if meaningful changes in technique have occurred between training blocks.

3.4.5. Lifter Kinematics and Kinetics

The interaction of the lifter with the barbell and their ability to apply force within the constraints of the technique against maximal loads is important to understand as these interactions will enable researchers and practitioners to gain better insight into key limiting factors of weightlifting performance relating to force generating capabilities and technique, consequently allowing us to make better informed decisions around training. To date only one study has analysed the system kinetics of weightlifting within competition. Baumann *et al*. (1988) collected snatch kinetics and kinematics during the 1985 world championships. In this investigation the authors reported three values relating to the absolute vGRF at two peaks and a minimum during the pull phase. Their findings showed that maximum force developed during the two peaks was significantly correlated with ascending system load ($r > 0.97$) suggesting greater magnitudes of force are required as load increases and provides justification for the development of absolute strength. While the investigation is the only one to ever collect vGRF data at a major weightlifting competition, it comes with some limitations. While Baumann *et al*'s (1988) work provides some insight as to the forces generates throughout the snatch it does not provide temporal insight into the forces created within each phase of the lift and with respect to time (impulse). This would provide greater insight into the vGRF required to raise the system centre of mass (CoM) and consequently displace the barbell to favourable positions relative to the body's CoM across each phase. Additionally, impulse is directly proportional to velocity and therefore greater impulses created by increasing the magnitude of force, given that time is constrained by technical execution thus, may help optimise barbell displacement to enable the catch. Further issues with Baumann *et al.* (1988) reporting peak forces is that the sample frequency was 100 Hz and given that precautionary measures were taken to reduce noise, the low sampling frequency within a rapid movement, such as the snatch, may fail to accurately measure peak values and therefore impulse could have been more appropriate and informative.

Prior laboratory-based research from Enoka (1979) investigated kinetics of the pull in five experienced weightlifters, lifting to 100% of their daily maximum. The author stated however, that this equated to 70-85% of their best loads lifted, therefore the likely magnitude of the kinetics maybe lower than if they had performed lifts with their true 1RM. Enoka (1979) highlighted three distinct phases within the force time curve where two impulses (area under the curve) were above that of the system weight and one which was below. These were termed, weighting 1 and 2 and unweighting, respectively. Findings suggested that the pooled average impulse for weighting 1, unweighting, and weighting 2 were 834.2 ± 128.01 N·s, 177.2 ± 64.46 N·s and 362.6 ± 89.75 N·s, equating to 124.60 ± 9.31%, 86.00 ± 6.70% and 132.00 ± 5.65% above that of system weight. This suggests that approximately 25-35% of impulse above that of system is required during weighting 1, with weighting 2 requiring an impulse between approximately 32-36% of the system. What should be noted is that although Enoka (1979) used system weight to define these phases, they do not correspond with the phases measured by the change in knee joint angle. Therefore, it cannot be generalised that the force characteristics displayed in this study are representative of the phases suggested in Figure 3.3. The authors therefore suggest that future research investigate force characteristics of phases defined through changes in knee joint angle and vertical barbell displacement to help provide a better understanding of phase specific kinetics and how force application may differ with relation to load, weightclass, sex and level.

Kauhanen, Häkkinen and Komi (1984) compared district and elite weightlifters, where they simultaneously collected vGRF data and changes in knee joint angle. The authors state that the force-time curves were divided based on the change in knee joint angle, therefore being able to present specific kinetic characteristics for each phase, thus providing greater specificity. Their findings suggested that the maximal force generated as a percentage of the system weight during the first pull for the snatch equated to 136.60 ± 8.30% and 129.30 ± 5.60% for the clean, with the second pull, which they term the third pull, equating to 157.60 ± 10.2% and 149.40 ±

17.40% for the snatch and clean, respectively. These values are similar to the maximum values from the values reported by Enoka (1979), which equated to 131.00 ± 13.83% and 153.00 ± 11.93% of the system weight for weighting 1 and weighting 2, respectively. This indicates that the potential use of maximal values as a percentage of system weight may be relatively similar regardless of whether the knee joint angle or the system weight method is used for phase definition. However, given that maximal force values provide little insight into the mechanistic property of each phase, the authors would suggest calculating impulse for the reason previously mentioned. Therefore, the time characteristics of the phases will be affected by the method of phase definition employed, and this is evident through the greater durations presented by Kauhanen, Häkkinen and Komi (1984) compared to those presented by Enoka (1979). In turn this would increase the values of impulse given that the maximal force is relatively similar between the two methods, but the time spent applying the force in the knee angle method is greater.

The remaining two studies that used force plates reported peak vGRF (Ammar *et al.*, 2020), average vGRF, and RFD (Ammar *et al.*, 2017). In the 2020 study Ammar (Ammar *et al.*, 2020) compared rest intervals between cleans performed at 1RM. While this is not the focus of the review, it provides some kinetic information on maximal clean performance, suggesting that peak force following a 2-minute recovery reach values of 3169 ± 276 N, equating to approximately 130% of system weight. Additionally, Ammar (Ammar *et al.*, 2017) previously investigated power production during the clean. Their vGRF data were extracted from phases defined using the change in knee joint method, to enable the authors to calculate average vGRF and RFD. Findings indicate that significantly greater average force was produced during the pull with 90-100% of their maximal clean load when compared to the 85% load, with peak RFD being greatest during the transition. Because of the higher average force generated in the pull at 90-100%, greater work was performed. It becomes evident that the use of vGRF data can provide further insight into the force characteristics required for successful weightlifting performance at maximal loads, however, considerations into the phase definitions of which the force data will be obtained and the sensitivity of change of the force data requires further investigation to allow for appropriate monitoring following training interventions.

Joint kinetics, such as the net joint moments (NJM), should also be considered of importance to better understand determining factors of technique. Information about the NJM during different phases of the lift may provide some insight into training specific muscle groups to develop phases of the lift that limit performance. Within the current search results, one study reported NJM (Baumann *et al.*, 1988) while another reported segment energy transfer (Garhammer, 1982). Both studies obtained data from competitive international and national competitions, respectively. Baumann *et al.* (1988) reported NJM information on the snatch, while Garhammer (1982) reported segmental energies for the snatch and clean in two world champions. Interestingly, Garhammer reported that the difference in energy flow among segments between the two lifts were small, and that the magnitude of the difference could be attributed to the slower movement execution during the clean, likely due to heavier loads.

During the first pull knee extension motion is created from an increase in extensor NJM of the quadriceps. The results from the two studies on joint kinetics show that as the first pull is conducted, the trunk segment's linear energy increases and the hip NJM remains constant (Baumann *et al.*, 1988; Garhammer, 1982). The energy flow between segments of the shank, thigh, trunk, and arms suggests that the first pull generates large amount of energy in the hip and knee joints, which subsequently flow through the torso, arms and eventually to the barbell. This suggests that erector spinae strength plays a pivotal role in in keeping the torso position steady during the first pull.

As the knee begins to reach first peak knee extension, a flexion NJM of the hamstrings is experienced, creating an eccentric muscle action, thus slowing down knee extension. This flexion NJM continues and subsequently overcomes the extension NJM causing the knee to flex, moving it into the transition phase. The thigh and shank segment energies decrease as the bar passes the knees, and the knees move forward under the barbell (Garhammer, 1982). This repositioning is thought to aid the weightlifter reach a more mechanically advantageous position to utilise the stretch reflex and produce high forces during the second pull. During the transition phase, the trunk segment's linear energy decreases while the rotational energy increases (Garhammer, 1982). The trunk segment thus becomes more upright in preparation for the second pull.

Whilst this knee flexion during the transition occurs an extensor NJM is experienced causing an eccentric muscle action at the quadriceps. Once in the 'power position' the hip, knee and ankle begin to extend, the observed decrease in energy flow during the transition phase is reversed, and a rapid increase in energy are observed for the foot, shank, and thigh segments with large extensor NJM observed at the knee (Garhammer., 1982). The large increases in linear energy of the trunk prior to maximal barbell vertical velocity consequently highlight the importance of training the hip and knee extensors.

Baumann *et al*. (1988) also reported a strong correlation ($r = 0.95$) between maximum hip NJM and total system mass, which suggests that increases in barbell load occur concurrently with increases in the load on the hip joint, and therefore justifies hip dominant movements as being an important factor to train (Buamann *et al.,* 1988). Furthermore, knee joint flexor and extensor moments did not proportionally increase with external loads, and only showed moderate correlation coefficients of 0.61 and 0.51, respectively (Buamann *et al.,* 1988). Nevertheless, considering the aforementioned energy flow findings even small correlations may still indicate that concurrent training of all extensors, and knee flexor, muscles should be utilised, with a focus on strength and weightlifting derivatives to enhance key physical and technical factors that limit performance.

Our literature review shows that 9/37 (33%) within-competition investigations reported a measure of CoM or centre of gravity (CoG) (Burdett, 1982; Garhammer, 1980; Garhammer, 1982; Garhammer, 1991; Hoover *et al*., 2006; Liu *et al*., 2018; Mastalerz *et al*., 2019; Nagao *et al*., 2023; Whitehead *et al*., 2014) with only 1/10 (10%) reporting it in laboratory-based investigations (Hadi *et al*., 2012). It is important to highlight that often the terms CoG and CoM are used interchangeably in sports biomechanics (Robertson *et al*., 2014) and this is evident from our results. From the 10 total studies which investigated CoM or CoG, 7 reported CoM (Burdett, 1982; Garhammer, 1980; Garhammer, 1982; Garhammer, 1991; Hoover *et al*., 2006; Nagao *et al*., 2023; Whitehead *et al*., 2014) with 3 reporting CoG (Hadi *et al*., 2012; Liu *et al*., 2018; Mastalerz *et al*., 2019). The CoM can be defined as the distribution of mass across a system. For example, as the barbell is a uniform shape the CoM is situated at the centre of the barbell. Center of gravity is defined as the point from which weight of a system is considered to act and is the same as CoM if gravity is uniform, as is the case in weightlifting and may therefore be a reason as to why such terms have been used interchangeably. Additionally, the methods presented across the 10 studies when calculating the bodies and barbells CoM (or CoG) presented similarities to warrant the use of the terms interchangeably. For continuity, the authors will refer to the CoG as the CoM when alluding to the studies conducted by Liu *et al.* (2018), Mastalerz *et al.* (2019) and Hadi, Akkus and Harbili (2012).

The barbell and body's CoM should be kept as close together as possible, so it's combined CoM as close over the base of support as possible to provide balance and to optimise force transference in projecting the barbell. Therefore, information on the CoM can provide a holistic overview of the kinetic and kinematic outputs produced by weightlifters. To obtain measures of the athlete's centre of gravity, segments must be created utilising the proximal and distal end point of the segment, to which their CoM is calculated using segment models, with the weighted average of all segments providing the body's CoM. From all investigations reporting CoM, six used the single camera method, which could be considered a methodological limitation because of joint centre occlusion impacting the identification of segments (Burdett, 1982; Garhammer, 1980; Garhammer, 1982; Garhammer, 1991; Hoover *et al.*, 2006; Whitehead *et al.*, 2014). The most common variable extrapolated with reference to the CoM is power output. This was first reported by Garhammer in 1980 (Garhammer, 1980) and was subsequently used in future investigations (Hoover *et al.*, 2006). Those using multi camera systems reported a far greater number of variables on CoM activity. These related to vertical and horizontal displacement, vertical velocity and vertical power (Hadi *et al.*, 2012; Liu *et al.*, 2018; Nagao *et al.*, 2023), with one also reporting the displacement between the CoM of the barbell and the body (Liu *et al.*, 2018). This provides a greater insight between the interaction of the body and the barbell, while also more likely carrying greater accuracy given the use of multiple cameras. From the findings of all investigations, it can be extrapolated that drop velocity of the CoM during the turnover to the catch is a determining factor between differing levels with higher skilled lifters taking significantly less time to move from the end of the second pull to the point of peak barbell height (p <0.05, 0.23 ± 0.03 s vs. 0.28 ± 0.05 s, respectively). The distance between the barbells CoM and the body's CoM does not differ between levels, although it is greater in sub-elite athletes from peak barbell velocity to peak barbell height (Liu *et al.*, 2018). This information suggests that to gain a better understanding of the barbell-lifter interaction, each of their respective CoM, should be analysed at each phase, thus providing coaches and scientists with a more in depth understanding of technique and better identifying key limiting factors.

3.5. CONCLUSION AND FUTURE RESEARCH

The current systematic scoping review provides an in-depth overview of biomechanical research conducted within competitive weightlifters. It becomes evident that many of the investigations are descriptive in nature which helps provide a foundation in which sport scientists and coaches within the sport have information to inform their technical and physical training. However, variations in the definitions of phases and the methodologies used to provide such information on performance must be approached critically. Performance science holds great ecological validity when collected in competition, however, steps towards understanding which variables carry low variability require multiple trials with the same load and therefore obtaining such information would be more suited toward laboratory-based testing or provide greater accessibility within the training environment. While we have alluded to a range of variables commonly reported within the literature, it is important to surmise these findings for the readership to make their own decision on what they may want to monitor. Given that force is mass x acceleration, vertical acceleration applied to the barbell (mass) can provide distinct information on how force is being applied to the barbell through the phases. This may be more informative than velocity alone, as it provides transient information where sudden changes in acceleration or deceleration may be of interest. Additionally, acceleration may provide a more comprehensive understanding of movement dynamics used to manipulate the barbell, for example reducing deceleration during the transition phase (Kipp and Harris, 2015), which may not always be obviated in velocity-time curves. It should be noted, however, that if acceleration is obtained through the double differentiation of displacement, this may amplify the noise to signal ratio, and therefore filtering and smoothing of the displacement data must be conducted. This becomes more important if calculating barbell force using double differentiation as appose to the work-energy method (Sandau, Chaabene and Granacher, 2021). From an applied perspective, where coaches may not necessarily have the required knowledge or ability to calculate and/or interpret acceleration-time curves, horizontal displacement may serve as a heuristic in helping the coach and athlete associate lifts that have been missed forwards or have caused them to move forward during the catch or recovery. While this has been reported to discriminate between successful and unsuccessful lifts (Stone et al., 1998), it’s sensitivity to change and thus utility in monitoring is yet to be investigated.

3.5.1 Future Research

Given the literature obtained from our results, it becomes apparent that there is a need to better identify key variables, which carry low variability and relate to an individual’s performance to provide coaches and scientists with the ability to monitor technique that influence performance over time to better inform training. Additionally, exploring the utility of more field-based methods of technical data capture using non-custom equipment is also warranted to increase accessibility.

CHAPTER 4: STUDY 3 - VALIDITY AND RELIABILITY OF A COMMERCIALLY AVAILABLE INERTIAL SENSOR FOR MEASURING BARBELL MECHANICS DURING WEIGHTLIFTING.

Chavda, S., Sandau, I., Bishop, C., Xu, J., Turner, A.N., and Lake, J.P. Validity and reliability of a commercially available inertial sensor for measuring barbell mechanics during weightlifting. *Sports Biomechanics*, Submitted March 2024. (Chapter 4)

4.1 INTRODUCTION

The monitoring of barbell mechanics is common in weightlifting to evaluate sport specific performance. In this context, barbell kinematics during the snatch have been used to identify causes of success and failure (Stone *et al*., 1998; Gourgoulis *et al*., 2009; Mastalerz *et al*., 2019; Nagao *et al*., 2019; Nagao *et al.,* 2023), to analyse differences in lifting technique between athletes with different performance levels (Kauhanen, Hakkinen and Komi, 1984; Burdett, 1982; Liu *et al*., 2018) and weight categories (Campos *et al*., 2006), as well as to assess the weightlifters' physical abilities (Garhammer, 1980). Based on the existing knowledge of barbell kinematics, this information may help coaches identify limiting factors during the lifts and therefore assist in the development of appropriate interventions.

Within the literature, kinematic measures of the barbell typically include its trajectory (Antoniuk *et al*., 2016; Musser *et al*., 2014; Cunanan *et al*., 2020; Balsalbore-Fernandez *et al*., 2020; Sandau, Langen and Nitzsche, 2023): vertical position plotted against horizontal position. Previously, this information has been used to identify common barbell trajectory patterns exhibited by weightlifters (Vorobyev., 1978; Hiskia, 1997), as well as their relationship to anthropometry (Musser *et al.,* 2014) and the common patterns exhibited within weight categories and countries (Cunanan *et al*., 2020). This information begins to highlight that even at the elite level, variations in trajectories exist and that the success of a lift is multifaceted (Stone *et al*., 1998). In addition to the barbell trajectory, barbell acceleration and velocity are often reported and have been shown to relate to key aspects of weightlifting performance (i.e. minimsing horizontal disaplcement and optimising vertical velocity) (Isaka, Okada and Funato, 1996; Sato, Sands and Stone, 2012). Furthermore, based on Newton's second law of motion, barbell kinetics (i.e., force, power) can be calculated from acceleration to provide information on the force application on the barbell (Kipp and Harris, 2014; Sandau *et al*., 2021).

The assessment of barbell mechanics is frequently realised using video analysis, with a large proportion of research using this as their primary method (Cunanan *et al*., 2020; Sandau, Langen and Nitzsche., 2023; Musser *et al.,* 2014; Antoniuk *et al*., 2016). While this method of data capture is highly applicable it may require multiple cameras or specialist software, often reducing accessibility to coaches. It is for this reason along with the enhancement of technology that alternative devices (e.g., inertial measurement units [IMU]) have become increasingly popular. For application within weightlifting, the over-the-counter IMU-based Enode (formerly known as VmaxPro) (Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany) is an easy-to-administer technology to measure time series barbell kinematics instantaneously providing clear, accessible information for coach and lifter. Additionally, it is also able to synchronise the sensor data to a hand-held tablet providing the user with simultaneous video feedback. The Enode system has previously been investigated for its validity in various strength-based exercises when assessing measures of average velocity, showing high levels of agreement with three-dimensional (3D) motion capture (mean difference: -0.014 $m{\cdot}s^{-1}$ [95% CI -0.057 – 0.029], $r^2 = 0.99$) (Menrad and Edelmann-Nusser, 2021). This is further supported by Fritschi, Seiler and Gross (2021) who found near perfect correlations between the Vmax Pro and 3D motion capture for mean and peak velocity, with standard error of estimates between 2.4-6.8% ($r = 0.99$ [0.94 – 0.96] and 0.99 [0.92 – 0.99], respectively) across five different exercises, including both strength and ballistic type movements. While this provides some insight into the utility of the Enode to measure mean and peak velocity during general training exercises, the usefulness to analyse barbell mechanics in weightlifting has not yet been investigated. Given that previous literature has reported the utility of barbell displacement, velocity, force, and power within weightlifting movements, this highlights that limiting measures from more typical strength exercises, such as mean and peak velocity, may not suffice in providing coaches with information that can influence training interventions and coaching, specific to weightlifting.

Therefore, the aim of this investigation is two-fold; 1) to assess the validity of the Enode relative to 3D motion capture criterion, and 2) to identify the within and between day reliability of various vertical and horizontal kinematic and kinetic barbell measures. It was hypothesised that the Enode would show good levels of concurrent validity for barbell kinematic and kinetic data relative to the 3D motion capture system. Additionally, we also hypothesized that the Enode systems would show acceptable within and between session reliability of barbell kinematic data potentially providing additional insight into the variability of the athlete's ability to perform the snatch.

4.2 METHODS

4.2.1 Experimental approach to the problem

An observational cross-sectional design was used to identify the validity of various kinematic and kinetic variables collected through the Enode during the snatch. Secondly, these measures were then assessed for intra- and inter session reliability. A relative intensity of 85% snatch 1RM was investigated as this is a common intensity utilised during moderate-heavy sessions, or when overreaching and tapering (Bazyler *et al.*, 2018), thus making the findings of the results more ecologically valid to training for weightlifting performance.

4.2.2. Participants

Participants for this study were recruited from Weightlifting clubs within the UK, consisting of trained and highly trained weightlifters as defined by (McKay *et al.,* 2021). All participants were over the age of 18 and provided written consent prior to participation. Both male and female subjects were allowed to participate in this study with descriptive data presented as group, with men and women in brackets, respectively (n = 13 (7;6); snatch 1RM: 80 ± 18 kg (92 ± 10; 62 ± 6 kg); 1RM relative to bodyweight: 1.05 ± 0.17 kg/kg (1.17 ± 0.13; 0.94 ± 0.17 kg/kg); 1RM relative to competition category: 1.05 ± 0.14 kg/kg (1.15 ± 0.13; 0.96 ± 0.12 kg/kg), height: 168 ± 8 cm (171.83 ± 3.41; 162.12 ± 6.72 cm); mass: 74.57 ± 10.32 kg (78.60 ± 6.58; 67.23 ± 8.26 kg); age: 30 ± 5.21 years (27.57 ± 1.84; 32.83 ± 6.01 years). All subjects met a criterion of being a competitive weightlifter at a level of no less than regional. All subjects were free of injury prior to testing days and were free to withdraw at any point. Ethics was granted via the London Sport Institute ethics committee (#25296) (Appendix 4.1). An online sample size calculator presented by Walter, Eliasziw and Donner (1998) for reliability studies suggested a sample size of 33 was required to achieved 80% power for detecting an ICC value of 0.75 ('good'), at a significance criterion of 0.05.

4.2.3. Procedures

All subjects were required to visit the laboratory to perform the snatch on two separate occasions within the space of 7 days and with at least 48 hours of recovery prior to testing. Subjects were also asked to attend their laboratory sessions at the same time of day for each session to reduce any diurnal affects along with the absence of caffeine. Upon arrival, the subjects were given 10 minutes in which they could perform a self-selected warm up, reflective of their day-to-day training. Following this, a standardised warm up for the snatch was undertaken consisting of 1-2 sets of 2-5 repetitions of overhead squat, hang snatch, snatch pulls and slow snatches. No familiarisation of exercises was required as all subjects conducted the warm up exercises regularly within their normal weightlifting training. Subjects were fitted with reflective markers on the right-hand side of the lower body. The relative intensity used in this investigation was based on the subjects' most recent 1RM, which was conducted within 14 days of test day one in their own training environment. Subjects performed 2 repetitions of loads starting at 70% increasing to 85% in 5% increments. One-minute recovery was given between repetitions and 2-3 minutes between loads. If a lift was missed the subject was provided with a 2-3minute rest to attempt the weight again.

4.2.4. Data Capture and Processing

A total of 21 markers were attached to the subjects right lower limbs and pelvis, specifically on the foot (metatarsal 1 and 5 and heel), ankle (lateral and medial malleolus), shank (tibial cluster), knee (lateral and medial epicondyle), thigh (femoral cluster, left and right greater trochanter) and hip (left and right anterior superior iliac spine, left and right posterior superior iliac spine). An additional 2 markers were placed on either end of the barbell. All snatches were recorded using a motion capture system (criterion) (Qualysis Track Manager, QTM v2020.1 Göteborg, Sweden) with 11 infrared cameras in a controlled laboratory environment, capturing at a frequency of 200 hertz (Hz). Competition calibre barbells (15kg for women and 20kg for men) and weight plates were used during testing days (Eleiko, Halmstad, Sweden). The barbell was fitted with an Enode sensor (Enode Pro, Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany) using a barbell sleeve provided by the manufacturer. The placement of the unit was between the right hand and the thigh when in the set position (Figure 4.1). This placement ensured the hip did not contact the device as per company suggestion, whilst also keeping it as close to the barbell centre as possible. Enode data were directly recorded in its native application (Enode Pro version 2.0.2, Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany). The tri-axial acceleration was collected directly by the sensor at a sampling rate of 1000 Hz through a Bluetooth (65 Hz) connection with a tablet (iPad pro, Apple, Silicon Valley, CA, USA). Additionally, the application's synchronized video recording function was used to capture the lifts for visual inspection of the first pull at 60 frames per second. To ensure the knee joint was not obstructed by the weight plates, the iPad camera was place on a tripod at an angle of 45 degrees to the front of the lifter, approximately four meters away and 1 m from the ground.

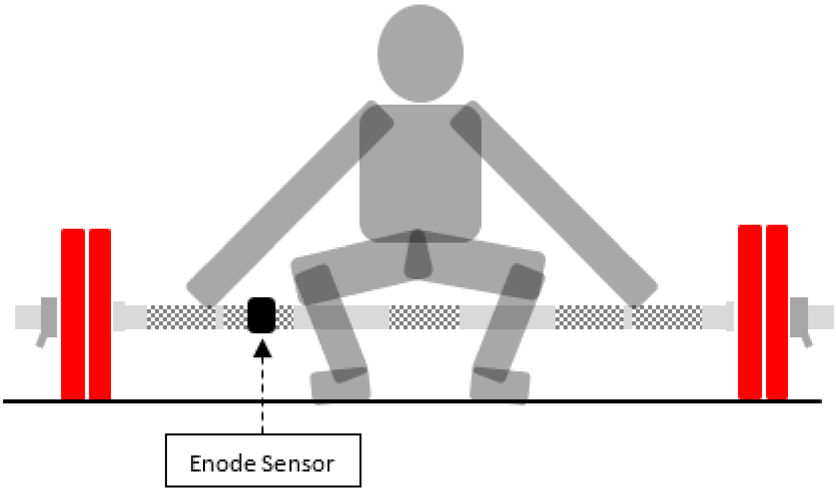


Figure 4.1. Enode placement relative to participant grip width during the set position.

Raw vertical (y) and horizontal (x) displacement data obtained from the reflective markers on the barbell was extracted from Qualysis into Visual 3D (Visual 3D x64, v2023.02.1, C-Motion, Boyds, MD, USA), where knee angle was also calculated. This along with raw left and right barbell y and x displacement data was extracted for analysis in a custom MATLAB script (MATLAB version R2022b) (Appendix 4.2). The raw displacement data was filtered using a low-pass, fourth order Butterworth filter with a cut off frequency of 4 Hz, as determined by residual analysis of 30 randomly selected samples of both left and right vertical barbell displacement (Appendix 4.3). The filtered barbell displacement data was then differentiated twice to obtain vertical velocity and vertical acceleration.

In the next step, lifting phases of the snatch were identified from the Enode and the motion capture system data as follows: 1st pull (lift off to first peak visible (Enode) or objective (criterion) knee extension), transition (first peak knee extension to first peak positive barbell horizontal displacement), 2nd pull (first peak positive barbell horizontal displacement to peak positive vertical barbell velocity), turnover (peak positive vertical barbell velocity to peak negative barbell velocity) and catch (peak negative barbell velocity to deep squat position). It should be noted that the end of the first pull was determined using the first peak knee angle value identified within the MATLAB script, however, as this is not possible using the Enode, the end of the first pull was instead identified when the knee visibly reached its first peak extension, one frame prior to the knee re-bending (Chavda *et al.*, 2021). This subjective method of identification has previously been reported (Sandau *et al.*, 2020). As per communications with the company, the acceleration measured from the Enode is integrated with respect to time and a threshold of 0.005 $\mathrm{m{\cdot}s^{-1}}$ is used to identify the start and end of the snatch movement. Once this threshold is reached, displacement is calculated. This threshold was matched within the motion capture analysis script to allow for comparison. Figures 4.2 and 4.3 displays the variables that were extracted analysed.

The calculation for barbell vertical force and power in the Enode application is as followed, as stated by the company;

Peak Power = (vertical acceleration + 1) × gravity × vertical velocity × mass (1)
Mean Power = vertical velocity × (9.81+vertical velocity/time) × mass (2)
Force = (vertical acceleration+1) × gravity × mass (3)

The script utilised within our methods calculated barbell vertical force and power using the methods adopted from Garhammer (1993);

Force = vertical work / vertical displacement (4)
Power = vertical force × vertical velocity (5)

Where work was calculated as the sum of kinetic and potential energy.

4.2.5. Statistical Analyses

Validity

Relative (compared to criterion) validity was assessed using Lin’s concordance correlation coefficient (CCC) with 95% CI (Lin, 1989) using the average of session 1 and session 2 from each device. Strength-of-agreement criteria for CCC were categorized as poor (CCC < 0.9), moderate (CCC < 0.95), substantial (CCC < 0.99), and almost perfect (CCC ≥ 0.99) (McBride, 2005).

Absolute levels of validity to assess for fixed and proportional bias was done using Passing – Bablok regression (MedCalc, v20.2017). This has previously been identified as an appropriate test to compare methods because it enables measurement error in both the *x* (Enode) and *y* (criterion) variable (Passing and Bablok, 1983). Interpretation of fixed and proportional bias (difference) were determined as follows: if the 95% CI of the intercept contained the value 0, then there was no fixed bias between devices (i.e., no fixed difference between variable A's measurement between the Enode and criterion). If the 95% CI of the slope contained 1 then there was no proportional difference so that no difference (proportional bias) exists between devices (i.e. as variable A's measurement value from the criterion increases, the difference between the measurements obtained by the Enode and criterion remains constant) (Lake *et al.*, 2018). In the instance where significant fixed and/or proportional bias was present, regression equations will be presented to allow for measurement correction. Residual standard deviation (RSD) was also presented to provide the absolute measure of error and was also expressed as a percentage of the Enodes mean.

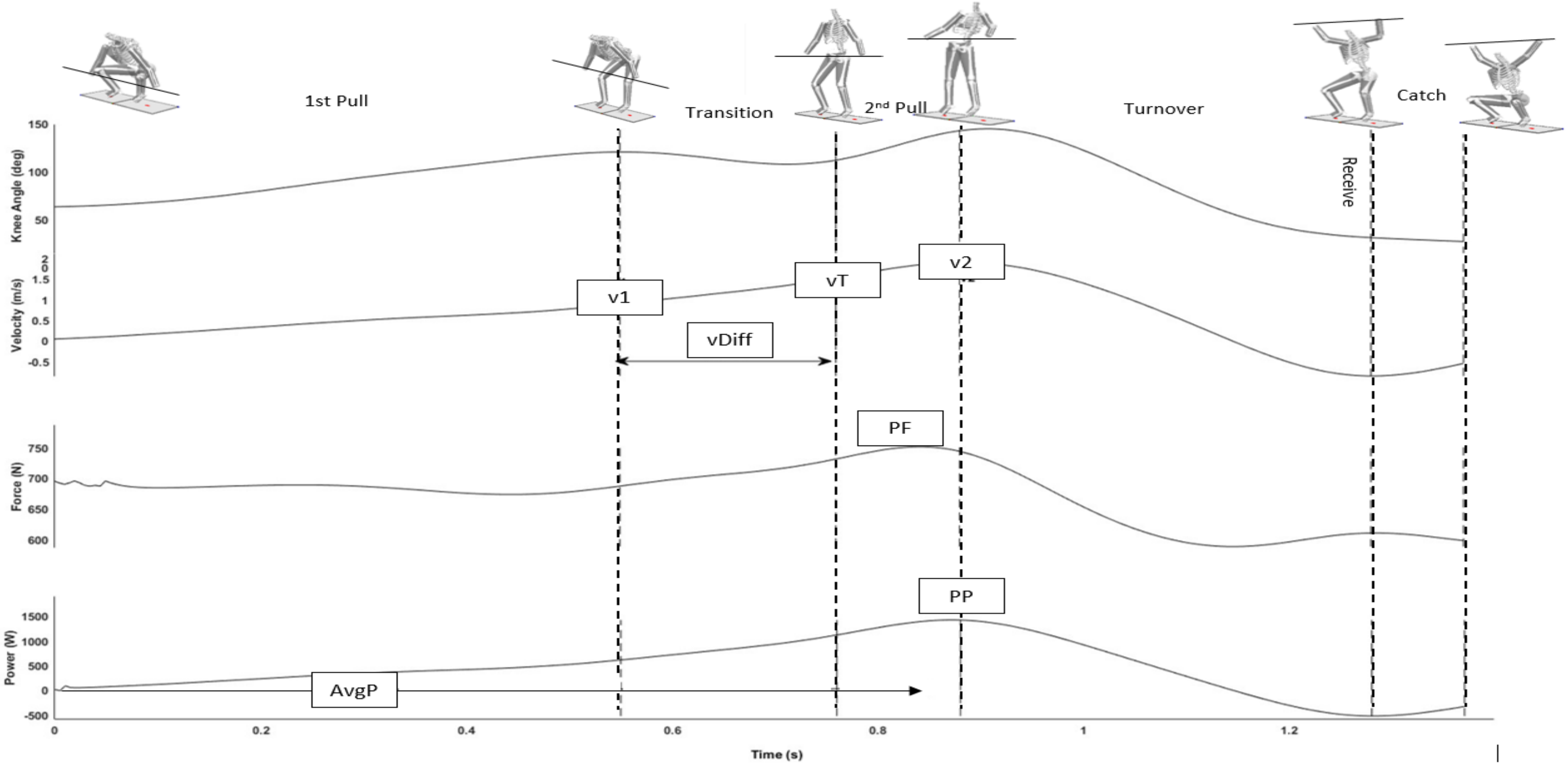


Figure 4.2. Kinematic and kinetic time series displaying discreet variable extrapolations, where v = velocity, 1 = first pull, T = transition, Diff = difference, 2 = second pull, PF = peak force, PP = peak power and AvgP = average power. The arrows distinguish in which phase(s) the data was extrapolated.

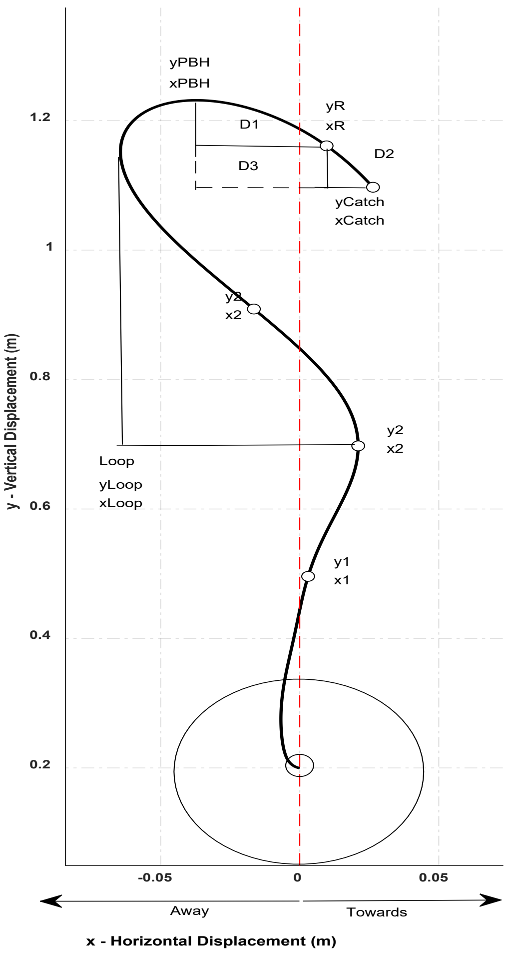


Figure 4.3. Barbell trajectory with identified coordinates extracted for analysis, where x refers to horizontal and y to vertical. 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch and D3 = vertical drop distance between PBH and catch, Loop = displacement between start of second pull and furthest horiztonal displacement. The red line displays a vertical intercept from the start of the lift with "away" and "Towards" identifying direction of the barbell trajectory relative to the athlete.

Reliability

Within and between session reliability of the Enode was assessed using the standard error of measurement (SEM) and Intra Class Correlation Coefficient (ICC; two-way random, absolute agreement) where ICC was determined using MedCalc with SEM calculated in a custom spreadsheet. ICCs were rated based on the guidelines suggested by Koo and Li (2016) using the 95% CI boundary, where discriptors of 'poor' (<0.5), 'moderate' (0.5-0.75), 'good' (0.75-0.9) and 'excellent' (>0.9) were used. Once relative reliability was established, SEM was determined to assess absolute, interunit reliability from the mean of each variable, where SEM is calculated as the product of the SD of the pooled mean values and the square root of 1 minus the ICC (Weir 2005).

$$\text{SEM}=\text{SD}_{\text{pooled}} \times \sqrt{1-ICC} \qquad (6)$$

Using the SEM, the smallest detectable difference (SDD) was calculated as:

$$\text{SDD} = (1.96 \times \sqrt{2}) \times \text{SEM} \qquad (7)$$

In practice, if the difference between two units ± SDD is identified this would indicate that a meaningful change outside of the error of the test-retest has occurred (Bernards *et al.,* 2017). Hedges g effect sizes were also calculated using a custom spreadsheet to analyse both within and between session differences of both the Enode and criterion. The effect size values and descriptors were interpreted using the conventions outlined by Cohen (1988) as; 'trivial' (<0.20), 'small' (0.21-0.50), 'moderate' (0.51-0.80) and 'large' (>0.80).

4.3. RESULTS

Validity

Table 4.1 displays the relative and absolute validity of the Enode. Passing-Bablok regression indicated fixed (yT, x2, xPBH and xLoop) and proportional bias (xT, xR, xCatch and PF) present in some of the variables. A correction for the differences between the Enode and criterion can be applied using the regression formula, using the intercept and slope provided in Table 4.1 (8):

$$\text{Enode(X)\_corrected} = \text{Intercept(X)} + \text{Enode(X)} \times \text{Slope(X)} \qquad (8)$$

Where X stands for the specific parameter (e.g., yT). All other variables displayed no fixed or proportional bias. Relative reliability displayed 95% confidence ranges from poor to near perfect (Figure 4.4). Residual standard deviation percentage displayed the greatest measurement errors within horizontal displacement variables. Collectively this suggests that the Enode is a valid tool in the measurement for some, but not all biomechanical measures of the barbell during the snatch.

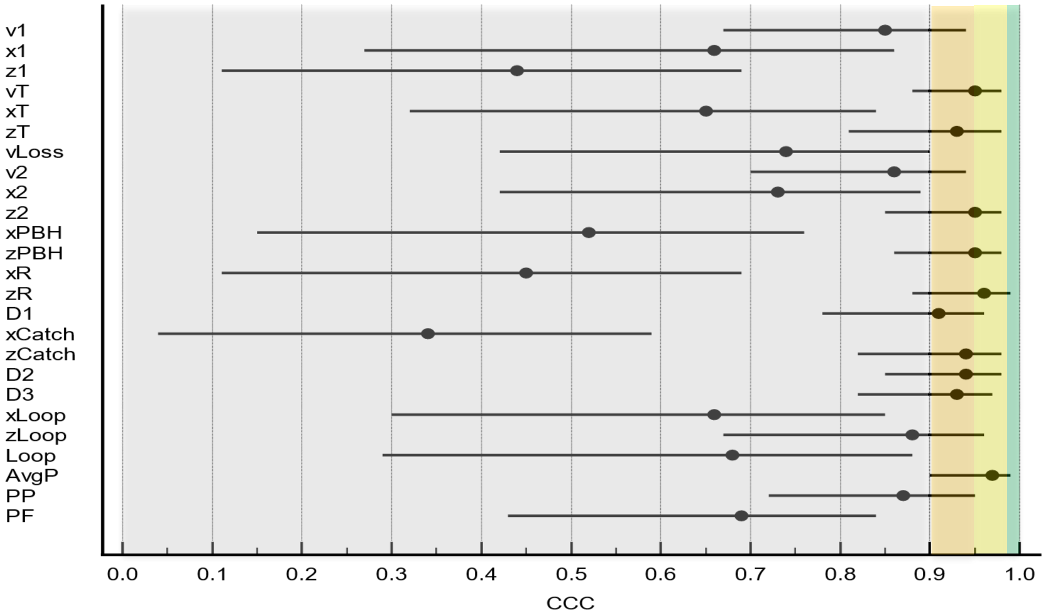


Figure 4.4. Strength of agreement between Enode and 3D criterion using concordance correlation coefficient. Grey = poor (<0.90), orange = moderate (<0.95), yellow substantial (<0.99), green = almost perfect (≥ 0.99)

Table 4.1. Between unit comparison of the Enode and criterion using the average of session 1 and 2.

Phase	Variable	Enode Mean ± SD [95% CI]	3D Criterion Mean ± SD [95% CI]	Intercept [95% CI]	Slope [95% CI]	RSD [95% CI]	RSD (%)
1st pull	v1	1.06 ± 0.18 [0.61-1.52]	1.15 ± 0.2 [0.66-1.65]	-0.01 [-0.2-0.17]	1.1 [0.94-1.29]	0.04 [-0.08-0.08]	4%
	x1	1.94 ± 1.65 [1.11-2.76]	1.04 ± 1.52 [0.6-1.49]	-0.45 [-1.98-0.06]	0.94 [0.64-1.73]	0.88 [-1.73-1.73]	45%
	y1	25.96 ± 4.27 [14.86-37.06]	30.95 ± 4.44 [17.72-44.18]	1.01 [-38.03-14.61]	1.17 [0.61-2.71]	2.48 [-4.86-4.86]	10%
Transition	vT	1.51 ± 0.16 [0.86-2.15]	1.51 ± 0.13 [0.87-2.16]	0.23 [0-0.51]	0.86 [0.67-1]	0.03 [-0.05-0.05]	2%
	xT	**5.3 ± 3.24 [3.04-7.57]**	**3.68 ± 2.18 [2.11-5.26]**	**0.75 [-1.67-1.6]**	**0.63 [0.3-0.99]**	**1.22 [-2.40-2.40]**	**23%**
	yT	***50.33 ± 6.51 [28.81-71.85]***	***51.03 ± 5.59 [29.21-72.84]***	***12.7 [0.68-22.63]***	***0.77 [0.58-1]***	***1.61 [-3.15-3.15]***	***3%***
	vDiff	0.44 ± 0.18 [0.25-0.63]	0.36 ± 0.15 [0.21-0.51]	-0.07 [-0.21-0.10]	0.93 [0.55-1.31]	0.07 [-0.14-0.14]	47%
2nd Pull	v2	2.08 ± 0.16 [1.19-2.97]	2 ± 0.15 [1.15-2.86]	0.07 [-0.35-0.31]	0.93 [0.81-1.12]	0.02 [-0.05-0.05]	1%
	x2	***-0.63 ± 4.85 [-0.36--0.89]***	***-1.81 ± 3.28 [-1.04--2.58]***	***-0.75 [-1.61--1.01]***	***0.67 [0.38-1.22]***	***1.87 [-3.67-3.67]***	***300%***
	y2	81.11 ± 6.33 [46.43-115.79]	79.65 ± 6.24 [45.6-113.71]	1.35 [-15.78-14.23]	0.97 [0.8-1.17]	1.16 [-2.27-2.27]	1%
Turnover	***xPBH***	***3.11 ± 5.53 [1.78-4.44]***	***-0.45 ± 3.68 [-0.26--0.64]***	***-1.96 [-3.66--1.19]***	***0.67 [0.39-1.06]***	***2.53 [-4.97-4.97]***	***81%***
	yPBH	118.62 ± 9.56 [67.91-169.34]	116.42 ± 8.99 [66.65-166.19]	4.88 [-13.71-24.4]	0.94 [0.78-1.09]	1.52 [-2.97-2.97]	1%
Receive	**xR**	**9.07 ± 6.85 [5.19-12.95]**	**3.83 ± 4.22 [2.19-5.47]**	**-0.64 [-3.5-2.03]**	**0.55 [0.28-0.89]**	**2.93 [-5.74-5.74]**	**32%**
	yR	108.66 ± 8.5 [62.2-155.11]	107.75 ± 8.35 [61.69-153.82]	0.88 [-24.82-21.61]	0.99 [0.79-1.23]	1.67 [-3.27-3.27]	2%
Catch	D1	9.96 ± 4.16 [5.7-14.22]	8.66 ± 3.53 [4.96-12.37]	0.22 [-1.85-1.33]	0.83 [0.73-1.09]	0.69 [-1.34-1.34]	7%
	xCatch	**12.2 ± 8.05 [6.98-17.41]**	**5.37 ± 4.26 [3.08-7.67]**	**0.55 [-3.64-3.91]**	**0.43 [0.14-0.8]**	**3.34 [-6.55-6.55]**	**27%**
	yCatch	94.87 ± 8.06 [54.31-135.42]	95.6 ± 8.26 [54.73-136.48]	-6.7 [-88.35-25.04]	1.08 [0.74-1.97]	2.14 [-4.2-4.2]	2%
	D2	13.79 ± 6.05 [7.9-19.69]	12.15 ± 6.15 [6.96-17.35]	-1.93 [-3.57-1.98]	1 [0.78-1.15]	0.99 [-1.94-1.94]	7%
	D3	23.76 ± 9.36 [13.6-33.91]	20.81 ± 8.97 [11.92-29.71]	-1.62 [-5.58-0.8]	0.94 [0.83-1.16]	1.46 [-2.87-2.87]	6%
	xLoop	***-3.26 ± 5.19 [-1.87--4.66]***	***-5.01 ± 3.44 [-2.87--7.15]***	***-2.79 [-4.48--1.18]***	***0.67 [0.32-1.09]***	***2.12 [-4.16-4.16]***	***65%***
	yLoop	101.23 ± 7.96 [57.95-144.5]	101.78 ± 6.98 [58.27-145.3]	19.83 [-29.72-41.07]	0.82 [0.61-1.3]	2.75 [-5.39-5.39]	3%
	Loop	8.67 ± 2.54 [4.96-12.37]	8.69 ± 1.81 [4.98-12.41]	2.47 [-4.78-5.92]	0.72 [0.35-1.61]	1.2 [-2.36-2.36]	14%
Force and Power	AvgP	770 ± 176 [441-1099]	745 ± 176 [427-1064]	-10 [-153.97-63.22]	0.97 [0.86-1.2]	31 [-61-61]	4%
	PP	1799 ± 473 [1030-2569]	1636 ± 372 [937-2336]	157.13 [-147.02-434.16]	0.82 [0.67-1.04]	85 [-166-166]	5%
	PF	**1005 ± 238 [576-1435]**	**838 ± 177 [480-1197]**	**102.32 [-62.44-200.07]**	**0.73 [0.61-0.93]**	**50 [-99-99]**	**5%**

Where SD = standard deviation, CI = confidence interval and RSD = Residual standard deviation. **Bold** *values represent fixed bias with* ***bold italics*** *representing proportional bias.* Where x refers to horizontal, y to vertical and v to vertical velocity ($m \cdot s^{-1}$). 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, vDiff = velocity difference between end of transition and start of second pull (Power position), D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch and D3 = vertical drop distance between PBH and catch, Loop = displacement between start of second pull and furthest horiztonal displacement, AvgP = average power of of pull, PP = peak power, PF = peak force.

Reliability

Given the sample size of 13, it was deemed that the statistical power of for detecting an ICC of 0.75 was 40%. Within session relative reliability showed ICC's ranging from poor to excellent, with trivial to small differences between repetitions for both session 1 (Table 4.2) and session 2 (Table 4.3). Between session reliability showed good to excellent ICC's, with the exception of xCatch which displayed a moderate ICC value of 0.689 [0.048, 0909], with mainly trivial differences displayed between sessions (Table 4.4). Overall, between session reliability was shown to be greater than that of within session reliability.

Table 4.2. Mean and standard deviation for all variables for the Enode, with within-session reliability statistics and Hedges *g* effect size data with 95% confidence intervals.

		Session 1					
		Repetition 1	Repetition 2	ICC	SEM	SDD	Hedges *g*
Phase	Variable	Mean ± SD [95% CI]	Mean ± SD [95% CI]				
1st pull	v1	1.08 ± 0.18 [0.62, 1.54]	1.04 ± 0.20 [0.59, 1.48]	0.940 [0.757, 0.983]	0.00	0.01	0.2 [-0.61, 1.02]
	x1	2.25 ± 2.13 [1.29, 3.21]	1.95 ± 1.76 [1.12, 2.79]	0.667 [0.208, 0.885]	0.08	0.23	0.14 [-0.67, 0.96]
	y1	26.43 ± 5.32 [15.13, 37.73]	26.18 ± 5.00 [14.99, 37.37]	0.871 [0.629, 0.959]	0.05	0.13	0.05 [-0.76, 0.86]
Transition	vT	1.52 ± 0.15 [0.87, 2.16]	1.52 ± 0.20 [0.87, 2.17]	0.727 [0.306, 0.909]	0.00	0.01	-0.04 [-0.85, 0.77]
	xT	5.53 ± 3.75 [3.17, 7.90]	5.52 ± 3.48 [3.16, 7.87]	0.837 [0.544, 0.948]	0.00	0.01	0.00 [-0.81, 0.81]
	yT	50.23 ± 6.62 [28.76, 71.71]	50.97 ± 7.05 [29.18, 72.76]	0.772 [0.407, 0.924]	0.18	0.49	-0.10 [-0.91, 0.71]
	vDiff	0.44 ± 0.20 [0.25, 0.62]	0.48 ± 0.23 [0.28, 0.69]	0.848 [0.587, 0.951]	0.01	0.03	-0.21 [-1.03, 0.60]
2nd Pull	v2	2.08 ± 0.16 [1.19, 2.97]	2.09 ± 0.17 [1.20, 2.98]	0.928 [0.783, 0.977]	0.00	0.00	-0.05 [-0.85, 0.76]
	x2	-0.14 ± 5.11 [-0.08, -0.20]	-0.09 ± 5.27 [-0.05, -0.13]	0.901 [0.705, 0.969]	0.01	0.02	-0.01 [-0.82, 0.80]
	y2	80.85 ± 7.21 [46.29, 115.42]	81.88 ± 6.34 [46.87, 116.88]	0.705 [0.280, 0.900]	0.28	0.77	-0.15 [-0.96, 0.66]
Turnover	xPBH	3.44 ± 5.98 [1.97, 4.91]	4.02 ± 6.98 [2.30, 5.73]	0.756 [0.371, 0.919]	0.14	0.39	-0.09 [-0.90, 0.72]
	yPBH	117.90 ± 10.18 [67.49, 168.31]	118.28 ± 9.79 [67.71, 168.84]	0.766 [0.386, 0.923]	0.09	0.25	-0.04 [-0.85, 0.77]
Receive	xR	9.42 ± 7.90 [5.39, 13.44]	9.74 ± 8.80 [5.57, 13.90]	0.629 [0.124, 0.871]	0.10	0.27	-0.04 [-0.85, 0.77]
	yR	108.09 ± 8.96 [61.88, 154.31]	106.79 ± 9.90 [61.14, 152.45]	0.728 [0.322, 0.908]	0.34	0.94	0.13 [-0.68, 0.94]
Catch	D1	9.81 ± 5.02 [5.61, 14.00]	11.48 ± 5.71 [6.57, 16.39]	0.841 [0.518, 0.950]	0.33	0.93	-0.3 [-1.12, 0.51]
	xCatch	12.62 ± 9.01 [7.23, 18.02]	12.19 ± 12.10 [6.98, 17.40]	0.519 [0.048, 0.827]	0.15	0.41	0.04 [-0.77, 0.85]
	yCatch	95.75 ± 8.96 [54.81, 136.68]	93.85 ± 10.58 [53.73, 133.98]	0.696 [0.271, 0.895]	0.52	1.45	0.19 [-0.62, 1.00]
	D2	12.35 ± 5.00 [7.07, 17.62]	12.94 ± 4.99 [7.41, 18.47]	0.877 [0.654, 0.960]	0.10	0.29	-0.11 [-0.93, 0.70]
	D3	22.15 ± 8.96 [12.68, 31.63]	24.42 ± 9.57 [13.98, 34.86]	0.925 [0.682, 0.979]	0.31	0.86	-0.24 [-1.05, 0.58]
	xLoop	-2.68 ± 5.31 [-1.53, -3.82]	-2.03 ± 6.73 [-1.16, -2.90]	0.822 [0.518, 0.942]	0.14	0.38	-0.10 [-0.91, 0.71]
	yLoop	101.25 ± 8.48 [57.96, 144.53]	100.42 ± 8.69 [57.49, 143.36]	0.584 [0.057, 0.853]	0.27	0.74	0.09 [-0.72, 0.90]
	Loop	8.21 ± 2.64 [4.70, 11.72]	7.95 ± 3.47 [4.55, 11.35]	0.850 [0.583, 0.952]	0.05	0.14	0.08 [-0.73, 0.89]
Force and Power	AvgP (W)	760 ± 177 [435, 1086]	760 ± 175 [435, 1085]	0.990 [0.968, 0.997]	0.01	0.02	0.00 [-0.81, 0.81]
	PP (W)	1781 ± 482 [1019, 2542]	1802 ± 511 [1032, 2572]	0.964 [0.889, 0.989]	2.03	5.63	-0.04 [-0.85, 0.77]
	PF (N)	1000 ± 236 [572, 1427]	1004 ± 248 [575, 1433]	0.985 [0.950, 0.995]	0.25	0.69	-0.02 [-0.83, 0.79]

where x refers to horizontal, y to vertical and v to vertical velocity (m·s^{-1}). 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, vDiff = velocity difference between end of transition and start of second pull (Power position), D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch and D3 = vertical drop distance between PBH and catch, Loop = displacement between start of second pull and furthest horiztonal displacement, AvgP = average power of of pull, PP = peak power, PF = peak force.

Table 4.3. Session 2 mean and standard deviation for all variables for the Enode, with within-session reliability statistics and Hedges *g* effect size data with 95% confidence intervals.

		Session 2					
		Repetition 1	**Repetition 2**	**ICC**	**SEM**	**SDD**	**Hedges g**
Phase	**Variable**	**Mean ± SD [95% CI]**	**Mean ± SD [95% CI]**				
1st pull	v1	1.06 ± 0.17 [0.61-1.52]	1.08 ± 0.2 [0.62-1.54]	0.835 [0.543, 0.947]	0.00	0.01	-0.1 [-0.91, 0.71]
	x1	1.98 ± 2.06 [1.13-2.82]	1.57 ± 2.01 [0.9-2.24]	0.829 [0.546, 0.944]	0.08	0.23	0.2 [-0.62, 1.01]
	y1	25.57 ± 4.19 [14.64-36.5]	25.65 ± 4.52 [14.69-36.62]	0.707 [0.266, 0.901]	0.02	0.06	-0.02 [-0.83, 0.79]
Transition	vT	1.49 ± 0.19 [0.85-2.12]	1.5 ± 0.19 [0.86-2.14]	0.738 [0.329, 0.913]	0.00	0.01	-0.05 [-0.86, 0.76]
	xT	5.52 ± 3.31 [3.16-7.88]	4.65 ± 3.52 [2.66-6.63]	0.836 [0.551, 0.947]	0.18	0.49	0.25 [-0.57, 1.06]
	yT	50.12 ± 7.01 [28.69-71.54]	50 ± 7.28 [28.62-71.37]	0.833 [0.534, 0.946]	0.02	0.07	0.02 [-0.79, 0.83]
	vDiff	0.42 ± 0.19 [0.24-0.6]	0.42 ± 0.15 [0.24-0.6]	0.869 [0.624, 0.958]	0.00	0.00	0.00 [-0.81, 0.81]
2nd Pull	v2	2.07 ± 0.18 [1.18-2.95]	2.09 ± 0.17 [1.2-2.99]	0.950 [0.841, 0.984]	0.00	0.01	-0.11 [-0.92, 0.70]
	x2	-0.38 ± 4.89 [-0.22--0.54]	-1.89 ± 5.34 [-1.08--2.7]	0.831 [0.520, 0.946]	0.31	0.86	0.29 [-0.53, 1.10]
	y2	81.05 ± 6.4 [46.4-115.71]	80.66 ± 7.62 [46.18-115.15]	0.861 [0.606, 0.956]	0.07	0.20	0.05 [-0.76, 0.86]
Turnover	xPBH	3.5 ± 6.46 [2-5]	1.5 ± 6.44 [0.86-2.14]	0.649 [0.206, 0.876]	0.59	1.64	0.30 [-0.51, 1.11]
	yPBH	118.42 ± 10.71 [67.79-169.05]	119.88 ± 10.72 [68.63-171.14]	0.893 [0.696, 0.966]	0.24	0.66	-0.13 [-0.94, 0.68]
Receive	xR	9.42 ± 8.2 [5.39-13.45]	7.7 ± 8.3 [4.41-10.99]	0.630 [0.156, 0.870]	0.52	1.45	0.20 [-0.61, 1.01]
	yR	108.84 ± 10.95 [62.31-155.37]	110.91 ± 10.21 [63.49-158.32]	0.760 [0.398, 0.919]	0.51	1.41	-0.19 [-1.00, 0.62]
Catch	D1	9.58 ± 5.34 [5.49-13.68]	8.98 ± 2.71 [5.14-12.81]	0.504 [0.057, 0.819]	0.21	0.59	0.14 [-0.67, 0.95]
	xCatch	13.02 ± 10.04 [7.46-18.59]	10.95 ± 10.61 [6.27-15.63]	0.613 [0.125, 0.863]	0.64	1.78	0.19 [-0.62, 1.01]
	yCatch	93.81 ± 7.86 [53.7-133.91]	96.05 ± 9.96 [54.99-137.12]	0.798 [0.477, 0.933]	0.50	1.40	-0.24 [-1.05, 0.57]
	D2	15.03 ± 8.67 [8.6-21.46]	14.85 ± 6.64 [8.5-21.2]	0.870 [0.625, 0.959]	0.03	0.09	0.02 [-0.79, 0.83]
	D3	24.62 ± 10.8 [14.09-35.14]	23.83 ± 9.05 [13.64-34.02]	0.962 [0.884, 0.988]	0.08	0.21	0.08 [-0.73, 0.89]
	xLoop	-3.22 ± 5.29 [-1.85--4.6]	-5.12 ± 5.76 [-2.93--7.3]	0.754 [0.374, 0.918]	0.47	1.31	0.33 [-0.48, 1.15]
	yLoop	100.89 ± 8.43 [57.76-144.03]	102.34 ± 10.48 [58.59-146.09]	0.835 [0.558, 0.946]	0.29	0.82	-0.15 [-0.96, 0.66]
	Loop	8.75 ± 2.59 [5.01-12.49]	9.76 ± 2.88 [5.59-13.93]	0.702 [0.287, 0.898]	0.28	0.76	-0.36 [-1.17, 0.46]
Force and Power	AvgP (W)	772 ± 183 [442 -1102]	785 ± 176 [450 -1121]	0.975 [0.924, 0.992]	1.03	2.85	-0.07 [-0.88, 0.74]
	PP (W)	1800 ± 476 [1031-2570]	1814 ± 443 [1039-2590]	0.968 [0.898, 0.990]	1.25	3.47	-0.03 [-0.84, 0.78]
	PF (N)	1014 ± 244 [580-1447]	1004 ± 234 [575-1433]	0.968 [0.902, 0.990]	0.89	2.48	0.04 [-0.77, 0.85]

where x refers to horizontal, y to vertical and v to vertical velocity ($m{\cdot}s^{-1}$). 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, vDiff = velocity difference between end of transition and start of second pull (Power position), D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch and D3 = vertical drop distance between PBH and catch, Loop = displacement between start of second pull and furthest horiztonal displacement, AvgP = average power of of pull, PP = peak power, PF = peak force.

Table 4.4. Between sessions mean and standard deviation for all variables for the Enode, with between-session reliability statistics and Hedges *g* effect size data with 95% confidence intervals.

Phase	Variable	Session 1 Mean ± SD [95% CI]	Session 2 Mean ± SD [95% CI]	ICC	SEM	SDD	Hedges g
1st pull	v1	1.06 ± 0.19 [0.61-1.51]	1.07 ± 0.18 [0.61-1.53]	0.917 [0.727, 0.975]	0.00	0.00	-0.05 [-0.86, 0.76]
	x1	2.1 ± 1.78 [1.2-3]	1.77 ± 1.95 [1.02-2.53]	0.732 [0.115, 0.918]	0.09	0.24	0.17 [-0.64, 0.98]
	y1	26.3 ± 4.98 [15.06-37.55]	25.61 ± 4.01 [14.66-36.56]	0.881 [0.620, 0.963]	0.12	0.33	0.15 [-0.66, 0.96]
Transition	vT	1.52 ± 0.16 [0.87-2.17]	1.49 ± 0.18 [0.85-2.13]	0.942 [0.816, 0.982]	0.00	0.01	0.17 [-0.64, 0.98]
	xT	5.52 ± 3.45 [3.16-7.88]	5.08 ± 3.29 [2.91-7.26]	0.919 [0.741, 0.975]	0.06	0.17	0.13 [-0.68, 0.94]
	yT	50.6 ± 6.42 [28.97-72.23]	50.06 ± 6.82 [28.66-71.46]	0.966 [0.890, 0.989]	0.05	0.14	0.08 [-0.73, 0.89]
	vDiff	0.46 ± 0.21 [0.26-0.66]	0.42 ± 0.17 [0.24-0.6]	0.862 [0.565, 0.957]	0.01	0.02	0.20 [-0.61, 1.01]
2nd Pull	v2	2.09 ± 0.16 [1.19-2.98]	2.08 ± 0.17 [1.19-2.97]	0.954 [0.850, 0.986]	0.00	0.00	0.06 [-0.75, 0.87]
	x2	-0.12 ± 5.05 [-0.07--0.16]	-1.13 ± 4.93 [-0.65--1.62]	0.937 [0.797, 0.981]	0.13	0.35	0.20 [-0.62, 1.01]
	y2	81.37 ± 6.25 [46.58-116.15]	80.86 ± 6.77 [46.29-115.43]	0.943 [0.817, 0.983]	0.06	0.17	0.08 [-0.73, 0.89]
Turnover	xPBH	3.73 ± 6.07 [2.13-5.32]	2.5 ± 5.88 [1.43-3.57]	0.834 [0.474, 0.949]	0.25	0.69	0.20 [-0.61, 1.01]
	yPBH	118.09 ± 9.35 [67.6-168.58]	119.15 ± 10.42 [68.21-170.1]	0.930 [0.777, 0.979]	0.14	0.39	-0.10 [-0.91, 0.71]
Receive	xR	9.58 ± 7.5 [5.48-13.67]	8.56 ± 7.44 [4.9-12.22]	0.818 [0.403, 0.945]	0.22	0.60	0.13 [-0.68, 0.94]
	yR	107.44 ± 8.75 [61.51-153.38]	109.87 ± 9.93 [62.9-156.85]	0.785 [0.324, 0.933]	0.56	1.56	-0.25 [-1.06, 0.56]
Catch	D1	10.65 ± 5.2 [6.09-15.2]	9.28 ± 3.65 [5.31-13.25]	0.825 [0.456, 0.946]	0.29	0.80	0.30 [-0.52, 1.11]
	xCatch	12.41 ± 9.23 [7.1-17.71]	11.98 ± 9.25 [6.86-17.11]	0.698 [0.048, 0.909]	0.12	0.33	0.05 [-0.76, 0.85]
	yCatch	94.8 ± 9.02 [54.27-135.33]	94.93 ± 8.53 [54.34-135.52]	0.826 [0.412, 0.948]	0.03	0.08	-0.01 [-0.82, 0.80]
	D2	12.64 ± 4.84 [7.24-18.05]	14.94 ± 7.45 [8.55-21.33]	0.897 [0.599, 0.970]	0.37	1.02	-0.35 [-1.17, 0.46]
	D3	23.29 ± 9.15 [13.33-33.25]	24.22 ± 9.87 [13.87-34.58]	0.966 [0.894, 0.99]	0.09	0.24	-0.09 [-0.9, 0.72]
	xLoop	-2.35 ± 5.77 [-1.35--3.36]	-4.17 ± 5.22 [-2.39--5.95]	0.862 [0.555, 0.958]	0.34	0.94	0.32 [-0.49, 1.14]
	yLoop	100.83 ± 7.6 [57.72-143.94]	101.62 ± 9.11 [58.17-145.06]	0.894 [0.655, 0.968]	0.13	0.36	-0.09 [-0.90, 0.72]
	Loop	8.08 ± 2.96 [4.62-11.53]	9.25 ± 2.55 [5.3-13.21]	0.787 [0.332, 0.934]	0.27	0.75	-0.41 [-1.23, 0.41]
Force and Power	AvgP (W)	760 ± 176 [435-1086]	779 ± 178 [446-1112]	0.986 [0.952, 0.996]	1.10	3.05	-0.10 [-0.91, 0.71]
	PP (W)	1791 ± 492 [1025-2557]	1807 ± 456 [1035-2580]	0.993 [0.978, 0.998]	0.66	1.84	-0.03 [-0.84, 0.78]
	PF (N)	1002 ± 241 [574-1430]	1009 ± 237 [578-1440]	0.997 [0.989, 0.999]	0.20	0.57	-0.03 [-0.84, 0.78]

where x refers to horizontal, y to vertical and v to vertical velocity (m$\cdot$s^{-1}). 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, vDiff = velocity difference between end of transition and start of second pull (Power position), D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch and D3 = vertical drop distance between PBH and catch, Loop = displacement between start of second pull and furthest horiztonal displacement, AvgP = average power of of pull, PP = peak power, PF = peak force.

4.4. DISCUSSION

The primary aim of this investigation was to assess the validity and reliability of a commercially available IMU (Enode) to measure barbell kinematics and kinetics during the snatch. The results showed that the Enode was valid and reliable for most variables, but often overestimated horizontal displacement related data of which all associated measures, excluding x1 displayed either fixed or proportional bias. These findings are important, because to the authors' knowledge this is the first study to establish validity and reliability of the Enode for the snatch and associated variables which have previously been identified as measures of technique. Furthermore, our findings indicate that the Enode may be an affordable and accessible option to help coaches monitor weightlifting technique in the snatch, particularly between sessions, providing an accessible method that does not rely on laboratory or bespoke motion capture systems.

While this may be the first study to investigate the validity and reliability of the Enode within the context of weightlifting, it has previously been studied for its validity and reliability across various lower body ballistic and non-ballistic movements, such as, squatting (Feuerbacher *et al*., 2023; Dragutinovic *et al*., 2023; Olaya-Cuartero *et al*., 2022; Fritschi *et al*., 2021; Held *et al*., 2021; Menrad and Nusser, 2021), jumping (Villalon-Gasch *et al*., 2023; Fritschi *et al.,* 2021; Jimenez-Olmedo *et al*., 2023), and the hang power snatch (Fritschi *et al*., 2021). The two primary variables extracted for comparison against 3D motion capture criterion has been mean and peak velocity. In the present study, peak velocity (and instantaneous end of phase velocity; v1, vT and v2) was extracted for analysis given it is important within weightlifting type exercises, as it provides an indication as to whether the barbell will be displaced at a high enough point for the athlete to receive it. Only one study to date has attempted to assess the validity and reliability of the Enode during a weightlifting derivative (Fritschi *et al*., 2021). This study showed that Enode peak velocity demonstrated proportional bias, but these data had been pooled across different, ballistic and non-ballistic exercises so should be interpreted with caution (Fritschi *et al*., 2021). Additionally, the aforementioned authors only used a 20 kg barbell for the hang power snatch, which may likely incur a longer active deceleration following the second pull, which may account for the systematic underestimation of mean velocity across all devices.

A potential consideration around unit validity vs. criterion is the placement of the unit with respect to the barbell. Ideally, a marker would be placed directly on the unit, however, pilot data from the authors detected inaccuracies in horizontal and vertical displacement of the marker due to the rotation of the barbell. As displacement measures were also assessed for validity and reliability, it was deemed appropriate to compare the Enode to the calculated barbell centre of mass (CoM), taken as the average of the two barbell end markers. The present study placed the Enode between the grip of the athlete and their thigh during the set position, as close to the centre of the barbell as physically possible. This was chosen as to i) avoid sensor and athlete contact, and ii) being a position that is repeatable for each individual based on their preferred snatch grip. Fritschi and colleagues (2021) reported similar findings to ours, where peak velocity standard error of estimate was 0.03 m/s when compared to that of barbell CoM velocity determined by criterion. These findings collectively suggest that the placement of Enode anywhere within the barbell collar would enable an accurate representation of barbell CoM peak velocity. This is an important finding to highlight given that the barbell will flex during heavy lifts and it is posited that peak velocity of barbell end relative to centre can display a 5-30% difference within the clean (Chiu *et al*., 2008), although this may likely be less for the snatch due to the lower loads and wider grip, thus creating less barbell deformation. Practically, this highlights that in some situations the Enode may potentially be a better option than traditional video analysis where viewing angle and barbell deformation may affect the outputs generated (Chiu *et al*., 2008).

It is worth noting that velocity identified at the end of each key phase of the lift (1st pull, transition and 2nd pull) measured by the Enode, showed excellent within and between session reliability, with SEM's of 0.00 m/s and SDD values no greater than 0.01 m/s. The current results are supported with the findings from Sandau and colleagues (2023) who found that, in elite German weightlifters, the variability (as measured by SEM) of vertical velocity at the end of each lifting phase is smaller than within time series measured phases. This may suggest that weightlifters utilise varied strategies between phases to elicit similar outcomes at the end of each phase, thus leading to discreet measures of velocity being highly reliable. Furthermore, Sandau (2023) also reported that the transition phase carried the greatest variability, relative to all other end of phase velocities. The relevance of obtaining velocity at the end of each phase is its potential use for identifying the key limiting phase within the lift using a load-velocity profile. A study on elite German weightlifters by Sandau and Granacher (2020) reported that a regression slope with the greatest negative value plotted across ascending loads could help identify the phase where the greatest loss of velocity occurs between each phase. Their study utilised a previously validated bespoke video capture software (Sandau, Jentsch and Bunk, 2019), which is in-accessible to most coaches. Along with the present findings, the implementation of the load-velocity profiling methods presented by Sandau and Granacher (2020) to identify limitations in technique, can now be widely adopted utilising a commercial IMU sensor.

While velocity is often the focal point of assessment, with the emergence of new technologies, a novel aspect of this investigation was to also assess vertical and horizontal displacements which are commonly reported within weightlifting analysis research (Musser et al., 2014; Stone et al., 1995; Isaka, Okada and Funato., 1996). Our results indicate that the Enode typically overestimates horizontal displacement with fixed or proportional bias, with large levels of variability present. Interestingly, the present findings seem to report similar SEM's to those presented by Sandau, Langen and Nitzsche (2023) even though different devices were used to capture these data in these studies. These are important findings, as it has been posited that horizontal displacement and its associated measures, such as loop of the barbell, are key factors between successful and unsuccessful attempts in the snatch (Stone *et al.,* 1998). Conceptually this makes sense, as the further the bar is from the applied centre of pressure and CoM, the greater difficulty the athlete will have applying the necessary forces to accelerate the barbell (Chavda *et al.,* 2021). However, it should be noted that the extremely large variability observed in measures of horizontal displacement means it should not be used to monitor technical changes as the present findings suggests and we would therefore suggest it is simply used as a heuristic within the coaching environment.

While this study has provided some practically useful results, it is not without its limitations. Firstly, only 85% of 1RM snatch was analysed. Although a commonly utilised intensity, particularly during heavier periods of training, it is not uncommon for loads to be used between 70 and 90% (Medvedyev, 1989), therefore the variability reported in the current study could change with load. This is highlighted by Sandau, Lanen and Nitzsche (2023), who compared the reliability of various barbell waveforms (displacement, velocity and acceleration) at 85% and 97% in elite German weightlifters. Their findings indicate that the trial to trial variability at submaximal intensities were greater than that of near maximum, suggesting submaximal loads may require less precision to achieve the intended outcome compared to maximal intensities. This highlights that future research may wish to investigate differences in waveforms or discreet measures of displacement, velocity and acceleration across varying loads to better understand the variability exhibited at a range of loads. This would help highlight which phase(s) of the lift are potential limiting factors that need addressing as heavier loads are lifted.

Although the practicality of the Enode holds high ecological validity within training, it is less useful in competition as nothing is allowed to be attached to the barbell. This is where video capture has a distinct advantage, although one must consider the utility of video cameras in a training environment along with appropriate software against a commercial IMU system. In the same instance, both methods would require standardised methods of identifying the key phases of the lift. The present study utilised changes in knee joint angle, objectively identified in the criterion analysis. However, this was not possible using the video captured by the Enode's native application. Therefore, some discrepancies within and between raters must also be investigated to ensure consistency in manual phase identification. Lastly, it should be noted that the Enode integrates acceleration collected from the accelerometer, this method of derivation differs from the criterion which collects the co-ordinates of each marker, which provides displacement. This displacement is then differentiated to obtain velocity and acceleration. It is unlikely that this would contribute to large differences between methods, however, signal noise is often attenuated when integrating acceleration (Lake *et al.,* 2019) and with small SEM's presented in the current investigation, this can not be discounted if utilising any of the proposed measures for monitoring purposes. A key limitation of this study was the low statistical power of 40%. Inherently this maybe a common issue within individual sports and therefore the application of these findings should be interpreted with some caution when applying them to population outside of those presented in the current study. Therefore, future research may consider looking into the within and between session reliability in novice or more experienced weightlifters and to investigate change in the mechanical measures of the barbell following longitudinal intervention.

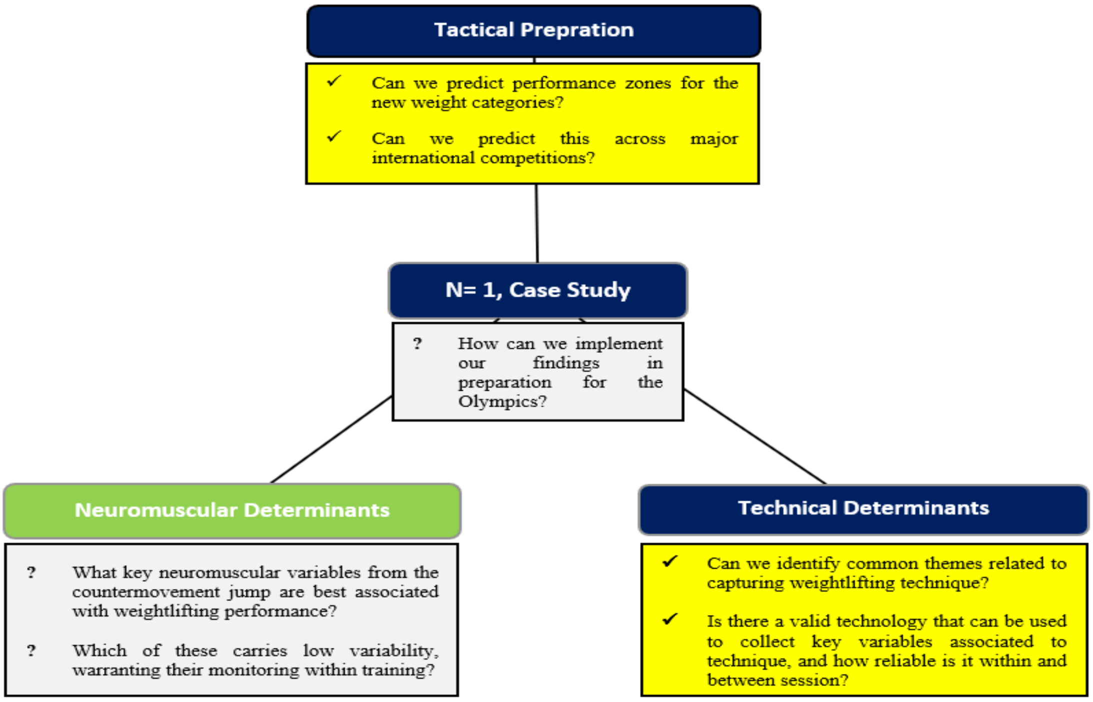
4.5. PRACTICAL APPLICATIONS

This study confirms the validity of the Enode and its software in the measure of barbell mechanics during the snatch. The Enode provides both valid and reliable measures of velocity and vertical displacements, with a majority of bias and variance occurring in measures of horizontal displacement. It is important to understand the use of technique analytics must not interfere with the natural ecology of the training environment and that selecting certain times to obtain data is likely more useful and less resource intensive than collecting data day to day. Additionally, given that within day variability was generally greater than between session variability, identifying key points within the training cycle to measure changes in technique over time (between sessions) would pay greater dividends than monitoring within session (between repetitions). Coaches interested in analysing and tracking the metrics that the current study shows to be reliable and valid in a training environment could use the Enode device with confidence, although we would urge some caution when loads different to those considered in the current study are used.

CHAPTER 5: STUDY 4 - NEUROMUSCULAR DETERMINANTS OF WEIGHTLIFTING PERFORMANCE.

Chavda, S., Lake, J. P., Comfort, P., Bishop, C., Joffe, S. A., & Turner, A. N. (2023).
Relationship between kinetic and kinematic measures of the countermovement jump and
national weightlifting performance. *Journal of Science in Sport and Exercise*, 1-13.
(Chapter 5)

It becomes apparent from chapter 3 that the technical execution of weightlifting movements has been extensively studied, but often utilising a range of methods to identify specific phases of the lift. A common theme within the literature suggests the importance of the pull where the knees extend, flex and extend again. This subsequently accelerates the bar and projects it to a height allowing the athlete to catch. Given that weightlifting success is determined by the most amount of load lifted, along with technical proficiency it also highlights the need for high levels of ballisitic neuromuscular ability. Since we have identified a valid and reliable method in capturing and monitoring technical information, investigation into the neuromuscular determinants of weightlifting performance is warranted. Therefore, chapter 5 will investigate a commonly used surrogate measure of weightlifting, the countermovement jump. This provides a highly efficient, low fatiguing method of understanding force characteristic changes that may be worth monitoring between training blocks.



5.1 INTRODUCTION

Weightlifting can be characterised as an athlete's ability to express their force generating capabilities within the technical constraints of the snatch and clean and jerk. This force is transferred to the barbell, displacing it from the floor to the shoulder during the clean, or directly overhead during the snatch (Garhammer and Gregor, 1992; Joffe and Tallent, 2020). To achieve this with the greatest load possible, the athlete must develop momentum of the system (bodyweight + barbell) throughout the 'pull'. This phase of the lift is of particular interest as it consists of vertical propulsion of the system which determines the vertical displacement of the barbell in the subsequent (turnover) phase. The pull can be divided into the first pull, transition, and second pull (Figure 5.1). Temporal kinetics of the weightlifting pull typically display impulses (the area under the force time curve) more than system weight for the first and second pull with a transition phase between the two. The transition phase often shows an impulse less than system weight (Enoka, 1979; Sorensen *et al.*, 2022), highlighting that this phase may not increase the momentum of the system.

During the first pull, the athlete is required to generate enough vertical ground reaction force (vGRF) to overcome the barbell inertia. This phase is marked by a longer duration but less force than the second pull, indicating a more gradual and sustained application of impulse (0.632 ± 0.10 s vs 0.156 ± 0.03 s, snatch; 0.640 ± 0.18 s vs 0.127 ± 0.34 s, clean) (Kauhanen, Häkkinen and Komi, 1984; Korkmaz and Harbili, 2015). The transition phase is characterised by a flexion of the knees to reposition the body, which consequently reduces the impulse applied into the floor, which can result in a plateau or decrease in barbell velocity (Bartonietz, 1996; Enoka, 1979; Isaka, Okada and Funato, 1996). This is an undesirable consequence as it requires more energy to re-accelerate the barbell. To overcome this and to facilitate proper vertical displacement of the barbell, it is necessary to apply a greater impulse to the floor during the second pull within the technical time constraints of the phase (snatch 0.14 and clean 0.19, respectively) (Gourgoulis *et al.,* 2009; Chiu *et al.*, 2008). It has previously been reported that as barbell load increases, there is a concurrent increase in both peak vGRF and knee extension torque during the second pull (Baumann *et al.*, 1988; Kipp *et al.*, 2012; Liu *et al.*, 2018). The increase in force and lower body joint torque exhibited during the second pull can be considered a key factor in increasing the athlete's ability to displace a heavier load to a height sufficient enough for them to catch it, and is therefore often a key focal point of weightlifting literature (Baumann *et al.*, 1988). However, it should be stated that the cumulative impulse generated from the entire pull (first and second pull) will ultimately determine the athlete's ability to generate sufficient force to accelerate the barbell.

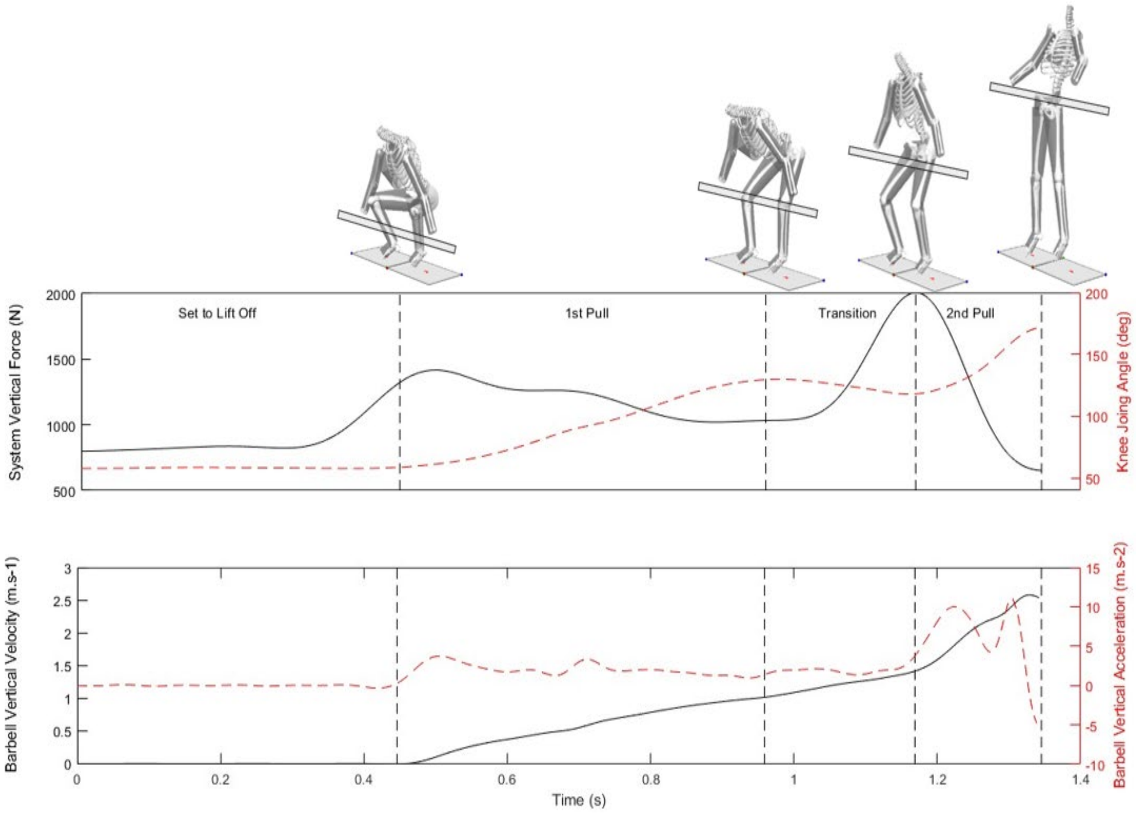


Figure 5.1. System, joint and barbell kinetics and kinematic of the pull during a snatch.

Given the importance of force production characteristics and the semi-ballistic nature of weightlifting, it is of no surprise that surrogate measures (e.g., isometric peak force, jump height, jump peak power) of weightlifting performance have been used to identify relevant relationships to performance (Carlock *et al*., 2004; Haff *et al*., 2005; Ince and Ulupinar, 2020; Joffe *et al*., 2022; Khaled, 2013; Stone *et al*., 2005) as well as to monitor changes in weightlifting performance over time (Hornsby *et al*., 2017; Joffe and Tallent, 2020). Such assessments can help practitioners evaluate the neuromuscular function of the athlete using performance tests, which share common kinetic and kinematic traits to the snatch and clean and jerk, therefore reducing the need to perform maximal lifts during specific training periods, while also providing information on physical qualities that underpin maximal weightlifting performance.

Ince and Ulupinar (2020), Khaled (2013), and Kite and Spence (2017) have used the Wingate test power output, isokinetic knee extension torque, hand grip force, standing broad jump distance, medicine ball throw for distance, and 800 m running time to assess their relationship to weightlifting performance. While these tests are easy to administer with singular outcome measures, they offer little insight into force generating capabilities and have little biomechanical similarities to weightlifting. The increased accessibility to force plates and the opportunity to better inform practitioners about force generating capabilities may explain why the isometric mid-thigh pull (IMTP) and the countermovement jump (CMJ) are common tests for weightlifting monitoring and assessment (Garhammer and Gregor, 1992; Haff *et al*., 2005; Hornsby *et al*., 2017; Joffe and Tallent, 2020; Joffe *et al*., 2022; Stone *et al*., 2005). The IMTP is a common method of assessing maximal and rapid force generating capabilities and has been investigated extensively within weightlifting research, with measures such as peak force (PF), rate of force development (RFD), and force at specific time points shown to have moderate to near perfect relationships to absolute, allometric, and ratio scaled weightlifting performance (r = 0.58 - 0.93) (Haff *et al*., 2005; Hornsby *et al*., 2017; Joffe and Tallent, 2020). However, while the IMTP has been extensively researched and utilised, the dissection of CMJ force-time characteristics in relation to weightlifting performance is far more limited.

Force-time characteristics displayed by the CMJ are similar to those observed in the transition phase to the end of the second pull (Garhammer and Gregor, 1992), particularly when lifting from the end of first pull (hang position). The force-time curve of the CMJ also shares similarities with the dip and drive phase of the jerk (Cushion *et al*., 2016), due to the temporal kinematic similarities across the hips, knees and ankles. While these similarities exist, prior researchers have often used the CMJ to provide proxy measures of lower body neuromuscular function, often reporting measures such as jump height, peak power, and peak force (Carlock *et al*., 2004; Fry *et al*., 2003; Haff *et al*., 2005; Hornsby *et al*., 2017; Joffe and Tallent, 2020). While these measures have been shown to be positively related to weightlifting performance (r = 0.59 – 0.93), they offer little insight into the strategies adopted during vertical jumping, nor do they provide sufficient information about the athlete's force generating capabilities within the discrete phases of the CMJ. Furthermore, the utility of CMJ metrics such as peak power and its relationship to performance has been questioned, with previous researchers suggesting that practitioners should prioritize metrics such as impulse (Ruddock and Winter, 2016). Given that jump height is dictated by relative net impulse applied to the ground (Winter, 2005), and weightlifting is a strength sport, which is also determined by net impulse, information relating to jump strategies (including but not limited to impulse) may enable practitioners to further explore whether temporal CMJ metrics can help explain weightlifting performance, while concurrently providing more insight into changes of force capabilities following training.

While research have shown relationships between weightlifting performance (WLp) and surrogate measures of neuromuscular performance (Carlock *et al*., 2004; Fry *et al*., 2003; Haff *et al*., 2005; Hornsby *et al*., 2017; Ince and Ulupinar, 2020; Joffe and Tallent, 2020; Joffe *et al*., 2023; Khaled, 2013; Kite and Spence, 2017; Stone *et al.,* 2005), these have often been in low sample sizes < 10, or have not explored information underpinning movement strategy, particularly for the CMJ. Therefore, to gain a deeper understanding into the relationship between the CMJ and weightlifting performance, the aims of this investigation were to establish the relationship between those CMJ strategy metrics that showed good reliability and relationship to weightlifting performance. It was hypothesized that metrics pertaining to the propulsive phase of the CMJ would be best related to WLp.

5.2 METHODS

5.2.1. Experimental Approach to the Problem

A Spearman's Rho, bivariate correlation was used to determine the relationship between WLp and CMJ kinetic and kinematics of national and international weightlifters. Counter movement jump, snatch (SN), clean and jerk (CJ) and total (TOT) were obtained at a national and international competition. A range of temporal kinetic (i.e., impulse, peak force) and kinematic (i.e., jump height, power) metrics were calculated from CMJ force-time data to help identify the best surrogate measure of weightlifting performance.

5.2.2. Participants

A total of 42 weightlifting athletes, 30 females and 12 males, that compete between national and international level, were recruited for this study. Participants were recruited across two major events in the British Weight Lifting competition calendar of 2019: the English Championship and the British International Open; the latter being a bronze qualifying event for the Tokyo 2020 Olympic games. Therefore, it can be assumed that each athlete would have been in peak physical condition at the point of data collection. All participants were over the age of 18 and provided consent during the sign up for the competition. Ethics was granted via the London Sport Institute ethics committee (#7811) (Appendix 5.1).

5.2.3. Procedures

Athlete Characteristics. A standard method of weigh-in was conducted as per competition rules set by the International Weightlifting Federation (IWF) by qualified technical officials. The athletes were weighed to the nearest hundredth of a kilogram (kg) on a digital scale (SECA 899, Hamburg, Germany) with minimal clothing. Following the weigh-in, athletes were measured for standing height (Ht) to the nearest centimetre (cm). Standing height was measured with the athlete standing in a stadiometer (Seca, Birmingham, United Kingdom) with the feet parallel to one-another.

Physical Performance Data. Following the competition, athletes were invited to participate in the CMJ. This was to ensure that the testing did not interfere in their preparation for competition. Every effort was made to ensure that athletes had sufficient recovery prior to the CMJ test, with self-selected periods between competition and testing being approximately 1-hour. Prior to testing, athletes were given a self-selected time to perform a general warm up, which typically consisted of dynamic stretches of the lower body followed by 2-3 submaximal jumps on the force plate to familiarise themselves with taking off and landing on the force plate, with hands on hips.

Countermovement Jump. The CMJ was performed on a portable force plate (Kistler 9286, Winterhur, Switzerland) sampling at 1,000 Hz. Athletes were asked to stand as still as possible on the force plate, with arms akimbo, for a minimum of 1 second, before they were instructed to jump as high as possible whilst keeping their hands on their hips (Chavda *et al.*, 2018). Once the athlete was ready, they were asked to perform 2 maximal CMJ's interspersed with ~1-minute rest between trials. All raw force-time data were extracted for analysis in a custom spreadsheet (Chavda *et al.,* 2018). Definitions of the extracted metrics can be found in in Table 5.1. Figure 5.2 and 5.3 is representative of a force and velocity-time (Figure 5.2) and power-time curve (Figure 5.3) with the unweighting, braking, and propulsion phases identified.

Table 5.1. Countermovement Jump metric definition and abbreviations.

Variable	Abbreviation	Unit	Definition
Jump Height	JH	m	Displacement of athletes centre of mass calculated as: ½ (Tov^2 / 9.81)
Reactive Strength Index Modified	RSI^{mod}	-	Jump height / Time to take off
Peak Force	PF	N	Peak net propulsive force value
Relative Peak Force	^{rel}PF	N/kg	Peak net force value / athletes body mass
Allometric Peak Force	^{allo}PF	N$^{\wedge 0.67}$	Peak net force value to the exponent of 0.67
Braking Impulse		N.s	Change in force * time from minimum velocity to 0 velocity.
Braking Impulse Duration		s	Duration of above
Propulsive Impulse		N.s	Change in force * time from 0 velocity to take off
Propulsive Impulse Duration		s	Duration of above
Average Propulsive Force	AvgPropF	N	Average force applied during propulsive phase.
Peak Power	PP	W	Peak power value
Relative Peak Power	^{rel}PP	W/kg	Peak power value / athletes body mass
Allometric Peak Power	^{allo}PP	W$^{\wedge 0.67}$	Peak power value to the exponent of 0.67
Braking Average Power	BrkAvgP	W	Average power produced during the braking phase
Propulsive Average Power	PropAvgP	W	Average power produced during the propulsive phase

where the braking phase is identified as minimum velocity to 0 velocity and propulsive phase is defined as 0 velcocity (end of braking phase) to take off.

Competition Performance. Competition performance was recorded as the heaviest successful SN and CJ, and therefore TOT. Official results were taken from the British Weightlifting website for each of the competitions (accessed: 26/01/2019 and 20/04/2019, respectively). Competition performance was taken as absolute (^{abs}WLp), relative to bodyweight (^{rel}WLp), relative to weight category (^{cat}WLP), and allometrically scaled (^{allo}WLp) to the exponent of 0.67 (Batterham and George, 1997).

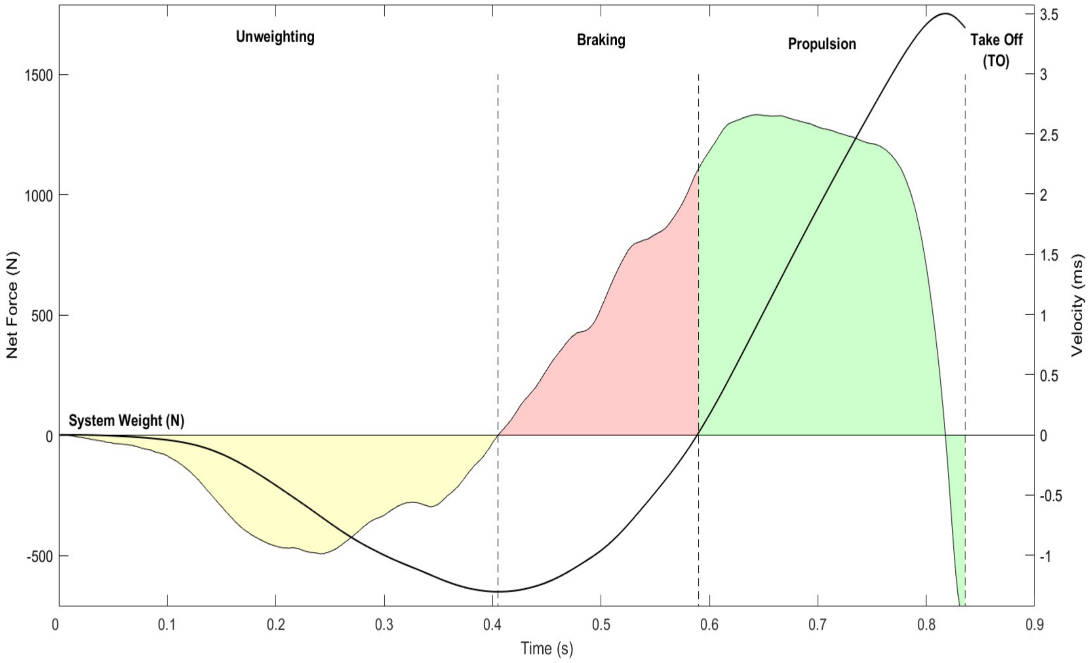


Figure 5.2. Force- and velocity- time curve of the countermovement jump.

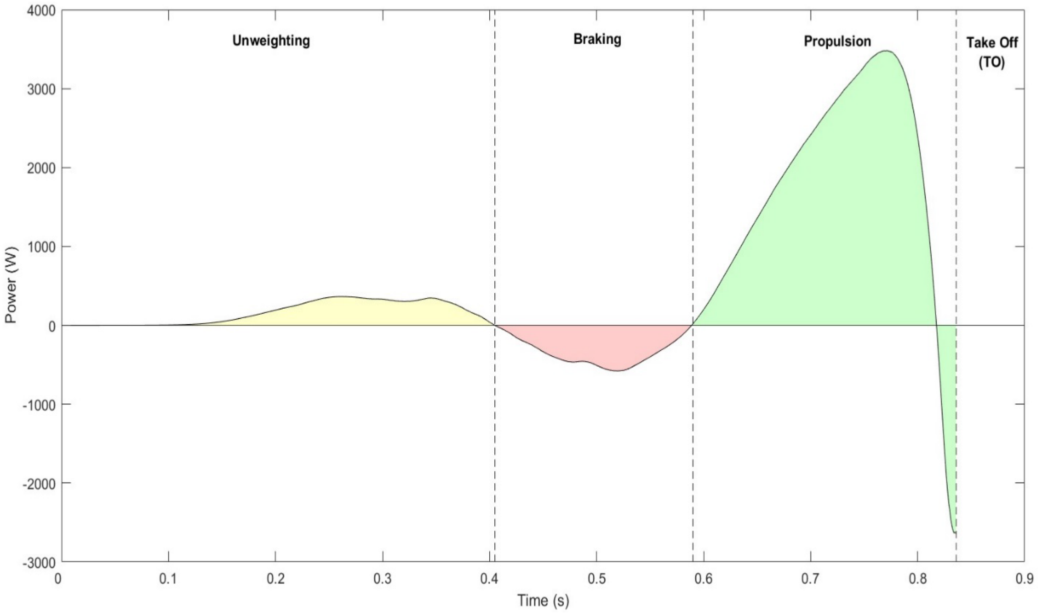


Figure 5.3. Power - time curve of the countermovement jump.

It has previously been indicated that allometric scaling is an effective way to normalise performance measures relating to strength by eliminating the effect of body size (Crewther *et al*., 2012). The curve linear relationship that exists between body mass and weight lifted (Batterham and George, 1997) meets the assumptions required by allometric scaling, with the additional assumption of log transformed data showing strong linear relationships between dependent (weight lifted) and independent (body mass) variables. While it has been suggested that independent exponents should be used based on the sample population, a study by Challis (1999) reported that weightlifting had an exponent of 0.64 [95%CI 0.51 – 0.78], which is close to that of the traditional 0.67 exponent used based on geometric symmetry (Jaric *et al*., 2005). Challis (1999) utilised weightlifting performances dating back to pre-1992, where weight classes have changed three times since, therefore the traditional 0.67 exponent was used as this (1) sits within the 95% CI range reported by Challis, and (2) is a common exponent used more recently when allometrically scaling surrogate weightlifting measures (Haff *et al*., 2005; Hornsby *et al*., 2017; Joffe and Tallent, 2020). In the present study, allometric scaling of the dependent and independent variables will provide an indication into relationships between WLp and various kinetic and kinematic surrogates whilst removing the effect of body mass.

The rationale for scaling WLp relative to weight category is a novel method of scaling. It negates the issue that exists with ratio scaling to bodyweight. Athletes within the same weightclass could display different absolute results which dictate performance outcome (i.e., achieving a medal or higher ranking), but may display different or same relative strengths. For example:

Athlete 1 – First place
44.9 kg bodyweight lifting 101 kg in the 45 kg weight category
= 2.25 kg/kg relative to bodyweight
= 2.24 kg/kg relative to weight category (45 kg)

Athlete 2 – Second place
44 kg bodyweight lifting 100 kg in the 45 kg weight category
= 2.27 kg/kg relative to bodyweight
= 2.22 kg/kg relative to weight category (45 kg)

By virtue of ratio scaling the performance to bodyweight, the athlete who came 2nd, is relatively stronger and may therefore provide an erroneous indication of relative physical qualities that underpin weightlifting performance. Given athlete 2 is not the best lifter in the group, scaling to weight category clearly enables a more meaningful exploration of relationships with the best performers in each weight category.

5.2.4. Statistical Analyses

All statistical analysis was computed using Statistics Package for Social Sciences (SPSS) version 27.0 (IBM, Armonk, USA). Descriptive statistics (mean ± SD [95% confidence interval]) were used to profile each metric. Based on previous literature which states that the CMJ can distinguish between sexes (McMahon, Rej and Comfort, 2017) and with known differences in WLp between sexes (Stone *et al*., 2005), it was decided to analyse women and men separately. A Shapiro-Wilk test of normality revealed that the three dependent variables for women and men (SN, CJ and TOT) were non-normally distributed (p <0.05), therefore a Spearman's Rho, non-parametric bivariate correlation was used to determine the relationship between the dependent and independent variables. Reliability was examined using two-way random effects model interclass correlation coefficient (ICC) with absolute agreement, coefficient of variation (CV), and the standard error of the measurement (SEM). Both the ICC and CV are presented along with their 95% CI's. Reliability was categorized as acceptable if the CV and 95% CI upper bound was ≤ 10% (Turner *et al*., 2015). Descriptors used to define reliability were; "good" if the lower bound 95% CI of the ICC fell between 0.75 and 0.90 and "excellent" if > 0.90 in line with ICC rankings proposed by (Koo & Li, 2016). Spearman Rho r_s correlational values were assigned descriptors using the following thresholds: 0.00 – 0.10 = "*very weak*", 0.11 – 0.30 = "*weak*", 0.31 – 0.50 = "*moderate*", 0.51 – 0.70 = "*strong*", 0.71 – 0.90 = "*very strong*", 0.91 – 1.00 = "*nearly perfect*" (Hopkins *et al*., 2009).

Given the large number of correlations, the alpha (α) value was determined using a Bonferroni correction factor by dividing the conventional threshold of 0.05, by the number of intended correlations to be made (Pallant, 2020). In this instance, the relationships between the dependent variables and independent performance variables which were considered as reliable were used. The purpose behind the Bonferroni correction was to reduce type I error rates, where the null hypothesis would be erroneously rejected. This would reduce the likelihood of false positives where a relationship is reported as statistically significant, when in fact it may not be.

With an increasing number of tests (i.e. correlations), the family-wise error rate increases, thus increasing the probability of producing false positives. Therefore, by using only reliable CMJ metrics, the number of total tests would be reduced, thus reducing family wise error rate, as it is calculated as $1-(1-\alpha)^n$, where the α value is 0.05 and n is the total number of tests.

Following recruitment and Bonferroni adjustment, a post-hoc power analysis was performed to identify statistical power (G*Power, v 3.1.9.7) (Faul *et al.,* 2007). The Bonferroni adjusted alpha level of 0.004 was used with the sample sizes of 30 and 12, for women and men, respectively. The post hoc analysis revealed that the ability to detect moderate (r = 50) and strong correlations (r = 0.70) was 49% and 95% for women and 10% and 38% for men, respectively.

5.3. RESULTS

All data are presented as mean ± SD with 95% CI (mean ± SD [95% CI]). Women's and men's descriptive and weightlifting performance data can be seen in Table 5.2. The CMJ presented a total of 13 metrics with excellent levels of reliability for women and men. Poor reliability was observed for duration of the braking phase (CV = 10.92% [8.16, 13.68], ICC = 0.366 [0.021, 0.636]) and average braking power (CV = 8.53% [6.37, 10.69], ICC =0.803 [0.626 - 0.901]) for women, with the men also showing poor reliability for braking phase duration (CV = 14.29 [8.57, 20.01], ICC = 0.499 [-0.038, 0.821]). Additionally, $\mathrm{RSI}^{\mathrm{mod}}$ also demonstrated poor levels of reliability for men (CV = 9.66 [5.80, 13.52], ICC = 0.659 [0.184, 0.887]]). All measures of reliability for each metric are presented in Table 5.3 and 5.4 for women and men, respectively.

Using the 13 reliable CMJ metrics, Family-wise error rate was determined to be 0.512 and 0.487 for women and men, respectively, suggesting there is a 51% and 49% probability of obtaining a type I error. Alpha level for statistical significance was set as 0.004, for both women and men. Following Bonferroni correction, family-wise error rate was reduced to 0.081 and 0.051 for women and men, respectively. The Spearman's Rho correlation revealed multiple meaningful relationships between measures of CMJ performance with WLp. All correlations relating to absolute performance along with 95% CIs for the SN, CJ and TOT can be found in Table 5.5, with correlation to relative weightlifting performance measures supplied in appendices 5.2 to 5.7.

Table 5.2. Women and Men's absolute and relative performance data (*n* = 42)

		Mean ± SD	**[95% LL – UL CI]**	**SEM**
Women	BM (kg)	63.31 ± 17.33	[56.84 - 69.78]	3.16
	Height (cm)	160.62 ± 8.06	[157.61 - 163.63]	1.47
	Snatch (kg)	70.83 ± 11.50	[66.54 - 75.13]	2.10
	CJ (kg)	87.45 ± 14.64	[81.88 - 93.02]	2.72
	Total (kg)	158.10 ± 26.03	[148.20 - 168]	4.83
	^{rel}SN	1.16 ± 0.19	[1.09 - 1.23]	0.04
	^{rel}CJ	1.43 ± 0.24	[1.34 - 1.53]	0.05
	^{rel}TOT	2.59 ± 0.44	[2.43 - 2.76]	0.08
	^{cat}SN	1.16 ± 0.18	[1.09 - 1.22]	0.03
	^{cat}CJ	1.44 ± 0.22	[1.35 - 1.52]	0.04
	^{cat}TOT	2.60 ± 0.40	[2.45 - 2.75]	0.07
	^{allo}SN	5.06 ± 0.64	[4.82 – 5.30]	0.12
	^{allo}CJ	6.26 ± 0.81	[5.95 – 6.57]	0.15
	^{allo}TOT	11.32 ± 1.44	[10.77 – 11.86]	0.27
Men	BM (kg)	85.50 ± 16.58	[74.97 - 96.04]	4.79
	Height (cm)	174.22 ± 5.83	[170.51 - 177.92]	1.68
	Snatch (kg)	118.83 ± 13.87	[110.02 - 127.64]	4.00
	CJ (kg)	148.55 ± 19.21	[135.64 - 161.45]	5.79
	Total (kg)	266.82 ± 32.77	[244.81 - 288.83]	9.88
	^{rel}SN	1.42 ± 0.20	[1.29 - 1.55]	0.06
	^{rel}CJ	1.78 ± 0.26	[1.60 - 1.96]	0.08
	^{rel}TOT	3.20 ± 0.47	[2.89 - 3.52]	0.14
	^{cat}SN	1.42 ± 0.16	[1.32 - 1.52]	0.05
	^{cat}CJ	1.80 ± 0.21	[1.66 - 1.94]	0.06
	^{cat}TOT	3.24 ± 0.35	[3.00 - 3.48]	0.11
	^{allo}SN	6.96 ± 0.72	[6.50 – 7.42]	0.21
	^{allo}CJ	8.72 ± 0.94	[8.09 – 9.35]	0.28
	^{allo}TOT	15.68 ± 1.63	[14.58 – 16.77]	0.49

Where, BM = body mass, kg = kilogram, cm = centimetre, ^{rel}SN = relative snatch, ^{rel}CJ = relative clean and jerk, ^{rel}TOT = relative total, ^{cat}SN = category relative snatch, ^{cat}CJ = category relative clean and jerk, ^{cat}TOT = category relative total, ^{allo}SN = allometrically scaled snatch, ^{allo}CJ = allometrically scaled clean and jerk, ^{allo}TOT = allometrically scaled total.

Table 5.3. Women's physical and performance characteristics reliability.

	Mean ± SD [95% CI]	CV [95% CI]	ICC [95% CI]	SEM
JH	**0.35 ± 0.05 [0.33 - 0.37]**	**2.76 [2.06 - 3.46]**	**0.941 [0.873 - 0.972]**	**0.01**
RSI^{mod}	**0.49 ± 0.11 [0.45 - 0.53]**	**7.91 [5.91 - 9.91]**	**0.822 [0.659 - 0.911]**	**0.02**
PF	**1044.36 ± 240.98 [954.38 - 1134.34]**	**5.10 [3.81 - 6.39]**	**0.915 [0.829 - 0.958]**	**44.00**
^{rel}PF	**16.33 ± 3.4 [15.06 - 17.6]**	**5.12 [3.82 - 6.42]**	**0.898 [0.797 - 0.950]**	**0.62**
^{allo}PF	**75.08 ± 14.21 [69.79 – 80.38]**	**5.10 [3.81 – 6.39]**	**0.880 [0.763 – 0.941]**	**2.59**
Braking impulse	**74.9 ± 24.07 [65.91 - 83.89]**	**4.80 [3.59 - 6.01]**	**0.959 [0.916 - 0.980]**	**4.40**
Braking impulse duration	0.34 ± 0.09 [0.31 - 0.38]	10.92 [8.16 - 13.68]	0.366 [0.021 - 0.636]	0.02
Propulsive impulse	**171.18 ± 38.6 [156.77 - 185.59]**	**1.79 [1.34 - 2.24]**	**0.989 [0.977 - 0.995]**	**7.05**
Propulsive impulse duration	**0.24 ± 0.04 [0.22 - 0.25]**	**3.72 [2.78 - 4.66]**	**0.937 [0.874 - 0.970]**	**0.01**
AvgPropF	**725.12 ± 167.94 [662.41 - 787.83]**	**3.84 [2.87 - 4.81]**	**0.956 [0.910 - 0.979]**	**30.66**
PP	**3449.28 ± 717.38 [3181.41 - 3717.16]**	**1.90 [1.42 - 2.38]**	**0.983 [0.965 - 0.992]**	**130.98**
^{rel}PP	**53.48 ± 5.84 [51.29 - 55.66]**	**1.92 [1.43 - 2.41]**	**0.943 [0.884 - 0.972]**	**1.07**
^{allo}PP	**244.27 ± 24.97 [234.95 – 253.59]**	**1.90 [1.42 – 2.39]**	**0.936 [0.869 – 0.969]**	**4.56**
BrkAvgP	-352.3 ± 115.4 [-395.39 - -309.21]	8.53 [6.37 - 10.69]	0.803 [0.626 - 0.901]	21.07
PropAvgP	**1937.9 ± 421.46 [1780.52 - 2095.28]**	**2.98 [2.23 - 3.73]**	**0.974 [0.947 - 0.988]**	**76.95**

*Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power. All measures in **bold** denote excellent reliability.*

Table 5.4. Men's physical and performance characteristics reliability.

	Mean ± SD [95% CI]	CV [95% CI]	ICC [95% CI]	SEM
JH	**0.45 ± 0.06 [0.41 - 0.49]**	**3.03 [1.82 - 4.24]**	**0.938 [0.808 - 0.982]**	**0.02**
RSI^{mod}	0.6 ± 0.11 [0.53 - 0.67]	9.66 [5.80 - 13.52]	0.659 [0.184 - 0.887]	0.03
PF	**1576 ± 426.19 [1305.21 - 1846.79]**	**3.92 [2.35 - 5.49]**	**0.971 [0.904 - 0.991]**	**123.03**
^{rel}PF	**18.48 ± 4 [15.94 - 21.02]**	**3.97 [2.38 - 5.56]**	**0.952 [0.844 - 0.986]**	**1.15**
^{allo}PF	**95.05 ± 21.02 [81.70 – 108.40]**	**3.91 [2.92 – 4.91]**	**0.963 [0.879 – 0.989]**	**6.07**
Braking Impulse	**107.57 ± 23.63 [92.56 - 122.58]**	**5.62 [3.37 - 7.87]**	**0.915 [0.736 - 0.975]**	**6.82**
Braking impulse duration	0.34 ± 0.09 [0.28 - 0.4]	14.29 [8.57 - 20.01]	0.499 [-0.038 - 0.821]	0.03
Propulsive impulse	**254.1 ± 37.46 [230.3 - 277.9]**	**1.39 [0.83 - 1.95]**	**0.984 [0.948 - 0.995]**	**10.81**
Propulsive impulse duration	**0.24 ± 0.03 [0.22 - 0.27]**	**3.13 [1.88 - 4.38]**	**0.922 [0.763 - 0.977]**	**0.01**
AvgPropF	**1045.66 ± 180.89 [930.72 - 1160.59]**	**2.90 [1.74 - 4.06]**	**0.950 [0.827 - 0.986]**	**52.22**
PP	**5341.51 ± 1194.29 [4582.7 - 6100.33]**	**1.75 [1.05 - 2.45]**	**0.988 [0.930 - 0.997]**	**344.76**
^{rel}PP	**62.97 ± 11.67 [55.55 - 70.39]**	**1.80 [1.08 - 2.52]**	**0.984 [0.906 - 0.996]**	**3.37**
^{allo}PP	**311.45 ± 58.30 [274.41 – 348.50]**	**1.75 [1.31 – 2.19]**	**0.985 [0.912 – 0.996]**	**16.83**
BrkAvgP	**-439.5 ± 150.79 [-535.3 - -343.69]**	**5.12 [3.07 - 7.17]**	**0.909 [0.720 - 0.973]**	**43.53**
PropAvgP	**2888.83 ± 563.93 [2530.52 - 3247.14]**	**2.47 [1.48 - 3.46]**	**0.969 [0.868 - 0.992]**	**162.79**

*Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power. All measures in **bold** denote excellent reliability.*

Table 5.5. All women and men's Spearman Rho correlations with absolute total performance (r_s [95% CI]). Significant correlations presented in bold.

		^{abs}SN	^{abs}CJ	^{abs}Total
Women	JH	0.128 [-0.24 - 0.47]	0.18 [-0.2 - 0.51]	0.161 [-0.21 - 0.49]
	RSI^{mod}	-0.097 [-0.45 - 0.27]	-0.062 [-0.41 - 0.31]	-0.078 [-0.43 - 0.29]
	CMJ PF	0.297 [-0.08 - 0.60]	0.326 [-0.04 - 0.62]	0.318 [-0.06 - 0.62]
	CMJ ^{rel}PF	-0.136 [-0.48 - 0.23]	-0.112 [-0.45 - 0.26]	-0.143 [-0.48 - 0.23]
	CMJ ^{allo}PF	0.018 [-0.34 - 0.38]	0.028 [-0.33 - 0.39]	0.008 [-0.35 - 0.37]
	Braking impulse	0.44 [0.08 - 0.70]	**0.532 [0.19 - 0.76]**	**0.543 [0.20 - 0.76]**
	Propulsive impulse	**0.676 [0.39 - 0.85]**	**0.687 [0.40 - 0.85]**	**0.719 [0.45 - 0.87]**
	Propulsive impulse duration	0.223 [-0.16 - 0.54]	0.277 [-0.10 - 0.59]	0.28 [-0.10 - 0.59]
	AvgPropF	0.341 [-0.03 - 0.63]	0.302 [-0.08 - 0.60]	0.33 [-0.04 - 0.62]
	PP	0.476 [0.12 - 0.73]	0.437 [0.08 - 0.70]	0.479 [0.12 - 0.73]
	rPP	-0.093 [-0.44 - 0.28]	-0.117 [-0.46 - 0.25]	-0.122 [-0.46 - 0.25]
	aPP	0.287 [-0.09 - 0.59]	0.211 [-0.17 - 0.53]	0.241 [-0.14 - 0.56]
	PropAvgP	0.469 [0.11 - 0.72]	0.464 [0.10 - 0.71]	0.492 [0.14 - 0.73]
Men	JH	0.168 [-0.45 - 0.68]	0.184 [-0.44 - 0.69]	0.245 [-0.39 - 0.72]
	CMJ PF	0.705 [0.15 - 0.92]	**0.845 [0.44 - 0.96]**	0.752 [0.23 - 0.94]
	CMJ ^{rel}PF	0.032 [-0.55 - 0.60]	0.196 [-0.43 - 0.70]	0.128 [-0.48 - 0.66]
	CMJ ^{allo}PF	0.351 [-0.3 - 0.78]	0.543 [-0.09 - 0.86]	0.419 [-0.23 - 0.81]
	Braking impulse	0.681 [0.11 - 0.91]	0.452 [-0.2 - 0.83]	0.524 [-0.11 - 0.86]
	Propulsive impulse	**0.765 [0.26 - 0.94]**	**0.817 [0.37 - 0.96]**	**0.793 [0.32 - 0.95]**
	Propulsive impulse duration	0.007 [-0.57 - 0.58]	0.097 [-0.51 - 0.64]	0.189 [-0.44 - 0.69]
	AvgPropF	0.396 [-0.25 - 0.80]	0.434 [-0.22 - 0.82]	0.333 [-0.31 - 0.77]
	PP	0.344 [-0.3 - 0.77]	0.37 [-0.28 - 0.79]	0.374 [-0.28 - 0.79]
	rPP	0.007 [-0.57 - 0.58]	-0.05 [-0.61 - 0.54]	-0.073 [-0.62 - 0.52]
	aPP	0.053 [-0.54 - 0.61]	0.073 [-0.52 - 0.62]	0.023 [-0.56 - 0.59]
	BrkAvgP	0.035 [-0.55 - 0.60]	0.347 [-0.3 - 0.78]	0.178 [-0.45 - 0.68]
	PropAvgP	0.386 [-0.26 - 0.79]	0.338 [-0.31 - 0.77]	0.255 [-0.38 - 0.73]

Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power

5.4. DISCUSSION

The primary aim of this investigation was to establish the relationship between CMJ strategy metrics and weightlifting performance in national weightlifting athletes. It was established that concentric impulse was the most reliable and correlated metric to weightlifting performance for both men and women.

5.4.1. Reliability

The use of kinetic data derived from a CMJ allows performance scientists and coaches a more extensive assessment of neuromuscular ability (Turner *et al.*, 2021) with many of these metrics shown to have excellent sensitivity to change (Claudino *et al.*, 2017). The present findings displayed excellent levels of reliability for 13 out of 15 metrics extracted for both women and men. The three metrics that showed unacceptable levels of reliability given the threshold stated in the methods, were braking phase impulse duration for both women and men, braking phase average power for women, and RSI^{mod} for men. Contrary to this, a near perfect and very low variability was observed for propulsive impulse across both women and men (Tables 3a and b). While there may be a high number of metrics found to be reliable, it is important to consider not just the reliability, but also the biological basis on which the metric is related to performance and the feasibility of consistent monitoring (Bishop *et al.*, 2022). These are further explored in the discussion of relationships.

5.4.2. Relationships

Women

Women displayed a significantly *strong* to *very strong* relationship between propulsive impulse and all measures of ^{abs}WLp ($r = 0.676 – 0.719$, $p < 0.004$). However, given that impulse is a product of force and time, one must also consider the duration of this phase (propulsive impulse duration). The relationship of propulsive impulse duration with ^{abs}WLp was *weak* and non-significant ($r = 0.223 – 0.280$, $p > 0.004$), suggesting that the magnitude of net force developed during the propulsive phase of the jump was the primary factor in its relationship to ^{abs}WLp. The importance of this as a surrogate measure of WLp, is that researchers have indicated that time increases as loads and efforts increase within jumping and weightlifting movements (Garhammer and Gregor, 1992), enabling the athlete to apply force for longer. While there may be full intent to accelerate the system as load increases, the additional load will decrease its velocity, therefore requiring additional time spent applying force. Garhammer (Garhammer and Gregor, 1992) observed that the average time spent applying force during the propulsive phase increased between 70% and 100% of max effort jump and reach. Concurrently, the authors also observed a slight decrease in the average maximum force applied. As impulse is a product of force and time, a decrement in one must be sufficiently large enough in order to reduce overall impulse. Therefore, given the current results, and when using impulse to monitor changes associated with superior weightlifting performance, it is suggested that performance scientists also monitor propulsive impulse duration to ensure that minimal changes are occurring, which would mean increases in propulsive force, since time during this phase is far less trainable. Additionally, the relationship between CMJ propulsive impulse and percent of fast twitch fibres in the vastus lateralis (VL) has been reported by Bosco (Bosco and Komi, 1979) ($r = 0.510$, $p < 0.01$). Although, this was conducted on physical education students, it was later purported (Fry *et al.*, 2003) that international and national male weightlifters possessed a large percentage of type IIA fibres in the VL, which were *nearly perfectly* related to ^{abs}SN ($r = 0.94$, $p < 0.05$) and *very strongly* related to ^{abs}TOT and CMJ PP ($r = 0.80$, $p < 0.10$ and 0.83, $p<0.05$, respectively). Collectively, this supports the notion that propulsive impulse may also be a good indicator of muscle fibre type characteristics conducive of superior weightlifting performance.

Braking impulse was also significantly related to ^{abs}CJ and ^{abs}TOT ($r = 0.532 – 0.543$, $p < 0.004$), but not to ^{abs}SN. A potential reason for this relationship is that the jerk portion of the CJ shares the same vGRF profile as a CMJ, with a proportion of the dip phase displaying a braking impulse (Soriano *et al.*, 2021). Given that CJ makes up a large portion of TOT, it is likely why this relationship also exists. Given an acceptable level of reliability of braking impulse for both women and men, it may warrant monitoring in providing information on jump strategies adopted by the athlete, however, it should be considered along with its duration. The mean ± SD of the braking impulse duration for both men and women were near identical (0.34 ± 0.09 vs 0.34 ± 0.09 s), but the braking impulse were greater in men (107.57 ± 23.63 vs 74.9 ± 24.07 N.s). This may suggest that women produced less force at the end of the braking phase. If a greater amount of braking impulse is produced over a shorter time period, it is likely to augment higher propulsive impulse through the utilisation of stretch shortening cycle (SSC) (McMahon, Rej and Comfort, 2017). Given that similarities existed between women and men in braking impulse duration, but higher values of braking impulse were identified in the men, it could be suggested that properties relating to the SSC of female weightlifters may be a limiting factor in performance, as those who displayed better braking impulse and propulsive impulse lifted greater loads, as evidenced by the *strong* and *very strong* relationships to ^{abs}WLp. The importance of the SSC within weightlifting is twofold. Firstly, it has been reported that a negative correlation (r = - 0.730, p < 0.01) exists between the force applied during the second pull and the transition phase (Kauhanen, Häkkinen and Komi, 1984), as it has been hypothesised that the SSC facilitated during the first pull and through the transition phase contribute to vGRF during the second pull (Kauhanen, Häkkinen and Komi, 1984). Secondly, higher performing weightlifters tend to display lower amortization phases between the dip and drive phase of the jerk (Grabe and Widule, 1988; Kauhanen, Häkkinen and Komi, 1984). While the present study did not directly investigate measures of SSC ability, Kauhanen and colleagues (1984) reported that weightlifters who had the ability to tolerate greater stretch loads and velocities during 60 - 100 cm drop jumps were able to produce greater vGRF during the second pull and were also able to perform the eccentric (dip) phase of the jerk faster. While not reported in the current manuscript, future research may consider exploring the reliability and utility of countermovement depth and force at minimum displacement during the CMJ, as to provide information on strategies adopted during the amortization phase. Furthermore, countermovement depth specifically may also help explain changes in impulse, as lower depths would likely equate to increased time spent during the propulsive phase.

Peak power is an often-reported measure of lower body neuromuscular ability within weightlifting (Carlock *et al*., 2004; Haff *et al*., 2005; Hornsby *et al*., 2017; Joffe and Tallent, 2020; Travis, *et al*., 2019). Power outputs produced in jump tests are thought to be similar to those produced in the pull phase of the SN and CJ (Garhammer, 1993). Previous researchers have reported *strong* to *near perfect* relationships (r = 0.60 – 0.93) between PP and ^{abs}WLp (Carlock *et al.,* 2004; Haff *et al*., 2005). The present investigation reported *moderate* non-significant relationships between PP and ^{abs}WLp (r = 0.437 – 0.479, p > 0.004). Strong negative correlations were observed between PP and all ^{rel}WLp measures (r = -0.603 to -0.573, p < 0.004), with only ^{rel}SN and ^{rel}TOT, being of significance. Upon observation of the raw data, there was a downward trend of ^{rel}WLp as the body mass increased, supporting the notion of ratio scaling favouring lighter lifters. Additionally, it has been reported that body mass influences power, jump height, and maximal dynamic strength (Carlock *et al*., 2004). For example, athletes with a larger mass must create proportionally larger forces than a lighter athlete to increase take off velocity. In turn this would enhance their peak power output and jump height. However, since strength (or the expression of force) is not proportional to mass (Batterham and George, 1997) it is unsurprising that negative relationships existed between PP and ^{rel}WLp. However, prior research reporting PP and ratio scaled WLp, have shown far lower, non-significant relationships, likely due to the grouping of different level and sex weightlifters making the group heterogenous.

Finally, JH displayed a *strong* positive, significant relationship to all measures of scaled WLp for SN, CJ and TOT ($r = 0.528 – 0.603$, $p < 0.004$). This finding is interesting, as correlations of JH to ^{abs}WLp were *weak* which conflicts with some previous findings in the literature (Carlock *et al*., 2004; Kite and Spence, 2017), but not others (Travis, *et al*., 2018). The findings from the present investigation indicate that those who had the best WLp, regardless of body size and weight category, jump the highest. This can be associated back to the *strong* and *very strong* relationships with propulsive impulse as this ultimately determines the momentum of a system (i.e. bodyweight plus barbell) and its resulting take off velocity (Ruddock and Winter, 2016). Therefore, while JH may not be an insightful metric with regards to force generating strategies, it may provide an easy to attain WLp surrogate using simple technologies such as jump mats and smart phone applications, which are more cost effective, require less expertise or data processing, and maybe more useful in talent mass testing. However, it should be noted that those going down in weight category may present positive changes in JH (i.e. increase) but negative to no change in propulsive impulse, and vice versa. Therefore, one must use a force plate to monitor such metrics, which not only carry greater relation to WLp, but also provide a deeper understanding to what neuromuscular changes have occurred, something JH alone cannot provide.

Men

Very much like the women, men also displayed *very strong* significant relationships between propulsive impulse and all measures of ^{abs}WLp ($r = 0.765 – 0.817$, $p < 0.004$). The duration of this phase (propulsive impulse duration) displayed *very weak* to *weak* relationships to ^{abs}WLp, suggesting that the magnitude of force developed during this phase is an underpinning factor relating to ^{abs}WLp.

A significant *very strong* negative correlation between AvgPropF and ^{cat}SN was also observed ($r = -0.792$ [-0.950, -0.320], $p < 0.004$). This suggests that the best snatchers in each weight category produced lower average forces during the propulsive phase of the CMJ. A potential reason for this could be due to the propulsive impulse duration, which had a *strong* but non-significant relationship with ^{cat}SN (r = 0.678 [0.1 – 0.91], p > 0.004), collectively suggesting that the best category snatchers spent longer applying force during the propulsive phase, likely over a longer range of motion, therefore reducing their AvgPropF. Given that the snatch has previously displayed longer second pull times (0.134 ± 0.35s) due to greater centre of mass displacement (Hakkinen, Kauhanen and Komi, 1984), the negative relationship between AvgPropF and ^{cat}SN becomes more plausible.

Peak propulsive force in the CMJ showed a *very strong* correlation with ^{abs}CJ performance (r = 0.845 [0.44, 0.96], p < 0.004). Observations from Garhammer and Gregor (1992) suggested that the maximum magnitude of force (PF) developed during submaximal and maximal jumping, were lower in those that exhibited greater jump heights. The authors went on to suggest that it is the time in which the athlete applies the force during the propulsive phase during higher effort jumps and snatches which dictated performance. Theoretically, this would suggest that although the athletes decrease their PF during jumping and snatch, the decrease would be disproportionate relative to the increase in time and therefore would increase the overall impulse. This supports the findings of the present study in which both women and men displayed *strong* and *very strong* relationships between propulsive impulse and WLp.

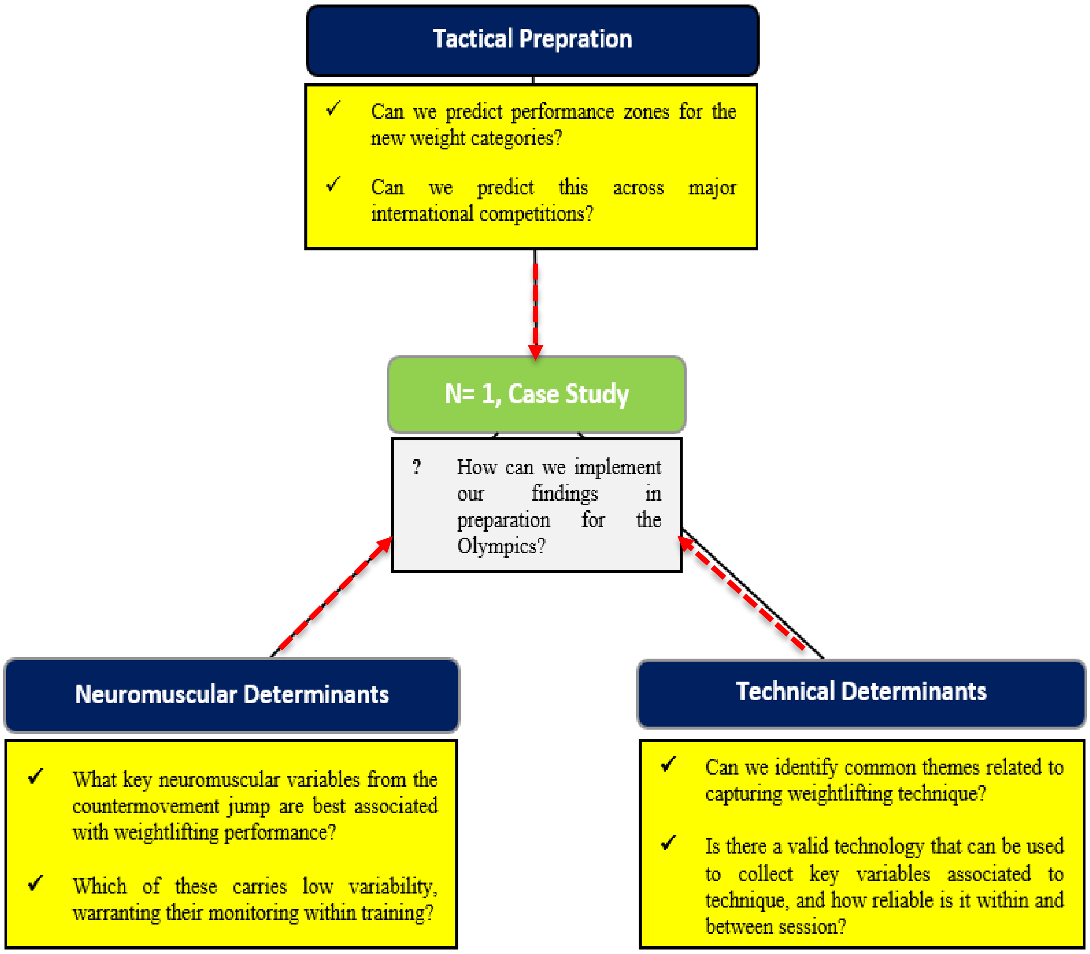
A limitation of this investigation was testing the athletes following their competition. Although every effort was made to ensure sufficient recovery was taken between the competition and the time they conducted the CMJ testing, there was no guarantee that residual fatigue from the competition would have fully dissipated. Contrary to this, however, it can be assumed that athletes would have tapered for the competition since testing took place during the two biggest events in the British Weight Lifting competition calendar and therefore athletes were likely to be in the best possible physical condition, providing physical performance measures truly representative of the sport. It should also be noted that the CMJ is just one component of maxmimal neuromuscular function and future studies may wish to include other surrogate measures that may share similar biological basis to weightlifting. Additionally, the current investigation simply provides a cross-sectional overview of the relationship between kinetic and kinematic measures of the CMJ and weightlifting performance, without any indication on causation. Therefore, a longitudinal study is required to determine if weightlifting performance increases when CMJ propulsive impulse increases, or vice versa. Further to this, the CMJ tests ballistic performance with no additional load to the athlete's body weight. Comparatively, this would be far less than the system load experienced within the SN and CJ and therefore future investigations may wish to evaluate the relationship of loaded jumps as a performance surrogate to assess ballistic ability under load. This would provide insight into the force-velocity relationship exhibited by the individual which would more closely represent the demands of weightlifting, allowing sport scientists and coaches to identify if the appropriate adaptations are taking place following specific training blocks (i.e. producing greater velocities at the same load following a competition block). Additionally, it has also been reported by Hornsby *et al.* (2017) that loaded squat jumps maybe superior to unloaded jumps in identifying fatigue in trained individuals. Therefore, to summarise, in future studies researchers may wish to explore the current findings and its utility in monitoring training adaptations longitudinally along with loaded jump performances.

5.5. PRACTICAL APPLICATIONS

The novel findings from the present study suggest that propulsive impulse and duration should be monitored in weightlifters. Propulsive impulse displayed a *strong* to *very* strong relationship with ^{abs}WLp for both women and men. This provides coaches with information on the ballistic qualities which are akin to the second pull and drive phase of the jerk, which are critical phases of the lifts. Furthermore, its high level of sensitivity allows for coaches to alter training strategies based on neuromuscular fluctuations. Longitudinal analysis and monitoring of propulsive impulse and propulsive impulse duration alongside WLp personal bests should also be considered, as this may help identify what changes in propulsive impulse are required in relation to additional kilograms on the barbell. While the data presented in this study is of a homogenous group, individual analysis should also be considered given the nature of the sport. Performance scientists within weightlifting may wish to identify individual levels of variance to make the monitoring process more individualised and specific to the athlete. This will help develop individual profiles in which athletes can compare themselves to along their weightlifting journey particularly during weight category changes.

CHAPTER 6: STUDY 5 - THE PLANNING, MONITORING AND TRAINING OF AN ELITE WEIGHTLIFTER: A LONGITUDINAL CASE STUDY IN PREPARATION FOR THE TOKYO OLYMPIC GAMES.

Chapter 6 is a longitudinal, holistic case study on an elite weightlifter and their road to the Tokyo Olympic games. This case study looked to implement the theories and underpinning findings from the previous chapters in an attempt to coherently look at weightlifting performance as a whole. It highlights some of the challenges faced due to the Covid-19 pandemic and how the monitoring and training process was adapted throughout.



6.1. INTRODUCTION

Weightlifting is an Olympic sport where an individual competes for their respective country following a qualification period. For example, the qualification process for the 2020 Tokyo Olympic games required athletes to compete in gold, silver and bronze ranked events hosted by the International Weightlifting Federation (IWF) between the dates of November 2018 and May 2021, with the additional year of qualification added due to Covid-19 (henceforth termed Covid). In order to achieve Olympic qualification, the athlete must have competed in at least six ranked events, with at least one being of a gold standard and another being either gold or silver. The top eight ranked athletes by the end of the qualification period would be provided with a place at the Olympics, with an additional 5 provided to the highest ranked continental athlete, one tripartite athlete and an additional place from countries which re-allocated an unused quota place, totalling a number of 14 athletes per weight category.

It is widely accepted that the Olympic Games is the pinnacle of sporting competition and therefore preparation for such an event is key when periodizing training, where key qualifying events must be approached with high importance to position the athlete as best as possible for a chance of qualification (Polataev and Cervera, 1995). Weightlifting is considered to be a strength-speed sport (Stone *et al*., 2005) in which the athlete must snatch and clean and jerk the most weight possible within three attempts of each, with an aggregate of the total determining success. Therefore, given the underpinning reliance of force capacity and its expression within the lifts, training must aim to develop both the physical and technical qualities of the athlete. Training such characteristics can be specifically targeted through sequential training blocks that help elicit neuromuscular adaptations that aim to transfer to the competitive lifts the closer an athlete gets to competition.

Longitudinal monitoring of changes in neuromuscular ability, biochemical adaptations, muscle cross sectional area and overall weightlifting performance have previously been reported in national and international level weightlifters (Hornsby *et al*., 2017; Bazyler *et al.,* 2018; Suarez *et al*., 2019; Joffe and Tallent 2020). The surrogate tests would often consist of a measure of maximal and ballistic force expression by the way of isometric mid-thigh pull (IMTP) or a jump (i.e. Countermovement or squat). Variables extrapolated from such tests such as peak force (PF), rate of force development (RFD), jump height (JH), and concentric propulsive impulse (^{con}Imp) have all been shown to have strong to very strong relationships with weightlifting performance as outlined in chapter 5 (Chavda *et al.*, 2023). The consensus of utilising such variables for monitoring purposes is that they carry high sensitivity to change, with the response of each variables dependent on the training block focus and thus training volume and intensity experienced (Suarez *et al.,* 2019; Bazyler *et al*., 2018; Hornsby *et al*., 2017). While insightful, the aforementioned studies only consider the physical preparation of weightlifting, investigations into technical changes are far less common, with research often characterising technique through barbell trajectories (Cao *et al*., 2022). For a coach to make well informed decisions on exercise selection and loading, a holistic approach of monitoring both neuromuscular and technical changes throughout training should be considered. However, the practicality of this within a high-performance environment using group-based research designs with optimal sample sizes can be difficult. This becomes inherently more impractical in individual sports, such as weightlifting, where controlled interventions may not be viable given the individual requirement of each athlete. Therefore, single subject case study's, particularly at an elite level, can provide necessary information into the effect of training on the physical preparedness of the athlete and its concurrent effect on performance.

Currently, there is a paucity of research on the longitudinal preparation of elite male weightlifters which not only consider the neuromuscular changes, but also its influence on barbell kinematics, which may have occurred over the years, with only one such study having been conducted (Sandau and Granacher, 2023). The Tokyo Olympic Games, saw the first Refugee weightlifting athlete selected to compete in the men's 96 kg weight category. As a consequence of his refugee status, the athlete was unable to qualify through the methods outlined previously, and instead was selected as one of 35 athletes to represent the second ever Refugee Olympic Team (EOR). This case study provides longitudinal analysis of that elite weightlifter highlighting changes in neuromuscular ability and its influence on barbell kinematics and how the restrictions of Covid were negotiated and overcome in preparation for the Tokyo Olympic games. It is hypothesised that longitudinal analysis of training conducted to positively effect weightlifting performance will reveal significant changes in neuromuscular ability and its influence to barbell kinematics. Furthermore, it is hypothesized that the impact of the Covid restrictions, both in terms of training logistics and competition preparation, will be evident in the athlete's performance and preparation strategies. This case study will contribute valuable insights into the holistic effects of training on both neuromuscular and technical aspects of weightlifting, with potential implications for future training methodologies and athlete preparation.

6.2. METHODS

6.2.1. Experimental Approach to the Problem

A quasi-experimental case study was conducted over a period of 3 years to evaluate neuromuscular, technical, and performance changes over a series of competitions leading into the 2020 Olympic Games. Given the constraints dictated by Covid, the training and monitoring process was adapted throughout the lead up to the OG. Neuromuscular performance was monitored within the first five days of competition using IMTP and CMJ. Technical analysis was conducted on the snatch only using an IMU interfaced with a native application on an iPad, where a select range of kinematic and kinetic variables were assessed. Due to changes in body weight category, competition performance of absolute load was monitored as well as relative to weight category. Leading into the OG, historic competition performances achieved by the opposition were calculated as mean ± SD along with success rate and average increment between attempts as a percentage to help identify opportunity to achieve highest possible rank. This was used synonymously with predicted performance zone predictions developed identified in chapter 2 (Chavda *et al.*, 2023) to help plan minimum loads required to achieve a top 10 finish. Over the three-year period, a total of 22 blocks of training were employed consisting of 4-6 sessions per week with each session lasting approximately two hours. Adaptations to the programme were made when necessary to account for injuries, illness and work schedule demands of the athlete.

6.2.2. Participant

The athlete was a 25-year-old male weightlifter competing in the 96 kg and 102 kg weight categories within the United Kingdom (UK), with his primary weight category being 96 kg. He had previously competed in weightlifting and had a training experience of 10 years at the time. His accolades prior to the initiation of this case study include competing at a continental championship (2013) and a commonwealth games (2014), achieving 5th in both cases. Alongside his training, he was also a full-time mental health nurse for the National Health Service (NHS), making him a dual career athlete and a key worker during the Covid pandemic. The athlete was part of the IOC's solidarity support programme and was a hopeful for the Tokyo Olympic Games as part of the EOR. The athlete provided verbal consent for his data to be used which was collected as part of his regular performance monitoring. No ethical approval was required for this study.

6.2.3. Procedures

Neuromuscular Performance Data. Following each competition, the athlete was asked to partake in the countermovement jump (CMJ) and isometric mid-thigh pull (IMTP). Every effort was made to ensure that the athlete had a sufficient recovery period prior to the testing day and it was mutually decided that this would be conducted within the first 5 days following competition. This decision was to ensure that the testing results did not have any psychological influence on the athlete's preparedness going into competition as well as not being affected by fatigue induced by normal training. Prior to testing, he was given a self-selected time to perform a general warm up, which typically consisted of dynamic stretches of the lower body followed by 2-3 submaximal efforts on the CMJ and IMTP, respectively. All neuromuscular performance tests were conducted in the morning as to reduce any diurnal effects.

Countermovement Jump. The CMJ was conducted in line with the methods described in chapter 4. All raw force-time data were extracted for analysis in a custom spreadsheet (Chavda *et al*., 2018). The primary variable analysed was propulsive net impulse, as this has previously been defined to have the greatest relationship with weightlifting performance in national and international weightlifters in chapter 4 (Chavda *et al*., 2023). As impulse is a product of force and time, time was also monitored as to identify whether changes in impulse were influenced by propulsion phase duration or magnitude of force produced. Furthermore, countermovement depth was also monitored as to help identify if this influenced the propulsion duration. This ensures that any changes in jump strategies which concurrently influence propulsive impulse, are accounted for (Bishop *et al.,* 2022; Bishop *et al.,* 2023).

Isometric-Mid Thigh Pull. IMTP was conducted on a portable force plate (Kistler 9286, Winterhur, Switzerland) sampling at 1,000 Hz, placed within a custom-made rig (Absolute Performance, Cardiff, UK) using a cold steel rolled bar. The bar was adjusted to a height that allowed the athlete to assume a position that approximated the beginning of a second pull of the clean, termed "the power position". Hip and knee angles were assessed at each testing session using a hand-held goniometer to verify that an angle of 140-150° and 125-145° was achieved, respectively (Chavda *et al*., 2020; Comfort *et al.,* 2019), with the athletes' range being 143±2° and 133±4° for the hip and knee, respectively. To eliminate the effect of grip loss lifting straps and chalk was used. Weightlifting shoes and a belt were also used during the test. Once familiar with the set up the athlete was given the opportunity to perform 2-3 submaximal pulls to familiarise themselves with the task and as part of their warm up (Comfort *et al.,* 2019). Once the athlete was ready, the force plate was zeroed, and he took his predetermined position and was asked to take the slack out of the bar whilst remaining relaxed (Comfort *et al.,* 2019). He was counted down from 3 and encouraged to drive the floor away as "fast and as hard as possible". Each trial lasted approximately 3-5 seconds. All raw force-time data was extracted for analysis in a custom spreadsheet (Chavda *et al.,* 2020), where net values of peak force (^{net}PF), relative PF (^{rel}PF), Force @ 150- and 200 ms (F^{150}, F^{200}) were extracted. Definitions and calculations of these variables can be found in previous publications (Chavda *et al.,* 2020).

Competition Performance. Domestic competition performance was recorded as the heaviest successful SN and CJ, and therefore TOT. Official results were taken from the British Weightlifting website (accessed between: 26/01/2019 and 20/04/2019). Competition performance was taken as absolute (^{abs}WLp) and relative to weight category (^{cat}WLP) due to weightclass changes in the period assessed. In preparation for the OG, prediction of performance zones was conducted using methods outlined in chapter 2 (Chavda *et al*., 2023). Additional competition performance TOT data for each opposition competitor within the 96kg weight class was also extracted from the IWF website following the final entries publication, accessible 22/07/2021. This was overlaid onto the predicted performance zones.

Barbell Kinematics Data Capture. Peak barbell vertical velocity (PBVv) was collected using Enode (Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany) interfaced with an iPad pro (2nd generation, Apple Inc, California, USA) to understand the influence of volume load and exercise type distribution during training block 19 to 22. Data capture occurred during the last training week of block 19, the first training week of block 20 and 21, the last week of block 21 and finally the start and end of block 22 during the taper. A standard load of 140kg was used as this was the heaviest, most commonly lifted load throughout the 4 training blocks. The validity of peak barbell velocity and its within and between session reliability was determined during chapter 3.

Training Programme. The training programme consisted of 22 blocks over a three-year period. Each block lasted between 2-9 weeks and had a specific focus centred around general preparatory phase (GPP), sport specific phase (SSP) and competitive phase (CP), which was designed, implemented and adjusted by an international weightlifting coach with input from the athlete. Appendix 6.1 contains supplementary information on block durations, timelines and notes of importance pertaining to Covid and accessibility. Confirmation of team selection was not made until June 2021, approximately 1.5 months prior to the start of the OG, therefore the 3-year training period was periodized for specific major competitions within this time frame. Loading across the 3-year period is depicted in Figure 6.1. Due to the constraints elicited by Covid and abrupt changes in accessibility, the 3-year period has been segmented into 3-time frames, representing pre, during and post Covid.

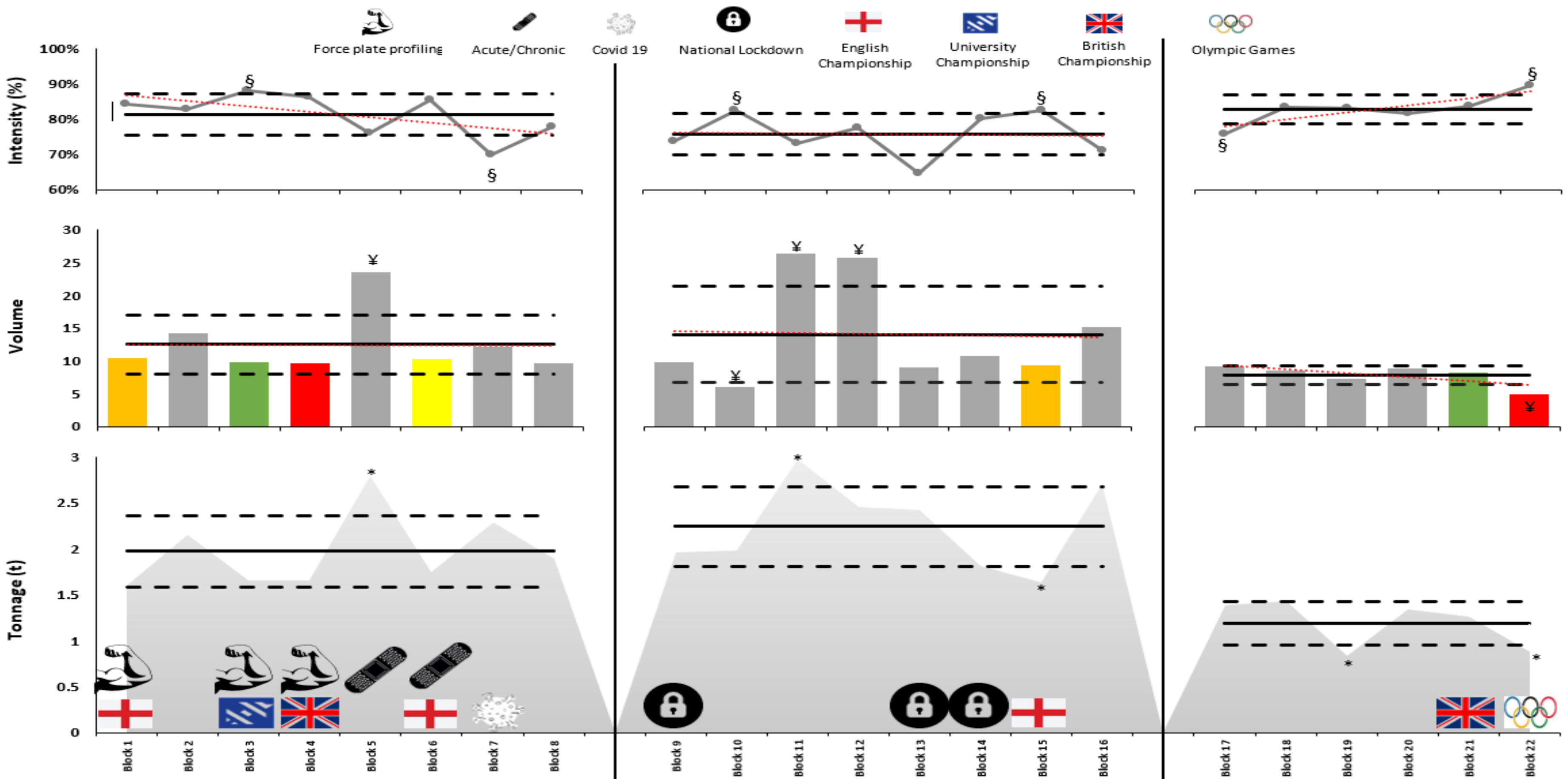


Figure 6.1. Macro cycle tonnages displayed over each mesocycle. Solid black line represents average tonnage, volume or intensity. Dashed black lines represent ± SD from the average for tonnage, volume and intensity. Red dotted line represents linear trend for average intensity and volume. * represents meaningful changes in average tonnage, ¥ represents meaningful changes in average volume, § represents meaningful changes in average intensity.

6.2.4. Statistical analyses

Often, sport science studies utilise conventional statistics based on means of a sample population (Kinugasa, Cerin and Hooper 2004). Whilst useful in providing the scientific community with generalisable findings in specific groups, it can often mask important information on individuals. This issue is concerning particularly around elite athletes that compete in individual sports, such as weightlifting. Single subject case study's therefore maybe preferable particularly in the case of analysing elite individuals (Sands *et al.,* 2019). An inherent issue with case study designs within the elite population often means there is a lack of a controlled experimental design, given the dynamic nature of training which may often interrupt phases of training and availability of monitoring (Sands *et al.,* 2019). Furthermore, the quasi-experimental nature of this study highlights the barriers that maybe experienced which are out of control of the scientist or coach.

Given the issues highlighted above, the application of traditional methods of statistical analyses means assumptions of the data will be violated, if at all available in the first instance. Therefore, the methods of analysis employed to determine meaningful changes in all performance measures (neuromuscular and technical) were made by adopting methods outlined by Sands *et al.* (2019) and more recently Turner *et al.* (2022), where the athletes own variability of the performance measurement is used to identify if change has occurred between time points.

All neuromuscular performance data and training technical data is presented as means ± standard deviation (SD). Inference as to whether meaningful change had occurred outside of the variability of the test, required the lower limit SD to be greater than that of the previous time points upper limit SD. This is depicted visually accompanied by percentage change, a value commonly used to help contextualise changes when reporting back to athletes. Peak vertical velocity derived from the snatch were also assessed using the mean ± SD. Performance predictions for the Tokyo OG were calculated utilising a polynomial regression equation extracted from chapter 2 (Chavda *et al.,* 2023), specifically;

$$-0.023x2 + 6.293x + -15.190$$

This was used in conjunction with the sum of the best snatch and CJ achieved from historic performance ± SD from each competitor within the 96kg weight category plotted with predicted zones. In addition to this, a competitor "cheat sheet" was also developed, allowing identification of opportunities to best position the athlete to obtain the highest rank possible with a realistic idea of whether the target of a top 10 rank could be achieved.

6.3. RESULTS

6.3.1. Changes in Training Load

Mean training volume-load pre Covid was 1.98 ± 0.38 tonnes which increased by 13% to 2.25 ± 0.43 during Covid. This was elicited from an increase in average volume which went from 12 ± 4 repetitions to 14 ± 7 accompanied with a concurrent decrease in average intensity reducing from 81 ± 6% to 75 ± 6%. Between Covid and post Covid, volume-load saw a significant decrease dropping from 2.25 ± 0.43 to 1.19 ± 0.24 tonnes. A primary reason for this was the increase in average intensity which rose from 75 ± 6% to 84 ± 4% and the reduction in average volume (14 ± 7 vs 8 ± 1 repetitions). The greatest variability in training load is evident during Covid where training accessibility was limited due to both facility, lockdown restrictions and key worker commitments (Figure 6.1). Training load distributions by block can be viewed in Appendix 6.4.

6.3.2. Neuromuscular Performance Changes

Due to acute wrist injury followed by national lockdowns, neuromuscular performance testing was only conducted during the first three competitions in 2019, pre Covid. Figure 6.2 depicts changes in CMJ jump height, propulsive impulse, countermovement depth and propulsion time. Figure 6.3 depicts the changes in IMTP performance for net peak force, relative net peak force and force at 150 and 200 ms. The most significant change occurred between EC19 and BU19, where net propulsive impulse had increased 12.1%, consequently increasing jump height. Mechanistically, the time taken during the propulsion phase did not change, however, depth of the countermovement increased by 17.1%, suggesting an improvement in the athlete's ballistic force expression. This increase in propulsive force expression was supported by a significant increase of 5.6% in net peak force during the IMTP. Interestingly, force at 150 ms and 200 ms both decreased between EC19 and BU19, but significantly improved between BU19 and BIO19 by 14% (150 ms) and 12.4% (200 ms). This was accompanied by an increase in net peak force (4.1%) and relative net peak force (4.7%).

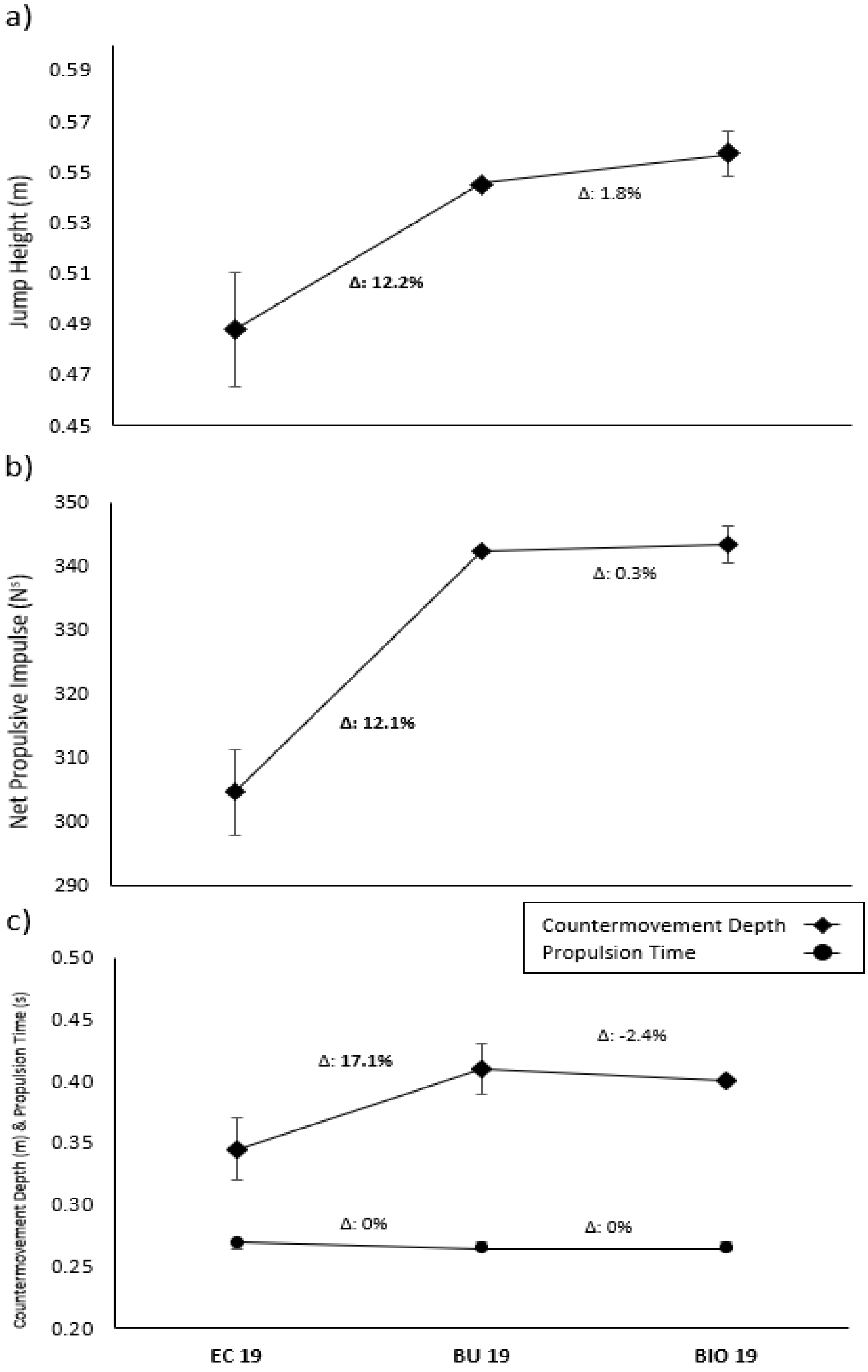


Figure 6.2. Changes in countermovement jump; a) jump height, b) propulsive net force, c) propulsive time and countermovement depth. All changes presented as mean ± SD over the 3 time points they were collected. Maximum values shown as hollow circle. Percentage change of mean score shown between time points. Where EC = English Championship, BU = British Universities Championship and BIO = British International Open.

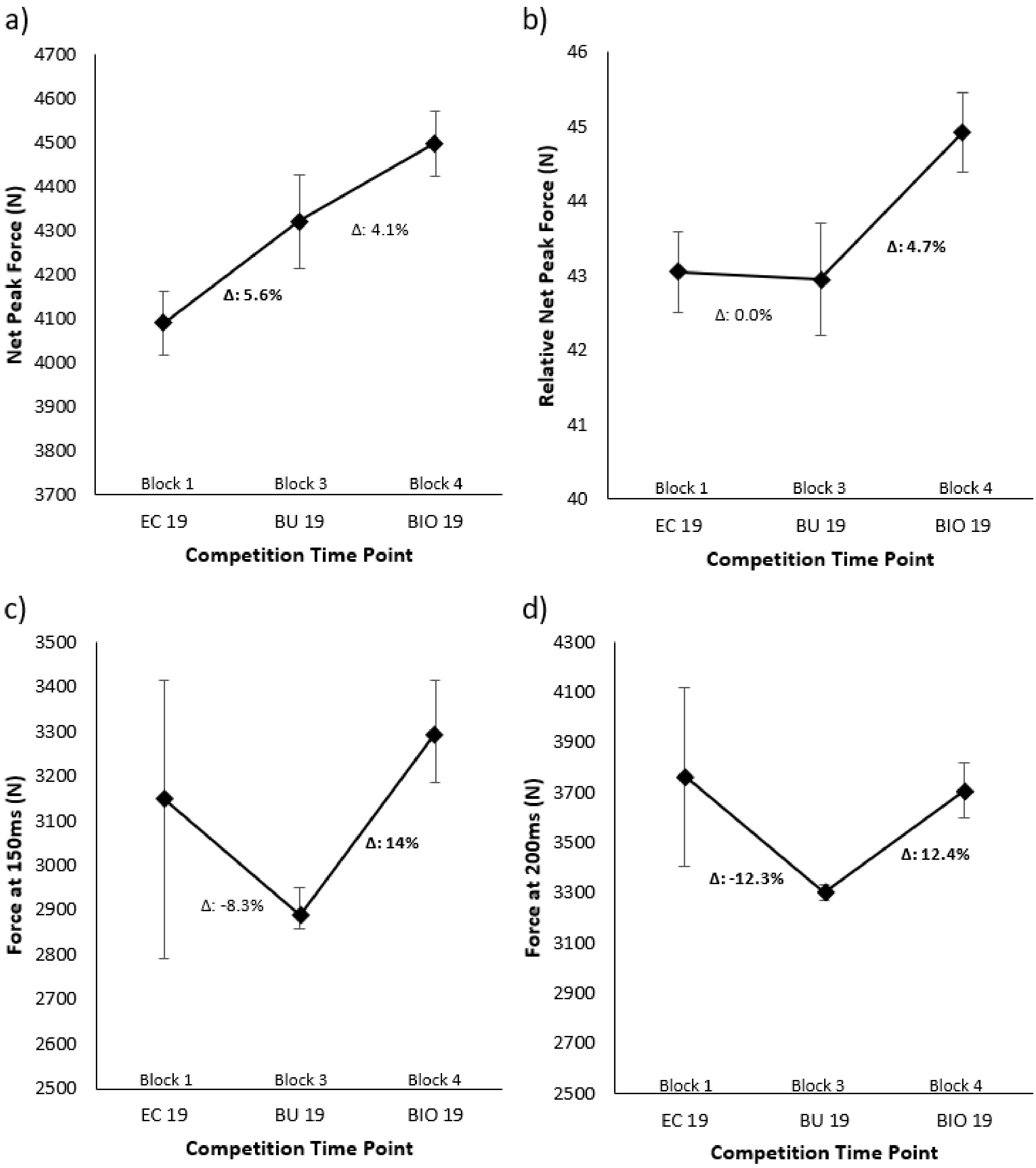


Figure 6.3. Changes in IMTP; a) net peak force, b) relative net peak force, c) force at 150 ms and d) force at 200 ms (mean ± SD). All changes presented as mean ± SD over the 3 time points they were collected. Percentage change of mean score shown between time points. Meaningful differences are shown in bold. Where EC = English Championship, BU = British Universities Championship and BIO = British International Open.

6.3.3. Competition Performance Changes

Competition performances are depicted in Figure 6.4. Changes in absolute performance total leading into the Olympics were 0.43 ± 3.20%, with the biggest decrement occurring during the EC21 (-4.71%) which took place virtually during national lockdown. The biggest increase in performance was between EC19 and BU19 for an increase of 5.56%, with a concurrent increase in bodyweight category from 96 kg to 102 kg. At his Olympic category of 96 kg, the athletes biggest increase in performance was between EC21 and BC21 for an increase of 2.86%. When total performance was made relative to weight category, his best performances were at the BC21 and OG achieving 3.65, where he achieved his highest snatch (160 kg) and CJ (195 kg) as a 96 kg, respectively. During this 3-year period, the athlete had broken multiple national records over two weight categories. Internationally, the athletes personal target of a top 10 finish at the OG was also achieved, likely due to the disqualification of 2 athletes and the 5.89% lower than predicted performances. Historic performance ± SD from each competitor within the 96 kg weight category plotted with the predicted zones can be seen in Figure 6.5. The competitor cheat sheet used during the OG can be seen in Appendix 6.2.

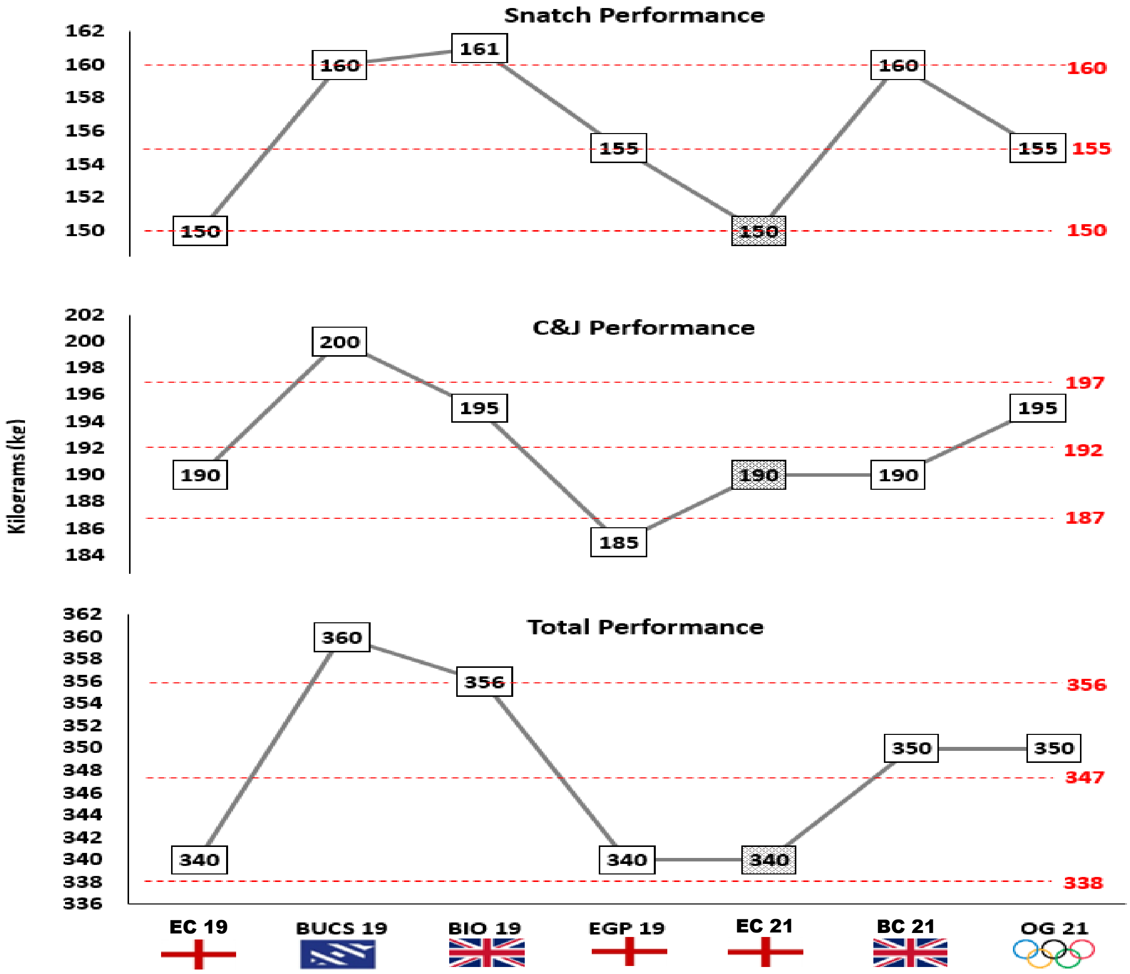


Figure 6.4. Weightlifting performances achieved at each competition. The grey patterned filled boxed denotes a competition within the Covid period. The red line represents mean ± SD of pre Covid performances (i.e. EC 19 to EC 21). A detailed breakdown of each competition is available in Appendix 6.3.

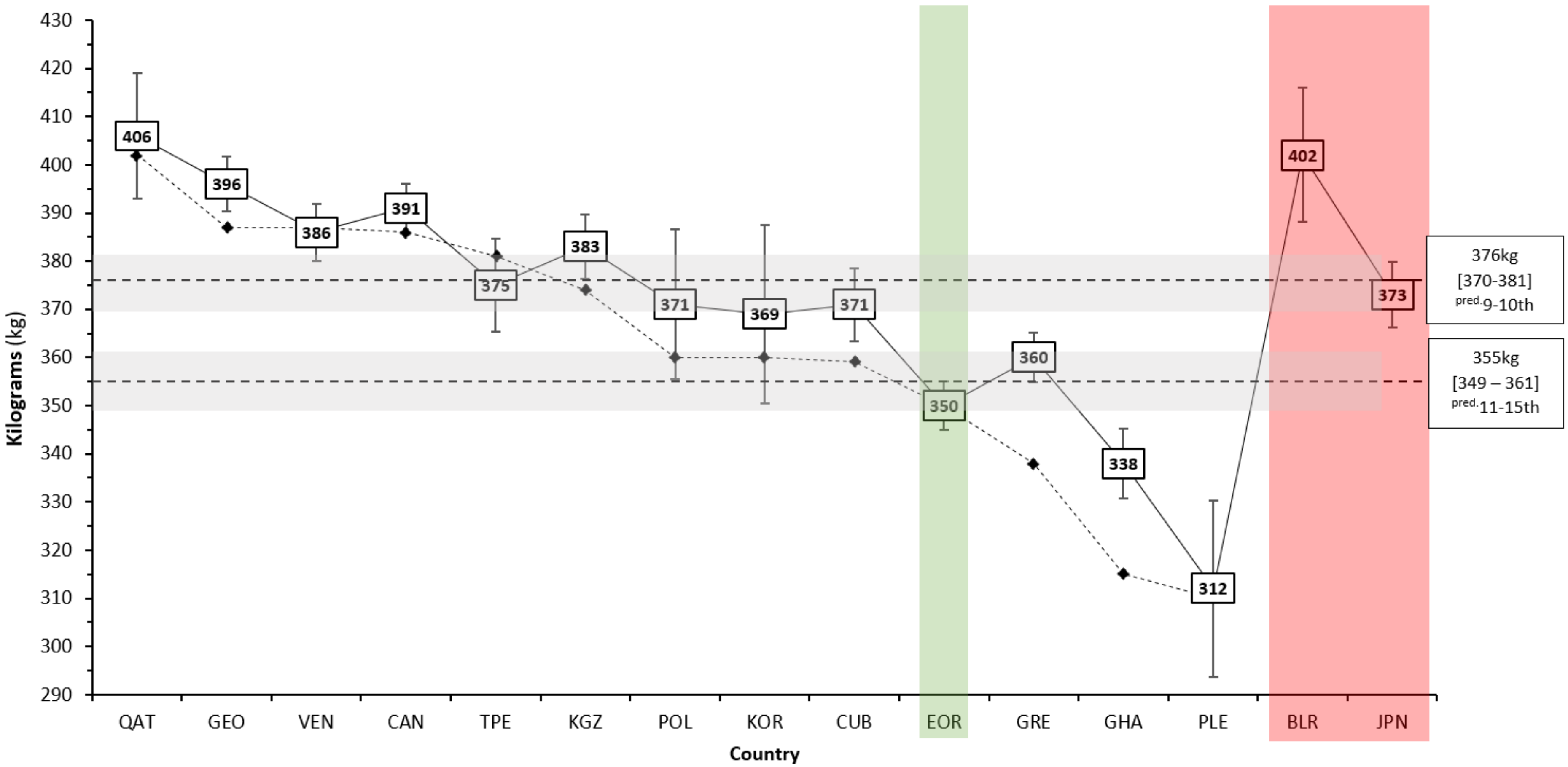


Figure 6.5. Competitor total based on best snatch and jerk performance, plotted against predicted performance zones for 11-15th and 9-10th place ± [SD]. Diamond markers identify the actual performance achieved. Order of competitor organised by rank at the end of competition (Men's 96 kg Olympic Games). Green indicates the athlete under investigation, with red denoting those who did not achieve a total.

Barbell Kinematic Changes

Changes in PBVv are depicted in Figure 6.6. The start of block 21 had a meaningful increase in PBVv relative to block 20, with PBVv also showing a meaningful increase toward the end of the taper in block 22, 7 days out from competition.

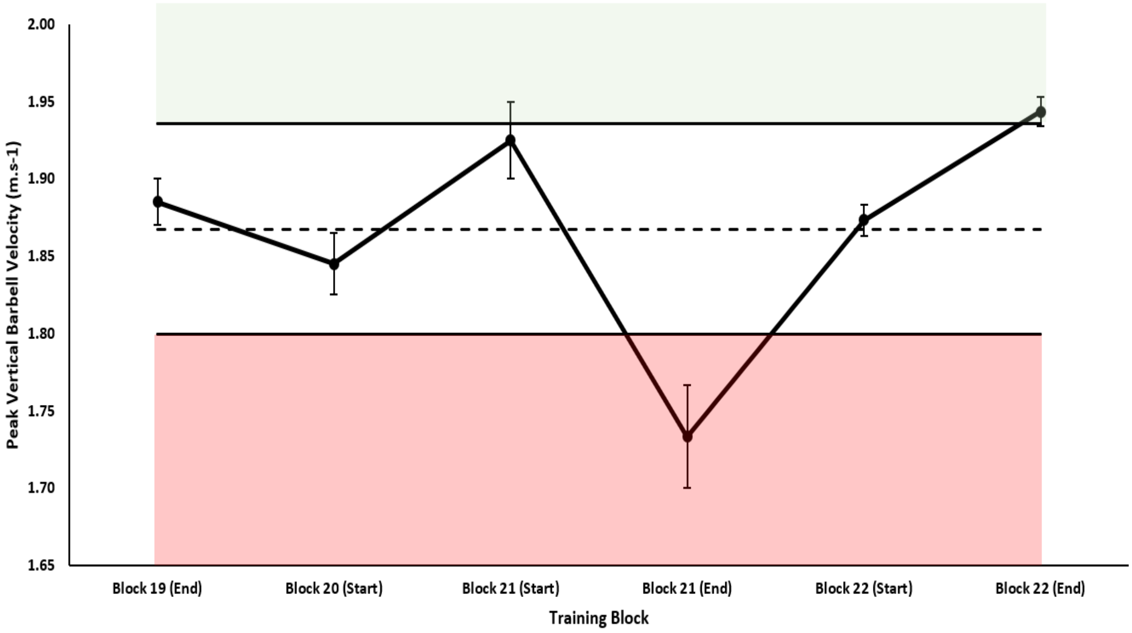


Figure 6.6. Changes in snatch peak barbell vertical velocity at 140kg over the sport specific training block (Block 19) leading into the competition training blocks (20-21) and taper (block 22).

6.4. DISCUSSION

The purpose of this case study was to examine time course changes in weightlifting performance in relation to changes in neuromuscular ability and barbell kinematics in an elite weightlifter preparing for the Olympic games over a 3-year period. To the authors knowledge this is the first study to present a holistic, longitudinal analysis of an elite weightlifter, that encompasses key aspects of weightlifting performance and is also the first study conducted on an Olympic refugee athlete. The primary results of this case study indicated that performance increases were evident during 2019 which also displayed concurrent increases in force capacity and expression as measured in the IMTP and CMJ. The disruption caused by Covid saw a decrease in average training intensity and a more varied application of volume. Evidently this caused a reduction in performance. Following Covid, and with an enhanced level of training accessibility, training intensity saw an exponential increase from block 17 to 22, in preparation for the OG. This had a positive effect on PBVv, particularly during the taper in block 22.

Concurrent decreases in volume in the lead up to the OG meant overall training load was significantly less than during Covid. Predicted competition performance at the OG highlighted that a top 10 finish would require a total of 376 kg. Given the pandemic was global phenomena with each country being affected differently, overall performance from the men's 96 kg weight class was 5.89% less than that of the prediction as depicted in figure 6.5 (Chavda *et al.,* 2023). Additionally, with 2 athletes failing to make a total, the top 10 target was achieved. This discussion will look to identify potential reasons for changes in performance as affected by the manipulation of training.

6.4.1. Pre Covid

Prior to Covid the athlete had competed in 3 competitions with a focus on the British International Open (BIO). Following the British University Championships (BU) 2019 in block 3, the athlete experienced the most meaningful increases in force capacity and expression through increases in isometric net peak force and concentric impulse. This seemed to have manifested itself into both the snatch and jerk, where lifetime personal best was achieved of 160 and 200 kg, respectively. A potential reason for these increases could be associated with training load and distribution elicited during blocks 2 and 3. Block 2 had a high proportion of training focused on pulls, squats and accessories (29%, 13% and 32% respectively). As the BU wasn't a key competition, block 3 continued to develop overall strength as evident by the continued focus on pulls, squats and accessories (39%, 12%, 27%). Clearly this had a positive impact on performance, with net peak force and propulsive impulse significantly increasing. Interestingly, while it is expected for isometric net force to increase during this period, propulsive impulse during the CMJ also increased, but so did the depth of the countermovement. However, the time take during the propulsive phase did not change, inferring that the expression of force during this phase had increased as a consequence of increased force and not time. This positive adaptation in force capacity and expression, occurred at a point when then athletes body weight increased, however, as relative net peak force (NPF) did not change between block 1 and block 3, this infers that bodyweight and force expression concurrently increased when moving from the 96 kg weight category to the 102kg weight category.

During block 4, in preparation for the BIO, the athlete further increased his snatch by 1 kg, although had a 5 kg reduction in the CJ achieved. While this may be the case objectively, the athlete had cleaned 205 kg during the competition, but missed the jerk, therefore being a no lift. This further increase in clean performance may have been associated with increases observed with NPF, relative NPF and force at 150 and 200 ms. Although force capacity and expression had increased within the IMTP, this was not obviated in the CMJ, where no change was evident. These findings are somewhat surprising, especially given that relative NPF had increased. Collectively, the changes observed in IMTP and CMJ over the 3 time points suggest the following: 1) the increases in NPF were associated with increases in both snatch and clean performance, 2) force at 150- and 200 ms maybe independent of performance given that there was a decrease in between block 1 and block 3, but with block 3 showing an overall increase in performance. During the BIO competition the athlete experienced some acute wrist and elbow pain, therefore a 3-week gap ensued before starting block 5, where volume exponentially increased with a decrement in intensity. The reason for the exponential increase in volume was due to the larger distribution to accessory type exercises (81%) coupled with pulls (19%) as to allow the wrist and elbow to heal. A review by Suchomel, Comfort and Stone (2015) suggests that by using weightlifting pulling derivatives, the athlete would decrease the number of collisions with the bar, thus decreasing the overall impact on the athlete's upper body (in this instance the wrist and elbow). Additionally, a position statement on the use of weightlifting for sport performance state that utilising pull only derivatives may concurrently enhance or maintain technique of the pull, but also enhance force generating capabilities (Comfort *et al.,* 2023).

As block 6 concluded with a national competition, it was decided that a shift to strength and re-addition of weightlifting exercises would need to be prioritised, thus the large reduction in volume and concurrent increase in intensity. As this competition was of low importance and following recovery from an injury, competition performance reduced from 356 kg to 340 kg, with the significant decrease in total performance associated to a reduction in the CJ performance (195 kg down to 185 kg). Additionally, the athlete's bodyweight was reduced to <96 kg with the hope of selection for the 2020 OG. Following the EGP, the athlete had a 10-week hiatus to structured training due to the increase workload within the NHS and subsequently had caught Covid during this period. Therefore, given that recovery was needed for his wrist and elbow and with Covid, personal time was taken, where training was not monitored due to lack of frequency.

6.4.2. Covid

On March 24th, 2020, it was announced that the Tokyo 2020 OG would be delayed to no later than summer 2021. This announcement shifted the training focus to GPP; however, the pandemic had a profound impact on accessibility to training and coaching contact. Therefore, training blocks were reduced to 4-week mesocycles to allow for more frequent adjustments in the training schedule, but also to allow for some loose structure. Between block 10 and 11 and 12 and 13, 7-week hiatus was taken in training. This was due to the change in lockdown rules and the athlete having to balance being a key worker. Consequently, the largest training volumes were during block 11 and 12, with a large proportion of training focusing on accessories, pulls and squats.

It has been established that training cessation for short periods of time (3-5 days) has minimal effect on lower body maximum strength (Travis et al., 2022). However, longer periods, such as those presented in the current case study due to Covid and the athlete's commitment as a key worker, may prove detrimental in the sustainability of such physical qualities. A meta-analysis from Bosquets et al (2013) report that only a small decrement in strength occurs following training cessation, but this grows significantly after a 3-week period. It is hypothesised that this is likely due to central factors, with peripheral factors contributing to a decay in strength as a function of time. As the expression of force in short amounts of time is of high importance in weightlifting, the influence of training cessation on rate of force development (RFD) should also be considered. A meta-analysis from Grgic and Ivana (2023) reported that minimal changes occur in RFD providing sufficient training had preceded it. It has also been reported that speed-strength is better maintained during training cessation if the previous methods of training had focused on developing explosive strength (i.e. Weightlifting) (Mujika and Padilla., 2012). In the instance of this case study, the athlete had continual blocks of training longer than that of the training cessation, thus likely better preserving strength (Grgic and Grgic, 2023). The attempt to reduce the impact of detraining and injury risk was mitigated by reintroducing preparatory mesocycles. This reintroduction of general preparation was to allow the athlete to develop a general capacity that may allow him to be more resilient to higher intensities in future training blocks (Stone *et al*., 2006). During block 15, elite athlete exemption was granted to enable full time training in the UK. As this block had an online competition, it was decided to use that as a benchmark of return to training. This meant a significant increase in training intensity was adopted coupled with a decrease in volume.

Evidently there was no change in overall total achieved since the previous competition (340 kg).

6.4.3. Post Covid

Once restrictions of Covid had been lifted (March 2021), training resumed as normal, with the focus being peaking for the OG. The team was announced 8th June 2021, 2 months prior to the games during block 20. However, in anticipation of selection the focus of blocks 17 to 19 was on gradually developing intensity in the competition lifts. This would also allow the athlete to prepare for an online national championship approximately 3 weeks prior to the OG. This then became a benchmark of performance going into the taper, where a target of 160 kg Snatch and 190 kg CJ was set. During block 19 to 22 it was possible to monitor barbell kinematics utilising an Enode sensor during some key sessions. Recently, longitudinal case study research on two elite weightlifters by Sandau and Granacher (2022) measured force-velocity relationships and theoretical snatch 1RM over a 40-week period in preparation for the European and World Championships, qualifying events for the Tokyo OG. The authors found that theoretical velocity ($\bar{v}_0$) decreased whilst theoretical force ($\bar{F}_0$) and power ($\bar{P}_0$) increased following a peak.

While the present study was unable to identify changes in force velocity profiling in relation dose-response, it was able to utilise pre-determined theories of velocity monitoring in understanding preparedness and neuromuscular adaptation. While maximal load for the snatch was not possible to analyse, monitoring the peak velocity of same load longitudinally should theoretically give an indication of adaptation. Given that displacement of the barbell remains relatively consistent within individuals during the snatch (~70% of height) (Ho *et al.,* 2014), an enhanced peak velocity at given load (i.e. 140 kg), would suggest that the force applied has increased, inferring a positive training adaptation has taken place.

Conceptually this has been evidence in velocity-based research utilising strength exercises, where it has been suggested that being able to move the same load faster is indicative of increased neuromuscular ability (Cunanan *et al.,* 2018). Similar to the loading paradigms presented by Sandau and Granacher (2022), the competition mesocycles were formulated of medium to large training loads and low volume, suggesting a focus on intensity to optimise strength in pulling movements and power in the competition lifts. In order to optimise training in preparation for a major competition, saturating key biomotors that influence outcome (in this case maximal force and power development) without overtraining must be considered. It is therefore imperative that an appropriate tapering strategy is utilised to best dissipate fatigue and induce supercompensation. A study by Winwood *et al.* (2023) identified some key practices by weightlifting athletes through a survey on 144 competitive weightlifters, 34 of which were international. Their findings suggested that tapering strategies would often use 8 ± 4.4 days with the most common taper being linear. During the taper it was common to see a reduction of volume of 41.3 ± 14.6%, values similar to that reported in a meta-analysis by Bosquets *et al.* (2007) of 41-60%. The purpose of the taper is to allow for fatigue dissipation accumulated from prior training weeks, which consequently results in an increase in performance. Both major competitions during this case study (BIO and OG) had a reduction in training volume of 57 and 53%, respectively. The heaviest lifts attempted were typically 6 days out from competition day with intensities reaching ~95%. This seems to align with practices outlined by Winwood *et al.* (2023) where the final heavy session would take place 5.3 ± 2.3 days out from competition. This is evidenced within block 22's microcycle, where the final heavy session was conducted 5 days prior to competition. A reflection of the success of the taper is evident from the increase in PBVv from the start of the taper to the end, which showed an increase of 4% (1.87 ± 0.01 m·s^{-1} vs 1.94 ± 0.01 m·s^{-1}), suggesting that the taper strategy provided the necessary supercompensation effect.

While easy to obtain and monitor, some considerations around using peak velocity in isolation must be considered to appreciate how the athlete is able to achieve optimal barbell height to successfully receive and catch it overhead. Following the end of the second pull, the barbell will achieve its peak vertical velocity, in which acceleration would be 0 m/s^2. It is postulated that a minimum threshold vertical velocity would need to be achieved to facilitate optimal vertical displacement (Sandau, Chaabene and Granacher, 2021). However, from this point, during the turnover, the athlete must continue to apply some upward (and slightly rearward) work on the barbell to position it over their base of support in order to receive it. Knowing the height at which peak velocity is achieved relative to peak barbell height, and the difference between the two may provide some indication on the effectiveness of the pull and turnover (i.e. a more efficient athlete having a smaller vertical displacement between the two).

It becomes obvious that adaptability in the support of elite athletes is a necessity in instances where objective methods of monitoring become difficult. Often, case studies are characterized by repeated observations of an individual made under unsystematic and uncontrolled conditions, often in retrospect (Heppner, Kivlighan, & Wampold, 2008). In the instance of this case study, while an effort was made in collecting consistent performance related data, accessibility to training and equipment due to Covid meant alternative strategies were adopted to help monitor and inform the training process as a means of adapting to the circumstances. Therefore, identifying limitations within this case study lends itself to a critical evaluation of practices that can be adopted for future monitoring and best practice within elite weightlifting.

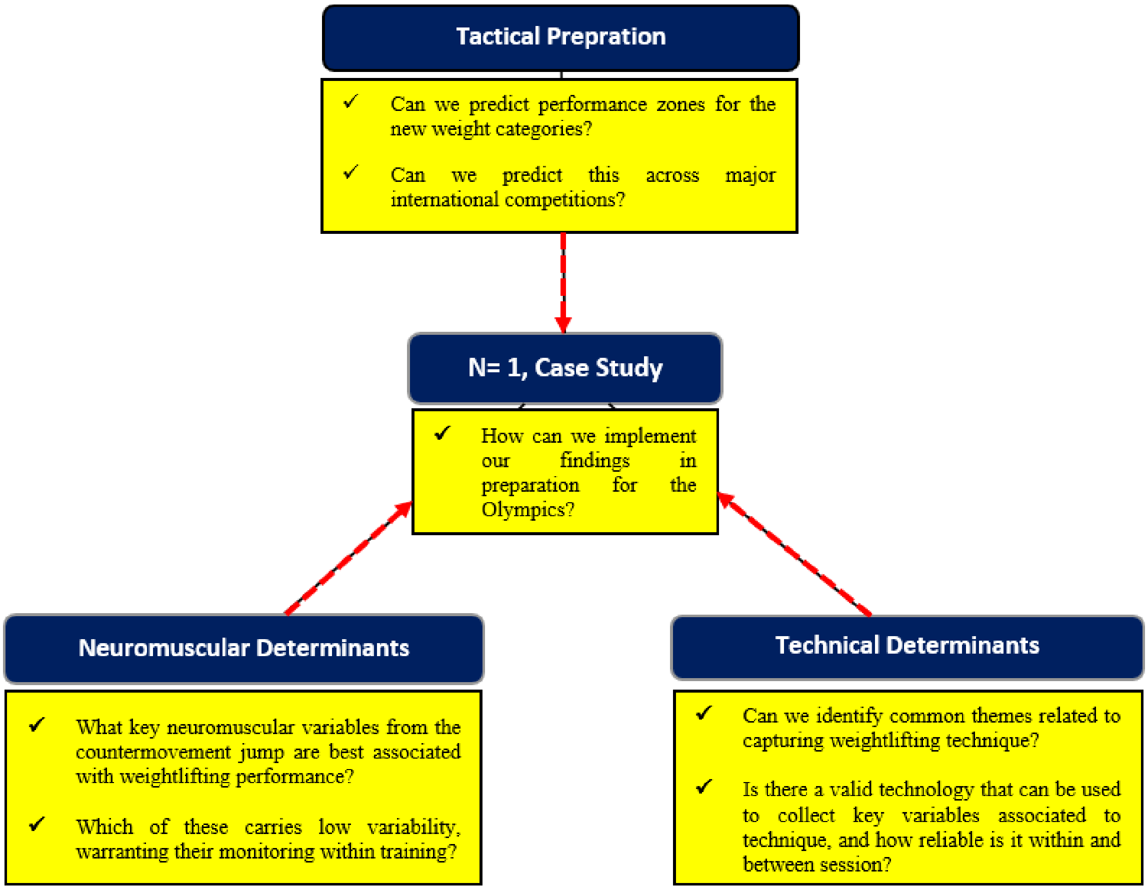
The present study utilised methods in isolation, due to accessibility, but still provides some insight into the dose-response of training throughout the macrocycle. Firstly, methods of monitoring neuromuscular ability in conjunction with barbell kinematics and gym based RM's may help to give a more holistic view of the adaptation process. Much like the pre-Covid implementation of neuromuscular testing, monitoring should be allocated at specific periods within the meso cycle as to help identify if the intended adaptation has occurred. Research from Neupert (2022) found that 84% of elite sports in the UK commonly conducted performance testing. Gym loading made up 80% of the monitoring which in the sport of weightlifting is a necessity. However, future research should consider the collection of prescribed vs actual loads lifted for a true indication of training load. This would also allow for greater flexibility in the programming allowing the athlete work between ranges (i.e. 85-90% 1RM top set) based on their current daily preparedness. In conjunction with this, methods utilising VBT for strength-based exercises (i.e. squat) may also help regulate neuromuscular stress experienced throughout training, thus potentially allowing the athlete to distribute more training volume or intensity on weightlifting exercises. In preparation for competition, particularly during the taper, methods presented by Sandau, Chaabene and Granacher (2021) on utilising force velocity profiling for the snatch high pull may help to identify the athletes current estimated 1RM snatch with good accuracy (Sandau, Chaabene and Granacher, 2021; Sandau, Chaabene and Granacher, 2022), this in conjunction with predictive performance zones may help with the selection of opening weights during competition.

Lastly, many studies, including the present, have utilised surrogate measures that do not identify specific deficits within the phases of the lifts. Research from Sandau and Granacher (2020) suggest that identifying the phase of lift in which the lifter loses the most velocity as the load increases may help to better direct training specificity. In the present study it was not possible to do this as retrospective data was used which excluded video capture, thus making it impossible to accurately identify the first pull. However, future research should look to identify the phase which limits overall barbell speed and distribute greater training volume to enhance this phase to see its influence on not only velocity loss, but also whether overall lift performance increased. This can also be coupled with additional isometric tests from the knee or set position to identify potential relationships between velocity changes at the end of each phase, relative to the maximal force at that phase. These alternative positional isometrics have been utilised in previous weightlifting research which identified strong relationships with weightlifting performance (Joffe, Price and Tallent, 2021; Ben-Zeev, Sadres, and Hoffman, 2023).

CHAPTER 7: GENERAL DISCUSSION

7.1 SUMMARY FINDINGS OF THE THESIS

This thesis aimed to provide a better understanding of weightlifting performance, through: a) predicting key performance zones at major international competitions, b) providing a review of methodologies used to monitoring and assess weightlifting technique, c) identifying a valid in-field technology to monitor weightlifting technique whilst concurrently identifying the reliability of key variables worth monitoring within and between sessions, d) identifying key variables from the countermovement jump that serve as a highly sensitive variable that is best associated to weightlifting performance and e) utilising the aforementioned findings in the preparation, monitoring and training of an elite weightlifter for the Tokyo Olympic Games. Figure 1.1 was used a schematic to highlight the chapter focus and the questions that were answered. Below depicts the complete figure.



Tactical Prepration

- ✓ Can we predict performance zones for the new weight categories?
- ✓ Can we predict this across major international competitions?

N= 1, Case Study

- ✓ How can we implement our findings in preparation for the Olympics?

Neuromuscular Determinants

- ✓ What key neuromuscular variables from the countermovement jump are best associated with weightlifting performance?
- ✓ Which of these carries low variability, warranting their monitoring within training?

Technical Determinants

- ✓ Can we identify common themes related to capturing weightlifting technique?
- ✓ Is there a valid technology that can be used to collect key variables associated to technique, and how reliable is it within and between session?

A key finding from study 1, chapter 2 was that performance zones utilising historic performance data could accurately predict some, but not all weight categories within different performance zones. It is likely that the actual data utilised to compare the predicted model values to may have been influenced by the pandemic where training accessibility across countries would have varied, potentially a reason for the common overestimation from the model. However, this study does provide some key information which may help in the selection process of athletes and may also help performance teams identify areas of opportunities where minimum performance can be met to sustain an athlete place on a national team or even influence funding received.

While understanding what loads need to be lifted to achieve a specific performance zone can be useful, exploration as to how these are achieved can be segregated into two simple themes; technique and neuromuscular ability. Chapter 3 provided a scoping review of the literature on the methods of biomechanical analysis in competitive weightlifters. A major finding was that many of the articles analysed captured data within competition, providing information that is highly ecologically valid. However, many of the studies, including those conducted within laboratories, were characteristic in nature or compared varying weight categories and, or successful and unsuccessful lifts. While this may provide insight into what factors coaches should pay attention to and thus train, it does not provide details into whether some of these variables are sensitive to change. Furthermore, the identification of phases throughout the literature varied, with the most common being using change in knee joint angle and barbell kinematics such as vertical displacement or velocity. This would often be dependent on the equipment used to capture the movements, which would typically consist of multi-camera set ups or custom equipment, not available to the public. Therefore, this highlighted that accessibility to such methods maybe difficult, particularly in busy coaching environments. Given the enhancement in technology, alternative methods should be explored, while concurrently identifying key variables to worth monitoring within and between sessions, to ensure meaningful changes in technique can be identified.

Following the identification of gaps in the existing literature, study 3 investigated the validity and concurrent within and between session reliability of a commercially available inertial measurement unit (IMU). The findings showed that the IMU demonstrated good validity for most variables, particularly in measuring peak velocity. However, it overestimated horizontal displacement, showing fixed or proportional bias. The within-session and between-session reliability of the IMU were good to excellent for variables such as velocity and vertical displacement. Horizontal displacement measures displayed larger variability. In conclusion, while the literature review in chapter 3 often stated that a differentiating factor between successful and unsuccessful lifts was the minimisation of horizontal barbell displacement, particularly following the second pull, our results found that horizontal displacement carried high variability and therefore identifying meaningful change may prove difficult.

The ability to favourably manipulate the barbell trajectory and achieve a displacement height on the barbell which provides the lifters enough time to turnover and receive the barbell will be partly governed by their neuromuscular ability. Often, various outcome measures of the countermovement jump have been utilised as surrogate measures of weightlifting performance. However, underpinning mechanisms that determine these outcome measures had yet to be investigated. Our findings were novel, in that propulsive impulse carried the greatest level of reliability and had the strongest association to snatch, clean and total performance in national weightlifters, for both men and women. Our findings reported stronger relationships than previously published articles on jump height and peak power. These findings provide performance scientists and coaches with information on the ballistic qualities which are akin to the second pull and drive phase of the jerk, which are critical phases of the lifts. Furthermore, its high level of sensitivity allows for coaches to alter training strategies based on neuromuscular fluctuations.

The final study was a case study which implemented the previous chapters key findings and implemented them longitudinally over a period of ~ 3 years, in preparation for the Tokyo Olympic Games. Unfortunately, the pandemic presented accessibility barriers in which the monitoring process was heavily disrupted and therefore were only able to be used in isolation at certain periods throughout those 3 years. Key findings, however, showed that increases in performance aligned with concurrent increases in isometric mid-thigh peak force and CMJ propulsive impulse. Furthermore, tapering strategies adopted prior to the games saw a meaningful decrease in volume load with a meaningful increase in average intensity, which saw peak barbell vertical velocity increase prior to competition. Lastly, the predictive model for the men's 96kg weight category overestimated the actual performance by ~6%, but due to the lower performance and 2 athletes not posting a total, the target of a top 10 finish was achieved, with an average snatch performance (155 kg) and above average CJ performance (195 kg).

7.2 KEY LIMITATIONS IDENTIFIED IN THIS THESIS

- Study 1 utilised actual performances taken directly after Covid restriction had been lifted and competitions could resume. This likely contributed to the overestimations shown by our models.
- Study 3 utilised regional and national weightlifters. The variability in barbell trajectory is likely to be lower at submaximal loads in higher performing weightlifters.
- Study 3 only investigated 85% of snatch 1RM. Investigation into maximal loads and loads less than 85% is warranted.
- Study 4 reported within session reliability, however, between session reliability is warranted to ensure variability in daily fatigue is accounted for if using propulsive impulse to monitor longitudinally.
- Study 5 was heavily affected by Covid. The monitoring process was unable to be holistic where surrogate measures from the neuromuscular testing and technical analysis using barbell kinematics could not be associated collectively with changes in performance.

7.3 ORIGINAL CONTRIBUTION TO KNOWLEDGE OF WEIGHTLIFTING PERFORMANCE

This thesis makes several original contributions to the field of weightlifting research and practice. These are outlined below:

1. **Development of predictive models:** The thesis provides a series of regression equations that can be used to develop predictive models for weightlifting performance. These models offer valuable insights into potential performance zones of interest at major international competitions, thus providing some utility in selection processes and optimisation of international rank.
2. **Predicitve model application among the wider weightlifting population**: the thesis presents a methodology that can be applied to develop predictive models for other demographics within weightlifting, such as females, juniors, and youth. This expansion

of predictive modeling techniques enhances the applicability and utility of the research findings across different populations.

3. **Appropriate identification of weightlifting phases**: The thesis identifies clear methods for defining the distinct phases of weightlifting movements highlighting how difference technologies may determine how the phases are defined. This clarity in defining movement phases contributes to a better understanding of the biomechanics and kinematics involved in weightlifting techniques.
4. **Validation of a commercial IMU for monitoring weightlifting technique:** the thesis offers insights into the validity of using a commercially available IMU for monitoring weightlifting technique within the training environment. This allows for data collection with minimal processing and offers immediate feedback which may aid in the coaching process.
5. **Identification of key barbell mechanics within and between sessions:** with validity of the IMU determined, investigation into the reliability of of common mechanical variables associated to weightlifting technique was determined within and between session. This may assist coaches and athletes objectively identify areas for improvement, and optimize training protocol, with confidence.
6. **Identifying key surrogate of weightlifting performance utilising CMJ kinetics**: this thesis identified that propulsive impulse best relates to weightlifting performance. This metric also carries low variability and thus maybe used for monitoring neuromuscular ability between training blocks and potentially talent identification.
7. **A multifacted approach in the planning, monitoring and training of an elite weightlifter:** this thesis aimed to provide insight into how the novel contributions above were utilised at an elite level in preparation for the Olympic Games. It highlighted that performance enhancement aligned with positive neuromuscular adaptations as identified through CMJ and IMTP testing. It was also identified that peak barbell velocity positively increased following an appropriate taper.

Overall, the thesis contributes valuable insights and practical tools for enhancing training strategies and assessing performance in the field of weightlifting. These original contributions advance our understanding of the sport and provide valuable resources for coaches, athletes, and researchers alike.

7.4 SUMMARY OF PRACTICAL IMPLICATIONS

- Using the predictive model values may help to identify performance zones of opportunity where key individuals maybe able to maximise their rank and in turn increase funding opportunity and, or opportunity to qualify for other major competitions (i.e. Olympics).
- The predictive model values may also provide insight into where governing bodies may want to provide greater resources if a performance zone opportunity is identified. For example, an athlete being in the 96 kg category with a total of 350 kg may rank 11-15th at a world championship, but moving to a non-Olympic category for a European championship may increase their chance of ranking above 10th with the same total.
- The phases of the lift should be determined using the change in knee joint angle and it is therefore important that this is visible when capturing data.
- The validation of the IMU enables the capture of trajectory and video simultaneously, therefore negate the need for additional cameras and space invasive set ups.
- Propulsive impulse maybe used as a part of a talent identification process given its high association with weightlifting performance.

7.5 CONCLUSION

In conclusion, this thesis presents a cohesive and holistic examination of elite weightlifting performance through a series of interrelated chapters. The chapters collectively provide a nuanced and insightful exploration of elite weightlifting performance. The interdisciplinary approach, spanning predictive modelling, biomechanics, neuromuscular factors, and real-world application, contributes to a comprehensive understanding of the subject. This thesis serves as a valuable resource for researchers, coaches, and practitioners in the field, offering practical insights and highlighting areas for future exploration.

7.6 FUTURE RESEARCH DIRECTIONS

Several future directions could expand on the themes developed in this thesis:

1. **Predictability of Performance Zones by Weight Categories**: As new weight categories in weightlifting have now been contested for several years, future research could investigate the predictability of performance zones within these categories. This

could provide valuable insights for coaches and athletes in optimizing training strategies and setting realistic performance goals.

2. **Predictability of Performance Zones for Other Subgroups**: Similarly, future research could explore the predictability of performance zones for other subgroups within weightlifting, such as women, juniors, and youth. By examining the unique characteristics and performance trends within these demographics, researchers could develop a better understanding of progression, particularly for youth weightlifters, while concurrently providing opportunities for governaning bodies to identify where to best invest funding.

3. **Reliability of Kinematics and Kinetics Across Load Ranges**: Another important area for future research is the reliability of kinematic and kinetic variables during weightlifting movements across varying load ranges. By systematically varying the intensity of loads (e.g., 70-100% of 1RM) and measuring kinematic and kinetic parameters, researchers can assess the consistency and reproducibility of movement patterns and performance metrics. This could provide valuable insights into the stability of technique and performance across different training intensities.

4. **Development of Multiple Regression Models for Weightlifting Performance**: Developing comprehensive multiple regression models that incorporate a wide range of neuromuscular measures, including gym-based repetition maxmimums and technical measures, to predict weightlifting performance. By including both traditional gym-related measures (e.g., squats, pulls, and their derivatives) and advanced neuromuscular assessments (e.g., force-time analysis), researchers can identify the most significant predictors of weightlifting success. This integrative approach could enhance our understanding of the multifactorial nature of weightlifting performance and inform the development of more effective training strategies.

5. **Looking beyond the pull**: The present thesis highlighted that a majority of the literature focused on the mechanics of the pull phase, with very little reported on the turnover, receive, and catch. While an athlete may have the necessary qualities to execute the pull, the active work conducted on the bar as load increases should also be

assessed to help identify whether the athlete requires additional attention on developing the technical and physical qualities to enhance this phase of the lift.

6. **Comprehensive profiling to identify physical and technical limitations of the competitive weightlifter:** The present thesis has identified a holistic approach into the planning and monitoring of weightlifting performance. Given recent literature have presented methods in identifying key limiting phases through load-velocity profiling, predictability of the snatch lift using high-pull velocity and the association of isometric positional force, it becomes logical to explore how these can be used in the wider planning of optimising weightlifting performance alongside those presented in the present thesis. Additionally, case series analysis of longitudinal monitoring may provide a deeper understanding of how an individual's technical and physical qualities may change during specific blocks of training and whether improvements in gym-based measures (i.e. derivative maximums) may reflect these changes.

Overall, these future directions offer exciting opportunities to further advance our knowledge of weightlifting performance and training optimization. By addressing these research questions, researchers can contribute to the continued growth and development of the sport, ultimately benefiting coaches, athletes, and practitioners in the field.

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APPENDICES

Appendix 2.1. Python data scrape script for study 1.

```
import requests, bs4, json, csv

rootUrl = "https://www.iwf.net"
pageUrls = []
eventUrls = []
eventNames = []
eventList = ["OLYMPIC GAMES","EUROPEAN CHAMPIONSHIPS","WORLD CHAMPIONSHIPS"]

#build list of page urls
for i in range(1998,2021):
    url = "https://www.iwf.net/results/results-by-events/?event_year=" + str(i)
    pageUrls.append(url)
    if(i >= 2018):
        url = "https://www.iwf.net/new_bw/results_by_events/?event_year=" + str(i)
        pageUrls.append(url)

#go to each page year by year and grab any events that match eventList, add it to eventUrls
print("Getting URLs")
for url in pageUrls:
    print(url)

    page = requests.get(url)

    try:
        page.raise_for_status()
    except Exception as exc:
        print('There was a problem: %s' % (exc))

    pageSoup = bs4.BeautifulSoup(page.text, 'html.parser')
```

```
    elems = pageSoup.select("tbody tr")
    print("Table rows: " + str(len(elems)))

    for item in elems:
        event = item.select("b")[0].text
        for e in eventList:
            if(e in event):
                if("JUNIOR" not in event and "YOUTH" not in event):
                    eventNames.append(event)
                    link = item.find("a", href=True)['href']
                    newUrl = rootUrl + link
                    eventUrls.append(newUrl)

data_file = open('data_file.csv', 'a',newline='')
csv_writer = csv.writer(data_file)
count = 0

print("Getting data")
#for each event page grab the json data and write it to csv
for eventPage in eventUrls:

    print(eventPage)
    page = requests.get(eventPage)

    try:
        page.raise_for_status()
    except Exception as exc:
        print('There was a problem: %s' % (exc))

    pageSoup = bs4.BeautifulSoup(page.text,'html.parser')
    elems = pageSoup.select('iframe')
    response = requests.get(elems[0].attrs['src'])
    iSoup = bs4.BeautifulSoup(response.text,'html.parser')
```

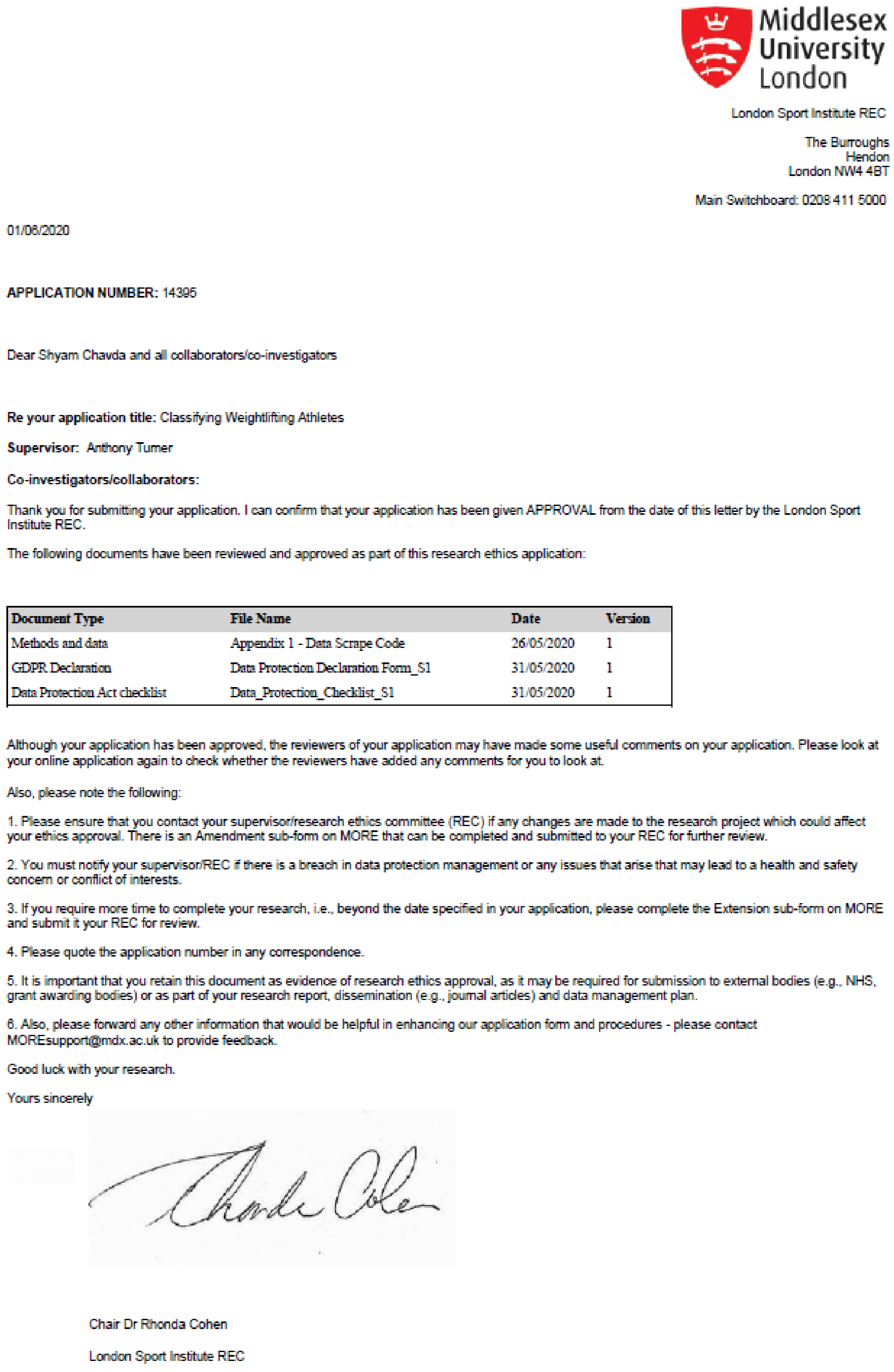
```
    dataElem = iSoup.select("#txt")
    jsonDataString = dataElem[0].text
    jsonDataString = jsonDataString[1:-1]
    jsonData = json.loads(jsonDataString)

    if(count == 0):
            head = jsonData[0]
            header = head.keys()
            csv_writer.writerow(header)
            count+=1

    for i, item in enumerate(jsonData):
        if i == 0:
            continue
        else:
            csv_writer.writerow(item.values())

data_file.close()
```

Appendix 2.2. Ethical Approval Letter for study 1.



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London NW4 4BT

Main Switchboard: 0208 411 5000

01/06/2020

APPLICATION NUMBER: 14395

Dear Shyam Chavda and all collaborators/co-investigators

Re your application title: Classifying Weightlifting Athletes

Supervisor: Anthony Turner

Co-investigators/collaborators:

Thank you for submitting your application. I can confirm that your application has been given APPROVAL from the date of this letter by the London Sport Institute REC.

The following documents have been reviewed and approved as part of this research ethics application:

Document Type	File Name	Date	Version
Methods and data	Appendix 1 - Data Scrape Code	26/05/2020	1
GDPR Declaration	Data Protection Declaration Form_S1	31/05/2020	1
Data Protection Act checklist	Data_Protection_Checklist_S1	31/05/2020	1

Although your application has been approved, the reviewers of your application may have made some useful comments on your application. Please look at your online application again to check whether the reviewers have added any comments for you to look at.

Also, please note the following:

1. Please ensure that you contact your supervisor/research ethics committee (REC) if any changes are made to the research project which could affect your ethics approval. There is an Amendment sub-form on MORE that can be completed and submitted to your REC for further review.

2. You must notify your supervisor/REC if there is a breach in data protection management or any issues that arise that may lead to a health and safety concern or conflict of interests.

3. If you require more time to complete your research, i.e., beyond the date specified in your application, please complete the Extension sub-form on MORE and submit it your REC for review.

4. Please quote the application number in any correspondence.

5. It is important that you retain this document as evidence of research ethics approval, as it may be required for submission to external bodies (e.g., NHS, grant awarding bodies) or as part of your research report, dissemination (e.g., journal articles) and data management plan.

6. Also, please forward any other information that would be helpful in enhancing our application form and procedures - please contact MOREsupport@mdx.ac.uk to provide feedback.

Good luck with your research.

Yours sincerely

Chair Dr Rhonda Cohen

London Sport Institute REC

Appendix 2.3. Matlab Polynomial Regression Script (written by Shyam Chavda and Silvio Matano)

```
%% Before using this - ensure you make a variable for the new weight category and rename it newcat.
%Also ensure you change the title of the graph to the relevant one at the
%bottom.

myDir = uigetdir; % open dialog box to select the working directory
myFiles = dir(fullfile(myDir,'m*.xlsx')); % locate all files with name % change to m to w for women

%import trials
BaseFileName=myFiles(15).name; % change (1) to the next trial when analysing
fullFileName=fullfile(myDir, BaseFileName); % builds full file name
data_in = readmatrix(fullFileName); % imports the data in from the above file.

%Extract data
BWx = data_in(:,2);
Toty = data_in(:,3);

coeff = polyfit(BWx,Toty,2);

% plot
figure
scatter(BWx,Toty,'MarkerEdgeColor','k','MarkerFaceColor','w');
[WL,gof] = fit(BWx,Toty,'poly2'); %this make the poly curve
plot(WL,BWx,Toty);
hold on
r = 1:3;
```

```
hold on

% Predict the future total of new categories using ypred optional
method is MZ_pp = polyval(MZ_coeff,newcat)
% Confidence Interval
https://uk.mathworks.com/help/stats/linearmodel.predict.html
mdl=fitlm(BWx,Toty,'quadratic');
[ypred,yci] =
predict(mdl,newcat,'Alpha',0.025,'Prediction','Curve');

% Prediction interval
https://uk.mathworks.com/help/curvefit/confidence-and-
prediction-bounds.html
fitresult = fit(BWx,Toty,'poly2');
PI = predint(fitresult,newcat,0.95,'observation','on'); % for
app change newcat to user input

% save CI and PI as lo and hi individual variables for easier
plot
loCI = yci(:,1);
hiCI = yci(:,2);
loPI = PI(:,1);
hiPI = PI(:,2);

% turns all data into a table to make it easy to save or transfer
to excel
data = table;
data.NewCatAvg = newcat;
data.Predicted = ypred;
data.lo95CI = loCI;
data.hi95CI = hiCI;
data.lo95PI = loPI;
data.hi95PI = hiPI;
```

Appendix 2.4. Data Validation: Trained vs Test model error rates.

	Zone	Trained Data Set				Test Data Set			
		RMSE	R^2	MSE	MAE	RMSE	R^2	MSE	MAE
OG	Medal Zone (1st-3rd)	9.38	0.97	88.02	7.59	9.16	0.96	83.83	7.28
	Zone 2 (4-5th)	8.45	0.97	71.389	6.116	5.187	0.99	26.907	3.821
	Zone 3 (6-8th)	10.94	0.96	119.57	7.99	8.62	0.97	74.38	6.98
	Zone 4 (9-10th)	14.57	0.92	212.14	10.66	14.12	0.92	199.40	8.79
	Zone 5 (11-15th)	23.78	0.79	565.27	18.13	28.02	0.60	784.93	21.91
WC	Medal Zone (1st-3rd)	10.90	0.96	118.75	8.80	10.11	0.95	102.28	8.36
	Zone 2 (4-5th)	10.12	0.96	102.31	7.86	8.02	0.97	64.31	6.24
	Zone 3 (6-8th)	10.94	0.95	119.75	8.33	10.86	0.96	118.14	8.33
	Zone 4 (9-10th)	12.40	0.94	153.74	9.46	13.53	0.93	183.09	9.30
	Zone 5 (11-15th)	15.61	0.90	243.60	11.67	13.95	0.89	194.51	10.97
EC	Medal Zone (1st-3rd)	13.84	0.94	191.63	10.62	11.96	0.95	143.15	9.15
	Zone 2 (4-5th)	11.15	0.96	124.41	8.83	10.04	0.95	100.71	8.30
	Zone 3 (6-8th)	13.98	0.93	195.41	10.29	12.81	0.93	164.04	9.24
	Zone 4 (9-10th)	18.14	0.87	328.91	13.97	16.15	0.89	260.00	13.52
	Zone 5 (11-15th)	22.16	0.75	491.10	16.71	22.24	0.77	494.54	17.82

Where RMSE = Root mean square error, MSE = Mean squared error, MAE = Mean absolute error, OG = Olympic Games, WC = World Championship and EC = European Championship.

Appendix 2.5. Olympic year vs year effect size

Years	Mean ± SD	*n*	Mean ± SD	*n*	ES	Descriptor
00 vs 04	352.58 ± 54.61	118	347.91 ± 55.93	110	0.08 [-0.18 - 0.35]	trivial [trivial - small]
00 vs 08	352.58 ± 54.61	118	342.84 ± 53.43	111	0.18 [-0.08 - 0.44]	trivial [trivial - small]
00 vs 12	352.58 ± 54.61	118	340.09 ± 52.94	106	0.23 [-0.03 - 0.5]	small [trivial - small]
00 vs16	352.58 ± 54.61	118	347.81 ± 55.78	114	0.09 [-0.17 - 0.35]	trivial [trivial - small]
04 vs 08	347.91 ± 55.93	110	342.84 ± 53.43	111	0.09 [-0.17 - 0.36]	trivial [trivial - small]
04 vs 12	347.91 ± 55.93	110	340.09 ± 52.94	106	0.14 [-0.13 - 0.41]	trivial [trivial - small]
04 vs 16	347.91 ± 55.93	110	347.81 ± 55.78	114	0.00 [-0.26 - 0.27]	trivial [small - small]
08 vs 12	342.84 ± 53.43	111	340.09 ± 52.94	106	0.05 [-0.22 - 0.32]	trivial [small - small]
08 vs 16	342.84 ± 53.43	111	347.81 ± 55.78	114	-0.09 [-0.35 - 0.17]	trivial [small - trivial]
12 vs 16	340.09 ± 52.94	106	347.81 ± 55.78	114	-0.14 [-0.41 - 0.13]	trivial [small - trivial]

Appendix 2.6. World Championships year vs year effect size

Years	Mean ± SD	*n*	Mean ± SD	*n*	ES	Descriptor
98 vs 99	342.35 ± 49.31	119	356.88 ± 52.28	120	-0.28 [-0.54 - -0.03]	small [moderate - trivial]
98 vs 01	342.35 ± 49.31	119	344.59 ± 54.22	111	-0.04 [-0.3 - 0.22]	trivial [small - small]
98 vs 02	342.35 ± 49.31	119	349.24 ± 52.32	109	-0.14 [-0.4 - 0.13]	trivial [small - trivial]
98 vs 03	342.35 ± 49.31	119	349.1 ± 53.31	119	-0.13 [-0.39 - 0.12]	trivial [small - trivial]
98 vs 05	342.35 ± 49.31	119	339.74 ± 58.28	118	0.05 [-0.21 - 0.3]	trivial [small - small]
98 vs 06	342.35 ± 49.31	119	341.18 ± 49.62	120	0.02 [-0.23 - 0.28]	trivial [small - small]
98 vs 07	342.35 ± 49.31	119	346.88 ± 50.4	120	-0.09 [-0.35 - 0.16]	trivial [small - trivial]
98 vs 09	342.35 ± 49.31	119	340.83 ± 49.23	120	0.03 [-0.22 - 0.29]	trivial [small - small]
98 vs 10	342.35 ± 49.31	119	346.93 ± 50.92	120	-0.09 [-0.35 - 0.16]	trivial [small - trivial]
98 vs 11	342.35 ± 49.31	119	350.39 ± 51.44	120	-0.16 [-0.41 - 0.1]	trivial [small - trivial]
98 vs 13	342.35 ± 49.31	119	338.54 ± 53.05	118	0.07 [-0.18 - 0.33]	trivial [trivial - small]
98 vs 14	342.35 ± 49.31	119	349.08 ± 51.88	120	-0.13 [-0.39 - 0.12]	trivial [small - trivial]
98 vs 15	342.35 ± 49.31	119	349.5 ± 50.5	120	-0.14 [-0.4 - 0.11]	trivial [small - trivial]
98 vs 17	342.35 ± 49.31	119	342.96 ± 51.46	113	-0.01 [-0.27 - 0.25]	trivial [small - small]
98 vs 18	342.35 ± 49.31	119	349.86 ± 48.59	145	-0.15 [-0.4 - 0.09]	trivial [small - trivial]
98 vs 19	342.35 ± 49.31	119	352.46 ± 48.76	146	-0.21 [-0.45 - 0.04]	small [small - trivial]
99 vs 01	356.88 ± 52.28	120	344.59 ± 54.22	111	0.23 [-0.03 - 0.49]	small [trivial - small]
99 vs 02	356.88 ± 52.28	120	349.24 ± 52.32	109	0.15 [-0.12 - 0.41]	trivial [trivial - small]
99 vs 03	356.88 ± 52.28	120	349.1 ± 53.31	119	0.15 [-0.11 - 0.4]	trivial [trivial - small]
99 vs 05	356.88 ± 52.28	120	339.74 ± 58.28	118	0.31 [0.05 - 0.57]	small [trivial - moderate]
99 vs 06	356.88 ± 52.28	120	341.18 ± 49.62	120	0.31 [0.05 - 0.56]	small [trivial - moderate]
99 vs 07	356.88 ± 52.28	120	346.88 ± 50.4	120	0.19 [-0.06 - 0.45]	trivial [trivial - small]
99 vs 09	356.88 ± 52.28	120	340.83 ± 49.23	120	0.31 [0.06 - 0.57]	small [trivial - moderate]
99 vs 10	356.88 ± 52.28	120	346.93 ± 50.92	120	0.19 [-0.06 - 0.45]	trivial [trivial - small]
99 vs 11	356.88 ± 52.28	120	350.39 ± 51.44	120	0.12 [-0.13 - 0.38]	trivial [trivial - small]
99 vs 13	356.88 ± 52.28	120	338.54 ± 53.05	118	0.35 [0.09 - 0.6]	small [trivial - moderate]
99 vs 14	356.88 ± 52.28	120	349.08 ± 51.88	120	0.15 [-0.11 - 0.4]	trivial [trivial - small]
99 vs 15	356.88 ± 52.28	120	349.5 ± 50.5	120	0.14 [-0.11 - 0.4]	trivial [trivial - small]
99 vs 17	356.88 ± 52.28	120	342.96 ± 51.46	113	0.27 [0.01 - 0.53]	small [trivial - moderate]
99 vs 18	356.88 ± 52.28	120	349.86 ± 48.59	145	0.14 [-0.1 - 0.38]	trivial [trivial - small]
99 vs 19	356.88 ± 52.28	120	352.46 ± 48.76	146	0.09 [-0.16 - 0.33]	trivial [trivial - small]
01 vs 02	344.59 ± 54.22	111	349.24 ± 52.32	109	-0.09 [-0.35 - 0.18]	trivial [small - trivial]

01 vs 03	344.59 ± 54.22	111	349.1 ± 53.31	119	-0.08 [-0.34 - 0.18]	trivial [small - trivial]
01 vs 05	344.59 ± 54.22	111	339.74 ± 58.28	118	0.09 [-0.17 - 0.35]	trivial [trivial - small]
01 vs 06	344.59 ± 54.22	111	341.18 ± 49.62	120	0.07 [-0.19 - 0.33]	trivial [trivial - small]
01 vs 07	344.59 ± 54.22	111	346.88 ± 50.4	120	-0.04 [-0.3 - 0.22]	trivial [small - small]
01 vs 09	344.59 ± 54.22	111	340.83 ± 49.23	120	0.07 [-0.19 - 0.33]	trivial [trivial - small]
01 vs 10	344.59 ± 54.22	111	346.93 ± 50.92	120	-0.04 [-0.3 - 0.22]	trivial [small - small]
01 vs 11	344.59 ± 54.22	111	350.39 ± 51.44	120	-0.11 [-0.37 - 0.15]	trivial [small - trivial]
01 vs 13	344.59 ± 54.22	111	338.54 ± 53.05	118	0.11 [-0.15 - 0.37]	trivial [trivial - small]
01 vs 14	344.59 ± 54.22	111	349.08 ± 51.88	120	-0.08 [-0.34 - 0.18]	trivial [small - trivial]
01 vs 15	344.59 ± 54.22	111	349.5 ± 50.5	120	-0.09 [-0.35 - 0.17]	trivial [small - trivial]
01 vs 17	344.59 ± 54.22	111	342.96 ± 51.46	113	0.03 [-0.23 - 0.29]	trivial [small - small]
01 vs 18	344.59 ± 54.22	111	349.86 ± 48.59	145	-0.10 [-0.35 - 0.15]	trivial [small - trivial]
01 vs 19	344.59 ± 54.22	111	352.46 ± 48.76	146	-0.15 [-0.4 - 0.1]	trivial [small - trivial]
02 vs 03	349.24 ± 52.32	109	349.1 ± 53.31	119	0.00 [-0.26 - 0.26]	trivial [small - small]
02 vs 05	349.24 ± 52.32	109	339.74 ± 58.28	118	0.17 [-0.09 - 0.43]	trivial [trivial - small]
02 vs 06	349.24 ± 52.32	109	341.18 ± 49.62	120	0.16 [-0.1 - 0.42]	trivial [trivial - small]
02 vs 07	349.24 ± 52.32	109	346.88 ± 50.4	120	0.05 [-0.21 - 0.31]	trivial [small - small]
02 vs 09	349.24 ± 52.32	109	340.83 ± 49.23	120	0.17 [-0.1 - 0.43]	trivial [trivial - small]
02 vs 10	349.24 ± 52.32	109	346.93 ± 50.92	120	0.04 [-0.22 - 0.31]	trivial [small - small]
02 vs 11	349.24 ± 52.32	109	350.39 ± 51.44	120	-0.02 [-0.28 - 0.24]	trivial [small - small]
02 vs 13	349.24 ± 52.32	109	338.54 ± 53.05	118	0.20 [-0.06 - 0.46]	small [trivial - small]
02 vs 14	349.24 ± 52.32	109	349.08 ± 51.88	120	0.00 [-0.26 - 0.26]	trivial [small - small]
02 vs 15	349.24 ± 52.32	109	349.5 ± 50.5	120	0.00 [-0.27 - 0.26]	trivial [small - small]
02 vs 17	349.24 ± 52.32	109	342.96 ± 51.46	113	0.12 [-0.14 - 0.39]	trivial [trivial - small]
02 vs 18	349.24 ± 52.32	109	349.86 ± 48.59	145	-0.01 [-0.26 - 0.24]	trivial [small - small]
02 vs 19	349.24 ± 52.32	109	352.46 ± 48.76	146	-0.06 [-0.31 - 0.19]	trivial [small - trivial]
03 vs 05	349.1 ± 53.31	119	339.74 ± 58.28	118	0.17 [-0.09 - 0.42]	trivial [trivial - small]
03 vs 06	349.1 ± 53.31	119	341.18 ± 49.62	120	0.15 [-0.1 - 0.41]	trivial [trivial - small]
03 vs 07	349.1 ± 53.31	119	346.88 ± 50.4	120	0.04 [-0.21 - 0.3]	trivial [small - small]
03 vs 09	349.1 ± 53.31	119	340.83 ± 49.23	120	0.16 [-0.09 - 0.42]	trivial [trivial - small]
03 vs 10	349.1 ± 53.31	119	346.93 ± 50.92	120	0.04 [-0.21 - 0.3]	trivial [small - small]
03 vs 11	349.1 ± 53.31	119	350.39 ± 51.44	120	-0.02 [-0.28 - 0.23]	trivial [small - small]
03 vs 13	349.1 ± 53.31	119	338.54 ± 53.05	118	0.2 [-0.06 - 0.45]	trivial [trivial - small]
03 vs 14	349.1 ± 53.31	119	349.08 ± 51.88	120	0.00 [-0.25 - 0.26]	trivial [small - small]
03 vs 15	349.1 ± 53.31	119	349.5 ± 50.5	120	-0.01 [-0.26 - 0.25]	trivial [small - small]
03 vs 17	349.1 ± 53.31	119	342.96 ± 51.46	113	0.12 [-0.14 - 0.38]	trivial [trivial - small]
03 vs 18	349.1 ± 53.31	119	349.86 ± 48.59	145	-0.01 [-0.26 - 0.23]	trivial [small - small]
03 vs 19	349.1 ± 53.31	119	352.46 ± 48.76	146	-0.07 [-0.31 - 0.18]	trivial [small - trivial]
05 vs 06	339.74 ± 58.28	118	341.18 ± 49.62	120	-0.03 [-0.28 - 0.23]	trivial [small - small]
05 vs 07	339.74 ± 58.28	118	346.88 ± 50.4	120	-0.13 [-0.39 - 0.13]	trivial [small - trivial]
05 vs 09	339.74 ± 58.28	118	340.83 ± 49.23	120	-0.02 [-0.28 - 0.24]	trivial [small - small]
05 vs 10	339.74 ± 58.28	118	346.93 ± 50.92	120	-0.13 [-0.39 - 0.12]	trivial [small - trivial]
05 vs 11	339.74 ± 58.28	118	350.39 ± 51.44	120	-0.19 [-0.45 - 0.06]	trivial [small - trivial]
05 vs 13	339.74 ± 58.28	118	338.54 ± 53.05	118	0.02 [-0.24 - 0.28]	trivial [small - small]
05 vs 14	339.74 ± 58.28	118	349.08 ± 51.88	120	-0.17 [-0.42 - 0.09]	trivial [small - trivial]
05 vs 15	339.74 ± 58.28	118	349.5 ± 50.5	120	-0.18 [-0.43 - 0.08]	trivial [small - trivial]
05 vs 17	339.74 ± 58.28	118	342.96 ± 51.46	113	-0.06 [-0.32 - 0.2]	trivial [small - small]

05 vs 18	339.74 ± 58.28	118	349.86 ± 48.59	145	-0.19 [-0.43 - 0.05]	trivial [small - trivial]
05 vs 19	339.74 ± 58.28	118	352.46 ± 48.76	146	-0.24 [-0.48 - 0.01]	small [small - trivial]
06 vs 07	341.18 ± 49.62	120	346.88 ± 50.4	120	-0.11 [-0.37 - 0.14]	trivial [small - trivial]
06 vs 09	341.18 ± 49.62	120	340.83 ± 49.23	120	0.01 [-0.25 - 0.26]	trivial [small - small]
06 vs 10	341.18 ± 49.62	120	346.93 ± 50.92	120	-0.11 [-0.37 - 0.14]	trivial [small - trivial]
06 vs 11	341.18 ± 49.62	120	350.39 ± 51.44	120	-0.18 [-0.44 - 0.07]	trivial [small - trivial]
06 vs 13	341.18 ± 49.62	120	338.54 ± 53.05	118	0.05 [-0.2 - 0.31]	trivial [small - small]
06 vs 14	341.18 ± 49.62	120	349.08 ± 51.88	120	-0.16 [-0.41 - 0.1]	trivial [small - trivial]
06 vs 15	341.18 ± 49.62	120	349.5 ± 50.5	120	-0.17 [-0.42 - 0.09]	trivial [small - trivial]
06 vs 17	341.18 ± 49.62	120	342.96 ± 51.46	113	-0.04 [-0.29 - 0.22]	trivial [small - small]
06 vs 18	341.18 ± 49.62	120	349.86 ± 48.59	145	-0.18 [-0.42 - 0.07]	trivial [small - trivial]
06 vs 19	341.18 ± 49.62	120	352.46 ± 48.76	146	-0.23 [-0.47 - 0.01]	small [small - trivial]
07 vs 09	346.88 ± 50.4	120	340.83 ± 49.23	120	0.12 [-0.13 - 0.38]	trivial [trivial - small]
07 vs 10	346.88 ± 50.4	120	346.93 ± 50.92	120	0.00 [-0.26 - 0.25]	trivial [small - small]
07 vs 11	346.88 ± 50.4	120	350.39 ± 51.44	120	-0.07 [-0.32 - 0.19]	trivial [small - trivial]
07 vs 13	346.88 ± 50.4	120	338.54 ± 53.05	118	0.16 [-0.1 - 0.42]	trivial [trivial - small]
07 vs 14	346.88 ± 50.4	120	349.08 ± 51.88	120	-0.04 [-0.3 - 0.21]	trivial [small - small]
07 vs 15	346.88 ± 50.4	120	349.5 ± 50.5	120	-0.05 [-0.31 - 0.2]	trivial [small - small]
07 vs 17	346.88 ± 50.4	120	342.96 ± 51.46	113	0.08 [-0.18 - 0.33]	trivial [trivial - small]
07 vs 18	346.88 ± 50.4	120	349.86 ± 48.59	145	-0.06 [-0.3 - 0.18]	trivial [small - trivial]
07 vs 19	346.88 ± 50.4	120	352.46 ± 48.76	146	-0.11 [-0.36 - 0.13]	trivial [small - trivial]
09 vs 10	340.83 ± 49.23	120	346.93 ± 50.92	120	-0.12 [-0.38 - 0.13]	trivial [small - trivial]
09 vs 11	340.83 ± 49.23	120	350.39 ± 51.44	120	-0.19 [-0.44 - 0.07]	trivial [small - trivial]
09 vs 13	340.83 ± 49.23	120	338.54 ± 53.05	118	0.04 [-0.21 - 0.3]	trivial [small - small]
09 vs 14	340.83 ± 49.23	120	349.08 ± 51.88	120	-0.16 [-0.42 - 0.09]	trivial [small - trivial]
09 vs 15	340.83 ± 49.23	120	349.5 ± 50.5	120	-0.17 [-0.43 - 0.08]	trivial [small - trivial]
09 vs 17	340.83 ± 49.23	120	342.96 ± 51.46	113	-0.04 [-0.3 - 0.22]	trivial [small - small]
09 vs 18	340.83 ± 49.23	120	349.86 ± 48.59	145	-0.18 [-0.43 - 0.06]	trivial [small - trivial]
09 vs 19	340.83 ± 49.23	120	352.46 ± 48.76	146	-0.24 [-0.48 - 0.01]	small [small - trivial]
10 vs 11	346.93 ± 50.92	120	350.39 ± 51.44	120	-0.07 [-0.32 - 0.19]	trivial [small - trivial]
10 vs 13	346.93 ± 50.92	120	338.54 ± 53.05	118	0.16 [-0.09 - 0.42]	trivial [trivial - small]
10 vs 14	346.93 ± 50.92	120	349.08 ± 51.88	120	-0.04 [-0.3 - 0.21]	trivial [small - small]
10 vs 15	346.93 ± 50.92	120	349.5 ± 50.5	120	-0.05 [-0.3 - 0.2]	trivial [small - small]
10 vs 17	346.93 ± 50.92	120	342.96 ± 51.46	113	0.08 [-0.18 - 0.34]	trivial [trivial - small]
10 vs 18	346.93 ± 50.92	120	349.86 ± 48.59	145	-0.06 [-0.3 - 0.18]	trivial [small - trivial]
10 vs 19	346.93 ± 50.92	120	352.46 ± 48.76	146	-0.11 [-0.35 - 0.13]	trivial [small - trivial]
11 vs 13	350.39 ± 51.44	120	338.54 ± 53.05	118	0.23 [-0.03 - 0.48]	small [trivial - small]
11 vs 14	350.39 ± 51.44	120	349.08 ± 51.88	120	0.03 [-0.23 - 0.28]	trivial [small - small]
11 vs 15	350.39 ± 51.44	120	349.5 ± 50.5	120	0.02 [-0.24 - 0.27]	trivial [small - small]
11 vs 17	350.39 ± 51.44	120	342.96 ± 51.46	113	0.14 [-0.11 - 0.4]	trivial [trivial - small]
11 vs 18	350.39 ± 51.44	120	349.86 ± 48.59	145	0.01 [-0.23 - 0.25]	trivial [small - small]
11 vs 19	350.39 ± 51.44	120	352.46 ± 48.76	146	-0.04 [-0.28 - 0.2]	trivial [small - small]
13 vs 14	338.54 ± 53.05	118	349.08 ± 51.88	120	-0.2 [-0.46 - 0.06]	small [small - trivial]
13 vs 15	338.54 ± 53.05	118	349.5 ± 50.5	120	-0.21 [-0.47 - 0.05]	small [small - trivial]

13 vs 17	338.54 ± 53.05	118	342.96 ± 51.46	113	-0.08 [-0.34 - 0.18]	trivial [small - trivial]
13 vs 18	338.54 ± 53.05	118	349.86 ± 48.59	145	-0.22 [-0.47 - 0.02]	small [small - trivial]
13 vs 19	338.54 ± 53.05	118	352.46 ± 48.76	146	-0.27 [-0.52 - -0.03]	small [moderate - trivial]
14 vs 15	349.08 ± 51.88	120	349.5 ± 50.5	120	-0.01 [-0.26 - 0.25]	trivial [small - small]
14 vs 17	349.08 ± 51.88	120	342.96 ± 51.46	113	0.12 [-0.14 - 0.38]	trivial [trivial - small]
14 vs 18	349.08 ± 51.88	120	349.86 ± 48.59	145	-0.02 [-0.26 - 0.23]	trivial [small - small]
14 vs 19	349.08 ± 51.88	120	352.46 ± 48.76	146	-0.07 [-0.31 - 0.18]	trivial [small - trivial]
15 vs 17	349.5 ± 50.5	120	342.96 ± 51.46	113	0.13 [-0.13 - 0.39]	trivial [trivial - small]
15 vs 18	349.5 ± 50.5	120	349.86 ± 48.59	145	-0.01 [-0.25 - 0.24]	trivial [small - small]
15 vs 19	349.5 ± 50.5	120	352.46 ± 48.76	146	-0.06 [-0.3 - 0.18]	trivial [small - trivial]
17 vs 18	342.96 ± 51.46	113	349.86 ± 48.59	145	-0.14 [-0.39 - 0.11]	trivial [small - trivial]
17 vs 19	342.96 ± 51.46	113	352.46 ± 48.76	146	-0.19 [-0.44 - 0.06]	trivial [small - trivial]
18 vs 19	349.86 ± 48.59	145	352.46 ± 48.76	146	-0.05 [-0.28 - 0.18]	trivial [small - trivial]

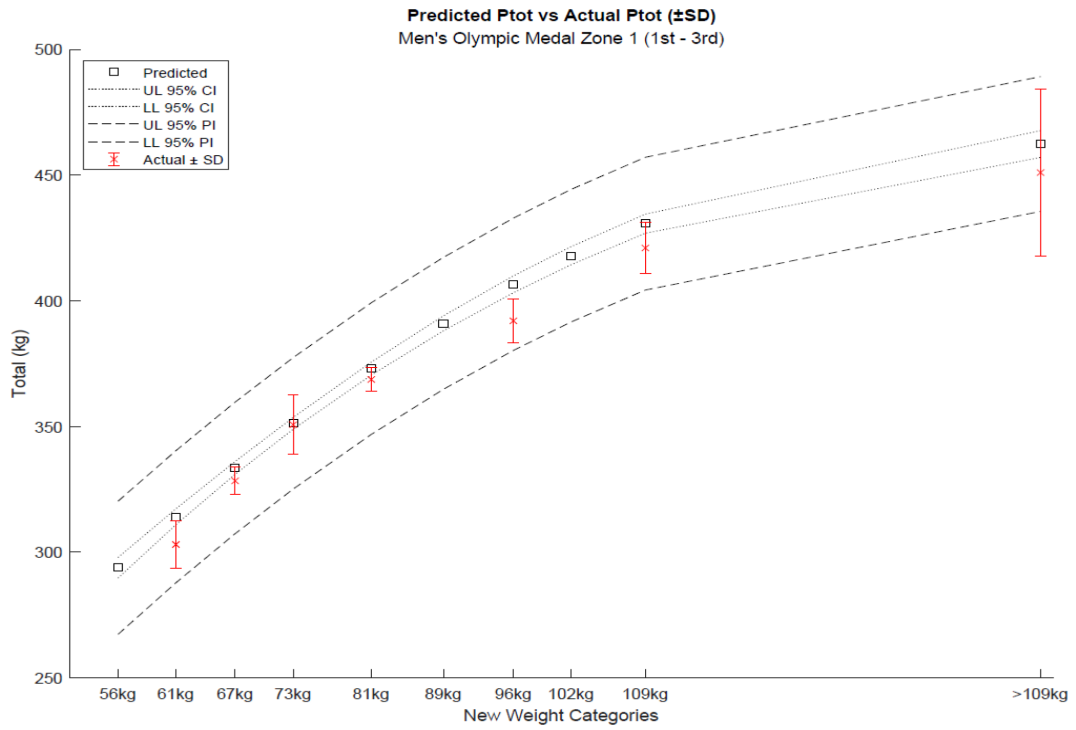
Appendix 2.7. European Championship year vs year effect size

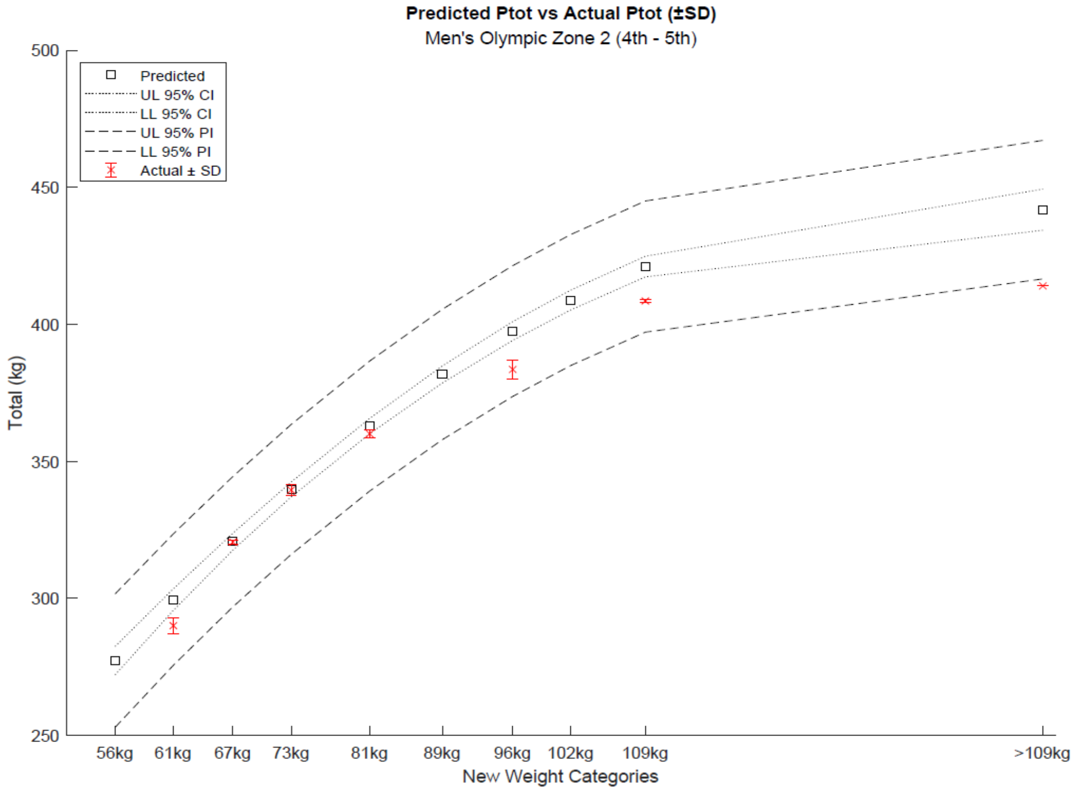
Years	Mean ± SD	*n*	Mean ± SD	*n*	ES	Descriptor
08 vs 09	328 ± 56.15	113	318.88 ± 56.62	111	0.16 [-0.1 - 0.42]	trivial [trivial - small]
08 vs 10	328 ± 56.15	113	323.42 ± 57.63	92	0.08 [-0.2 - 0.36]	trivial [trivial - small]
08 vs 11	328 ± 56.15	113	329.62 ± 50.79	94	-0.03 [-0.31 - 0.25]	trivial [small - small]
08 vs 12	328 ± 56.15	113	324.74 ± 53.73	117	0.06 [-0.2 - 0.32]	trivial [small - small]
08 vs 13	328 ± 56.15	113	329.61 ± 54.34	89	-0.03 [-0.31 - 0.25]	trivial [small - small]
08 vs 14	328 ± 56.15	113	331.93 ± 51.94	99	-0.07 [-0.34 - 0.2]	trivial [small - trivial]
08 vs 15	328 ± 56.15	113	334.33 ± 49.08	104	-0.12 [-0.39 - 0.15]	trivial [small - trivial]
08 vs 16	328 ± 56.15	113	327.34 ± 59.15	120	0.01 [-0.25 - 0.27]	trivial [small - small]
08 vs 17	328 ± 56.15	113	339.4 ± 51.5	105	-0.21 [-0.48 - 0.06]	small [small - trivial]
08 vs 18	328 ± 56.15	113	321.05 ± 46.24	97	0.13 [-0.14 - 0.41]	trivial [trivial - small]
08 vs 19	328 ± 56.15	113	338.64 ± 50.68	135	-0.2 [-0.45 - 0.05]	trivial [small - trivial]
08 vs 21	328 ± 56.15	113	331.12 ± 50.95	118	-0.06 [-0.32 - 0.2]	trivial [small - small]
09 vs 10	318.88 ± 56.62	111	323.42 ± 57.63	92	-0.08 [-0.36 - 0.2]	trivial [small - trivial]
09 vs 11	318.88 ± 56.62	111	329.62 ± 50.79	94	-0.2 [-0.47 - 0.08]	trivial [small - trivial]
09 vs 12	318.88 ± 56.62	111	324.74 ± 53.73	117	-0.11 [-0.37 - 0.16]	trivial [small - trivial]
09 vs 13	318.88 ± 56.62	111	329.61 ± 54.34	89	-0.19 [-0.47 - 0.09]	trivial [small - trivial]
09 vs 14	318.88 ± 56.62	111	331.93 ± 51.94	99	-0.24 [-0.51 - 0.03]	small [moderate - trivial]
09 vs 15	318.88 ± 56.62	111	334.33 ± 49.08	104	-0.29 [-0.56 - -0.02]	small [moderate - trivial]
09 vs 16	318.88 ± 56.62	111	327.34 ± 59.15	120	-0.15 [-0.41 - 0.11]	trivial [small - trivial]
09 vs 17	318.88 ± 56.62	111	339.4 ± 51.5	105	-0.38 [-0.65 - -0.11]	small [moderate - trivial]
09 vs 18	318.88 ± 56.62	111	321.05 ± 46.24	97	-0.04 [-0.32 - 0.23]	trivial [small - small]
09 vs 19	318.88 ± 56.62	111	338.64 ± 50.68	135	-0.37 [-0.62 - -0.11]	small [moderate - trivial]
09 vs 21	318.88 ± 56.62	111	331.12 ± 50.95	118	-0.23 [-0.49 - 0.03]	small [small - trivial]
10 vs 11	323.42 ± 57.63	92	329.62 ± 50.79	94	-0.11 [-0.4 - 0.18]	trivial [small - trivial]
10 vs 12	323.42 ± 57.63	92	324.74 ± 53.73	117	-0.02 [-0.3 - 0.25]	trivial [small - small]
10 vs 13	323.42 ± 57.63	92	329.61 ± 54.34	89	-0.11 [-0.4 - 0.18]	trivial [small - trivial]
10 vs 14	323.42 ± 57.63	92	331.93 ± 51.94	99	-0.15 [-0.44 - 0.13]	trivial [small - trivial]

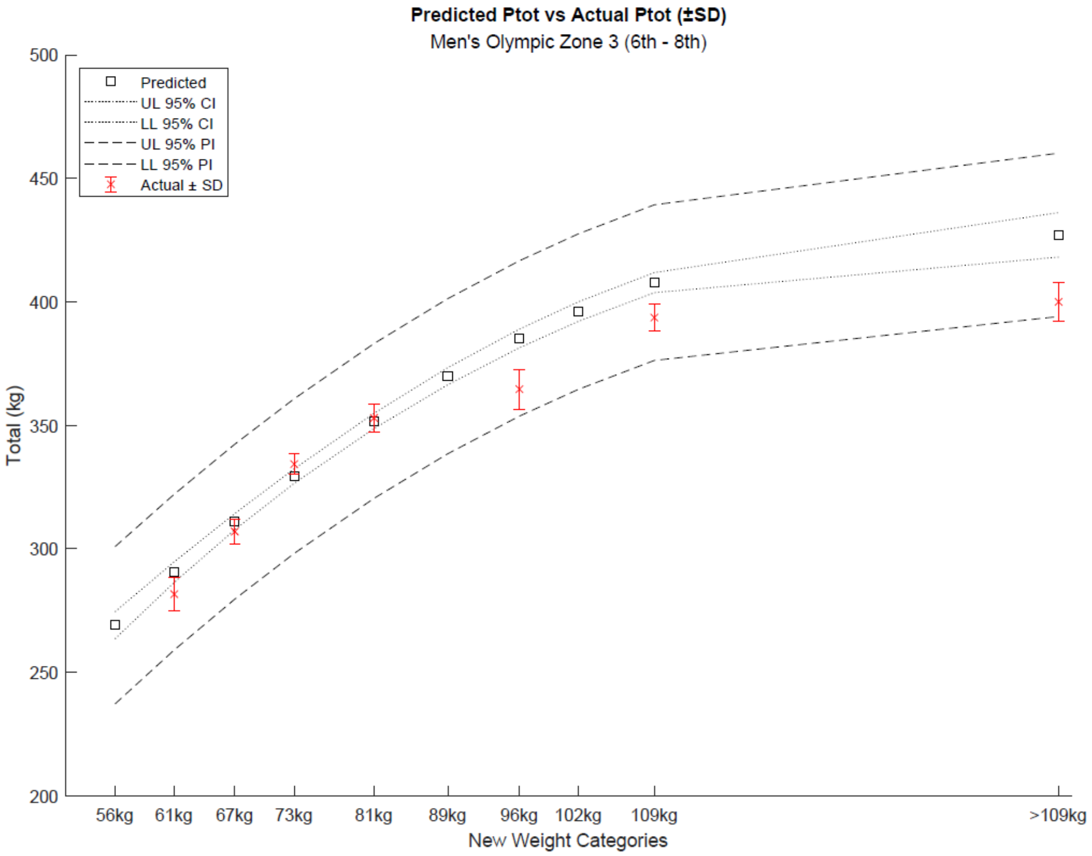
10 vs 15	323.42 ± 57.63	92	334.33 ± 49.08	104	-0.2 [-0.49 - 0.08]	small [small - trivial]
10 vs 16	323.42 ± 57.63	92	327.34 ± 59.15	120	-0.07 [-0.34 - 0.21]	trivial [small - small]
10 vs 17	323.42 ± 57.63	92	339.4 ± 51.5	105	-0.29 [-0.58 - -0.01]	small [moderate - trivial]
10 vs 18	323.42 ± 57.63	92	321.05 ± 46.24	97	0.05 [-0.24 - 0.33]	trivial [small - small]
10 vs 19	323.42 ± 57.63	92	338.64 ± 50.68	135	-0.28 [-0.55 - -0.02]	small [moderate - trivial]
10 vs 21	323.42 ± 57.63	92	331.12 ± 50.95	118	-0.14 [-0.42 - 0.13]	trivial [small - trivial]
11 vs 12	329.62 ± 50.79	94	324.74 ± 53.73	117	0.09 [-0.18 - 0.37]	trivial [trivial - small]
11 vs 13	329.62 ± 50.79	94	329.61 ± 54.34	89	0 [-0.29 - 0.29]	trivial [small - small]
11 vs 14	329.62 ± 50.79	94	331.93 ± 51.94	99	-0.04 [-0.33 - 0.24]	trivial [small - small]
11 vs 15	329.62 ± 50.79	94	334.33 ± 49.08	104	-0.09 [-0.37 - 0.19]	trivial [small - trivial]
11 vs 16	329.62 ± 50.79	94	327.34 ± 59.15	120	0.04 [-0.23 - 0.31]	trivial [small - small]
11 vs 17	329.62 ± 50.79	94	339.4 ± 51.5	105	-0.19 [-0.47 - 0.09]	trivial [small - trivial]
11 vs 18	329.62 ± 50.79	94	321.05 ± 46.24	97	0.18 [-0.11 - 0.46]	trivial [trivial - small]
11 vs 19	329.62 ± 50.79	94	338.64 ± 50.68	135	-0.18 [-0.44 - 0.09]	trivial [small - trivial]
11 vs 21	329.62 ± 50.79	94	331.12 ± 50.95	118	-0.03 [-0.3 - 0.24]	trivial [small - small]
12 vs 13	324.74 ± 53.73	117	329.61 ± 54.34	89	-0.09 [-0.37 - 0.19]	trivial [small - trivial]
12 vs 14	324.74 ± 53.73	117	331.93 ± 51.94	99	-0.14 [-0.4 - 0.13]	trivial [small - trivial]
12 vs 15	324.74 ± 53.73	117	334.33 ± 49.08	104	-0.19 [-0.45 - 0.08]	trivial [small - trivial]
12 vs 16	324.74 ± 53.73	117	327.34 ± 59.15	120	-0.05 [-0.3 - 0.21]	trivial [small - small]
12 vs 17	324.74 ± 53.73	117	339.4 ± 51.5	105	-0.28 [-0.54 - -0.01]	small [moderate - trivial]
12 vs 18	324.74 ± 53.73	117	321.05 ± 46.24	97	0.07 [-0.2 - 0.34]	trivial [trivial - small]
12 vs 19	324.74 ± 53.73	117	338.64 ± 50.68	135	-0.27 [-0.52 - -0.02]	small [moderate - trivial]
12 vs 21	324.74 ± 53.73	117	331.12 ± 50.95	118	-0.12 [-0.38 - 0.14]	trivial [small - trivial]
13 vs 14	329.61 ± 54.34	89	331.93 ± 51.94	99	-0.04 [-0.33 - 0.24]	trivial [small - small]
13 vs 15	329.61 ± 54.34	89	334.33 ± 49.08	104	-0.09 [-0.38 - 0.19]	trivial [small - trivial]
13 vs 16	329.61 ± 54.34	89	327.34 ± 59.15	120	0.04 [-0.24 - 0.32]	trivial [small - small]
13 vs 17	329.61 ± 54.34	89	339.4 ± 51.5	105	-0.18 [-0.47 - 0.1]	trivial [small - trivial]
13 vs 18	329.61 ± 54.34	89	321.05 ± 46.24	97	0.17 [-0.12 - 0.46]	trivial [trivial - small]
13 vs 19	329.61 ± 54.34	89	338.64 ± 50.68	135	-0.17 [-0.44 - 0.1]	trivial [small - trivial]
13 vs 21	329.61 ± 54.34	89	331.12 ± 50.95	118	-0.03 [-0.31 - 0.25]	trivial [small - small]
14 vs 15	331.93 ± 51.94	99	334.33 ± 49.08	104	-0.05 [-0.32 - 0.23]	trivial [small - small]
14 vs 16	331.93 ± 51.94	99	327.34 ± 59.15	120	0.08 [-0.19 - 0.35]	trivial [trivial - small]
14 vs 17	331.93 ± 51.94	99	339.4 ± 51.5	105	-0.14 [-0.42 - 0.13]	trivial [small - trivial]
14 vs 18	331.93 ± 51.94	99	321.05 ± 46.24	97	0.22 [-0.06 - 0.5]	small [trivial - moderate]
14 vs 19	331.93 ± 51.94	99	338.64 ± 50.68	135	-0.13 [-0.39 - 0.13]	trivial [small - trivial]
14 vs 21	331.93 ± 51.94	99	331.12 ± 50.95	118	0.02 [-0.25 - 0.28]	trivial [small - small]
15 vs 16	334.33 ± 49.08	104	327.34 ± 59.15	120	0.13 [-0.14 - 0.39]	trivial [trivial - small]
15 vs 17	334.33 ± 49.08	104	339.4 ± 51.5	105	-0.1 [-0.37 - 0.17]	trivial [small - trivial]
15 vs 18	334.33 ± 49.08	104	321.05 ± 46.24	97	0.28 [0 - 0.56]	small [trivial - moderate]
15 vs 19	334.33 ± 49.08	104	338.64 ± 50.68	135	-0.09 [-0.34 - 0.17]	trivial [small - trivial]
15 vs 21	334.33 ± 49.08	104	331.12 ± 50.95	118	0.06 [-0.2 - 0.33]	trivial [small - small]
16 vs 17	327.34 ± 59.15	120	339.4 ± 51.5	105	-0.22 [-0.48 - 0.05]	small [small - trivial]
16 vs 18	327.34 ± 59.15	120	321.05 ± 46.24	97	0.12 [-0.15 - 0.39]	trivial [trivial - small]
16 vs 19	327.34 ± 59.15	120	338.64 ± 50.68	135	-0.21 [-0.45 - 0.04]	small [small - trivial]

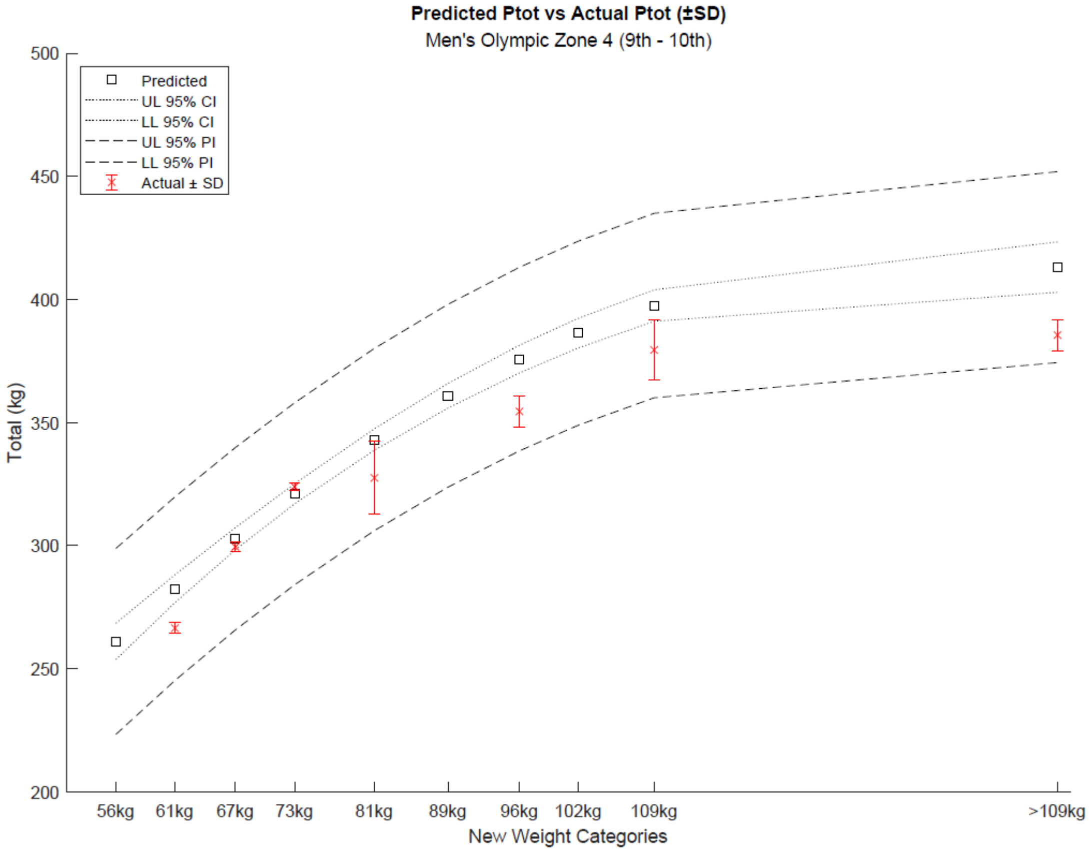
16 vs 21	327.34 ± 59.15	120	331.12 ± 50.95	118	-0.07 [-0.32 - 0.19]	trivial [small - trivial]
17 vs 18	339.4 ± 51.5	105	321.05 ± 46.24	97	0.37 [0.09 - 0.65]	small [trivial - moderate]
17 vs 19	339.4 ± 51.5	105	338.64 ± 50.68	135	0.01 [-0.24 - 0.27]	trivial [small - small]
17 vs 21	339.4 ± 51.5	105	331.12 ± 50.95	118	0.16 [-0.1 - 0.43]	trivial [trivial - small]
18 vs 19	321.05 ± 46.24	97	338.64 ± 50.68	135	-0.36 [-0.62 - -0.09]	small [moderate - trivial]
18 vs 21	321.05 ± 46.24	97	331.12 ± 50.95	118	-0.21 [-0.48 - 0.07]	small [small - trivial]
19 vs 21	338.64 ± 50.68	135	331.12 ± 50.95	118	0.15 [-0.1 - 0.4]	trivial [trivial - small]

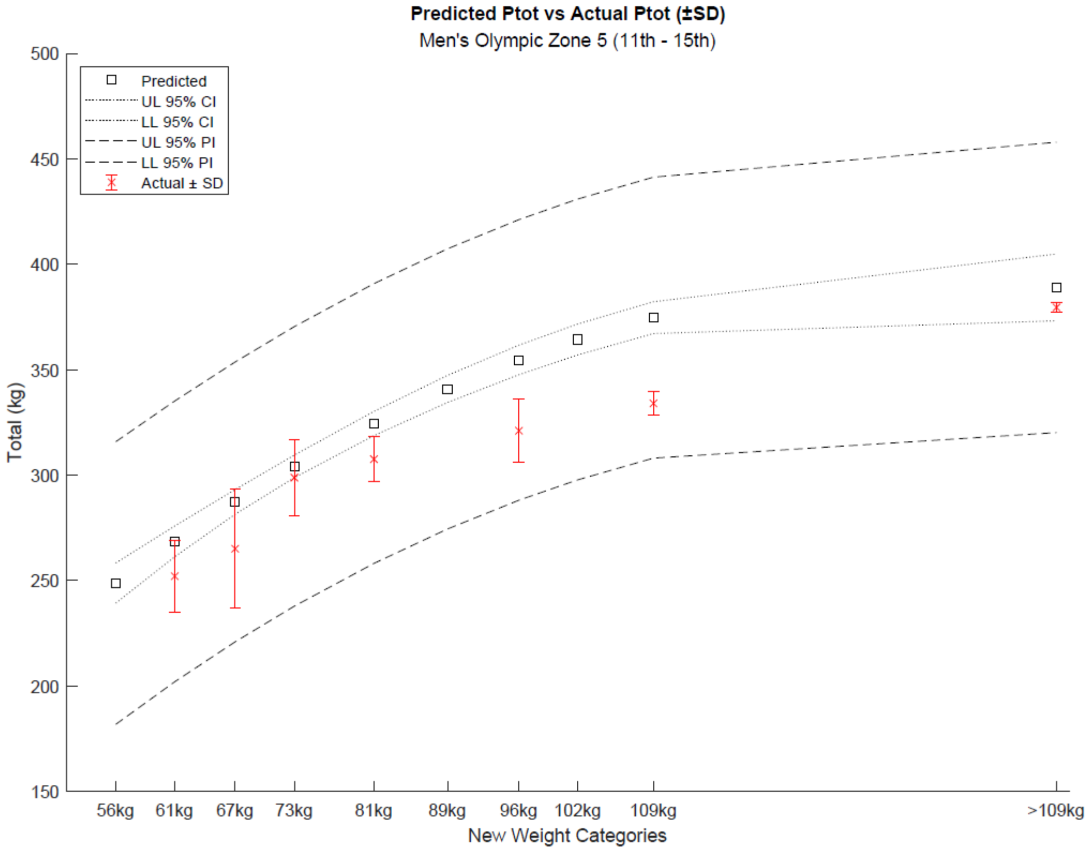
Appendix 2.8. Olympic performance zones 1 to 5 prediction plots.



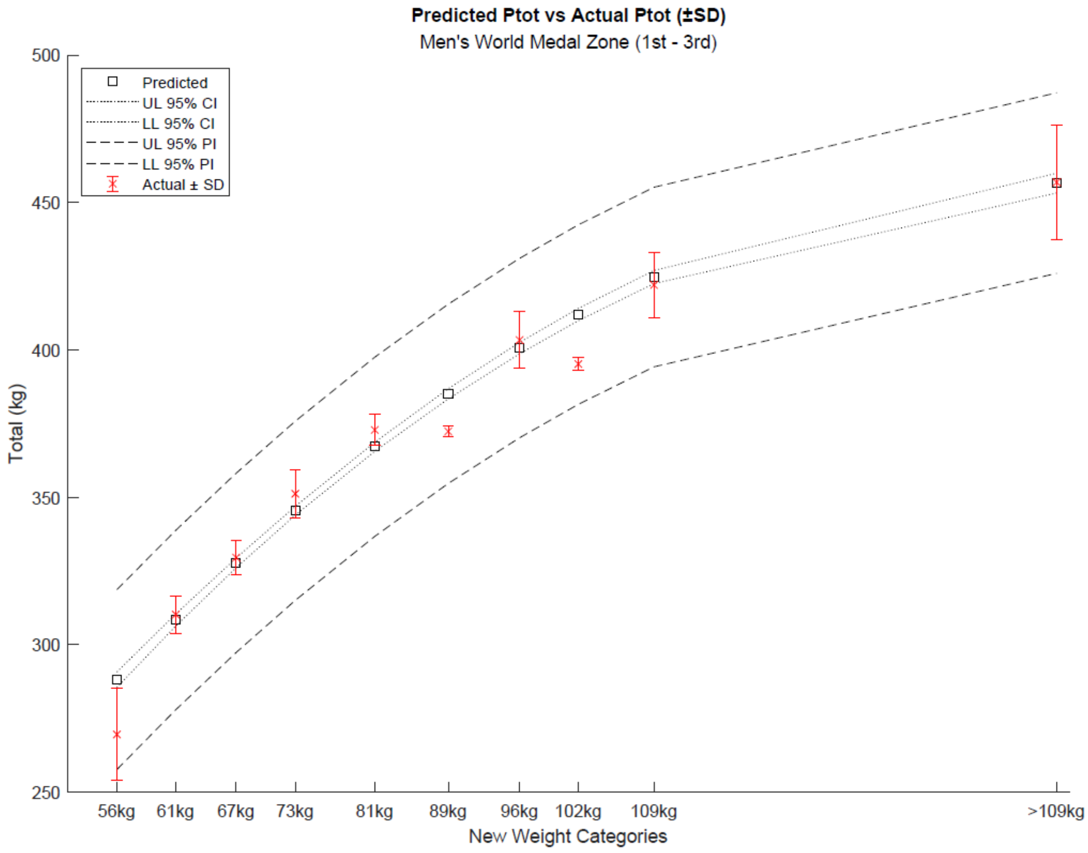


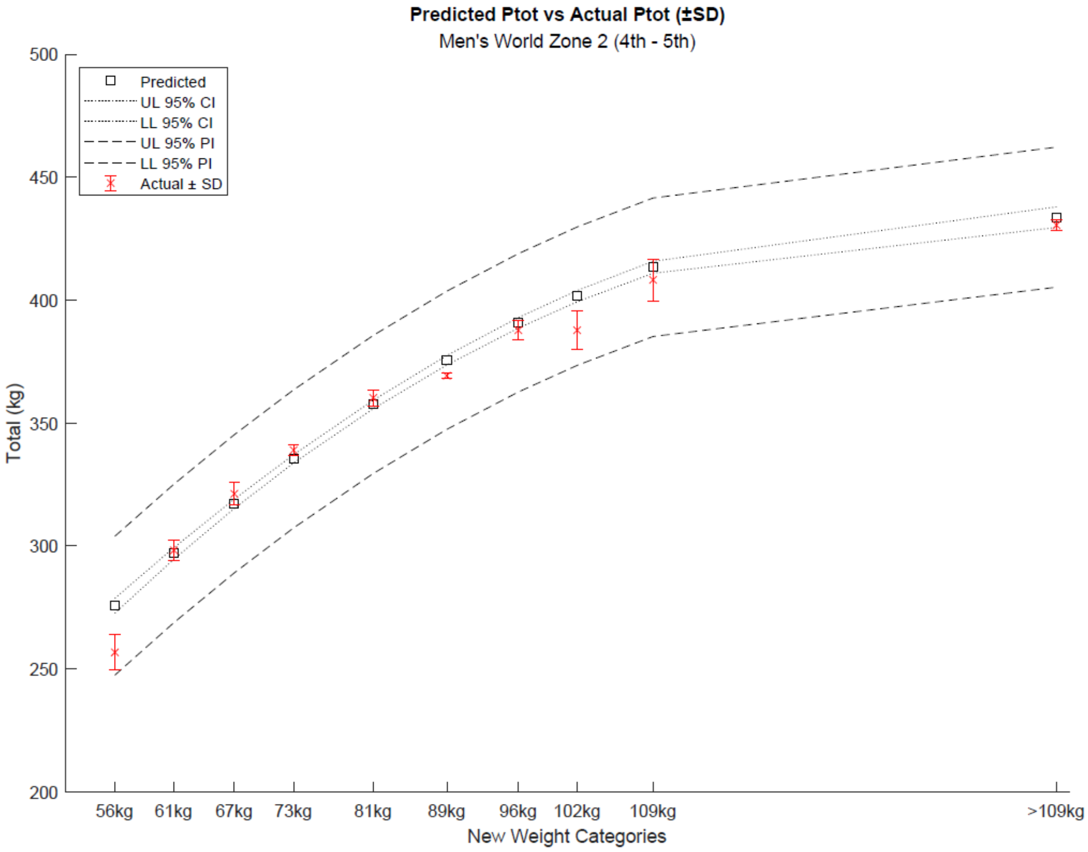

Predicted Ptot vs Actual Ptot (±SD)
Men's Olympic Zone 3 (6th - 8th)
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
500
450
400
350
300
250
200
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

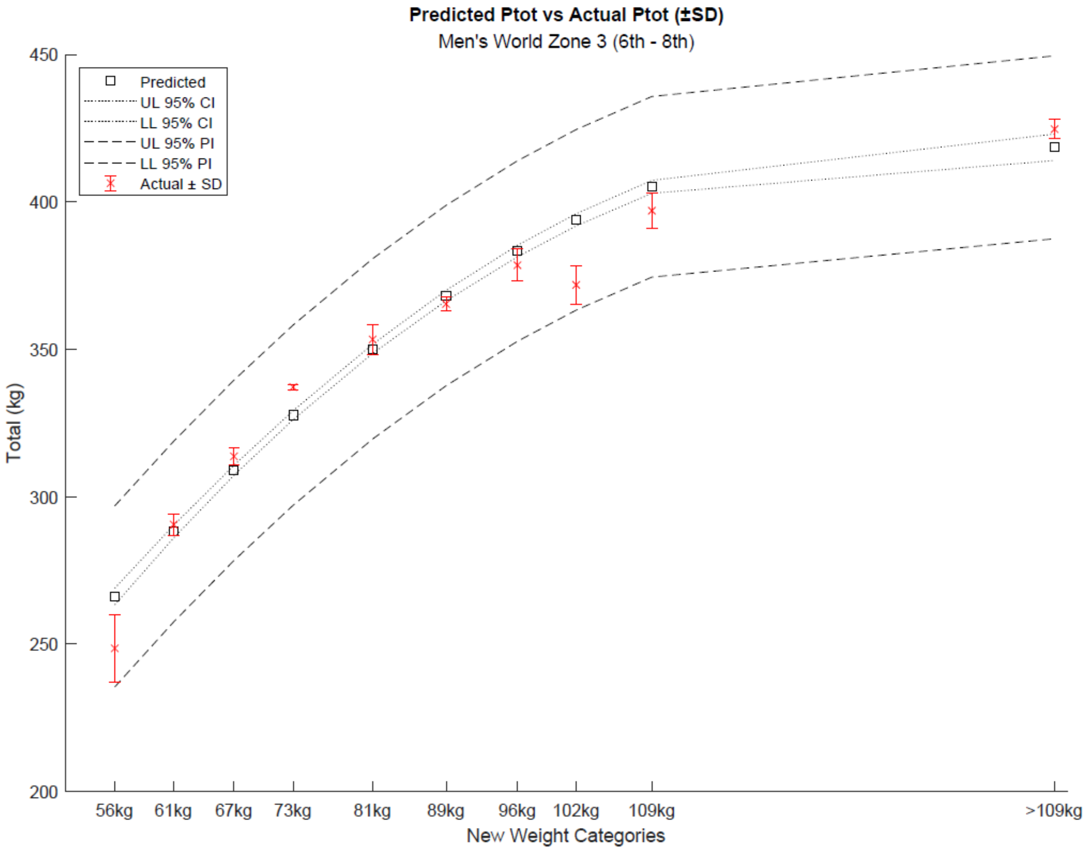

Predicted Ptot vs Actual Ptot (±SD)
Men's Olympic Zone 4 (9th - 10th)
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
500
450
400
350
300
250
200
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

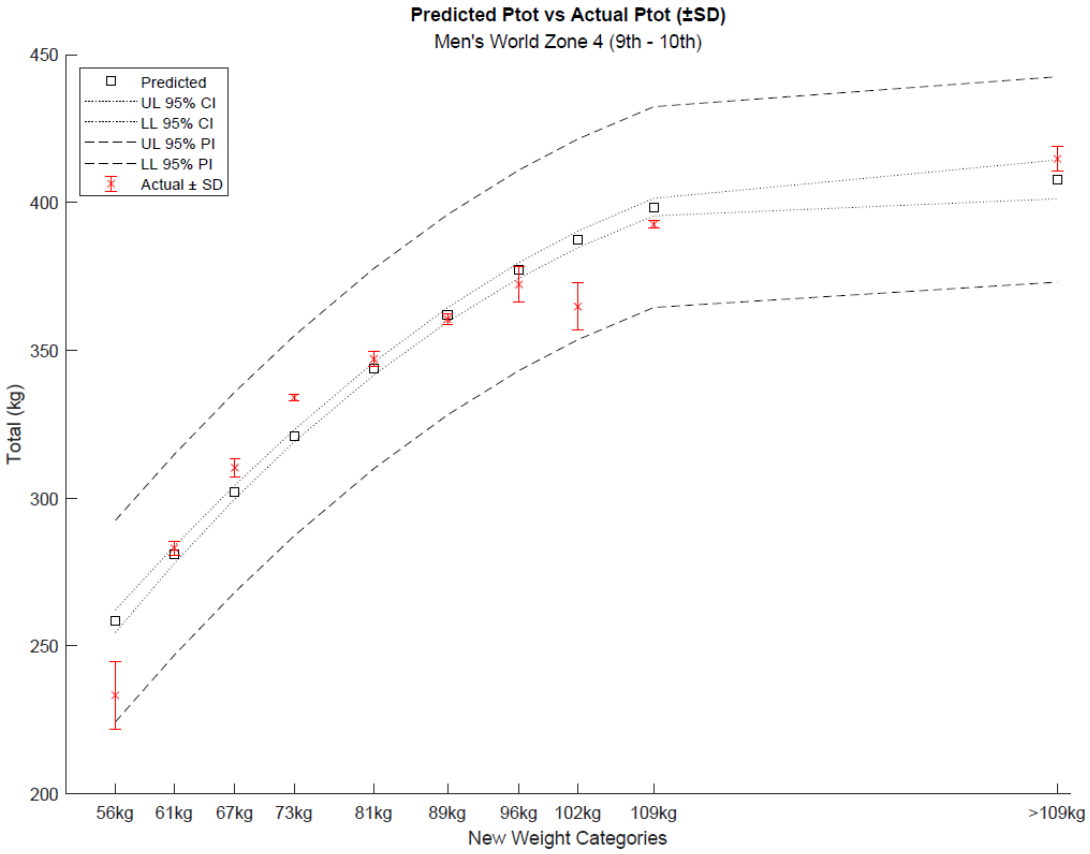

Predicted Ptot vs Actual Ptot (±SD)
Men's Olympic Zone 5 (11th - 15th)
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
500
450
400
350
300
250
200
150
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

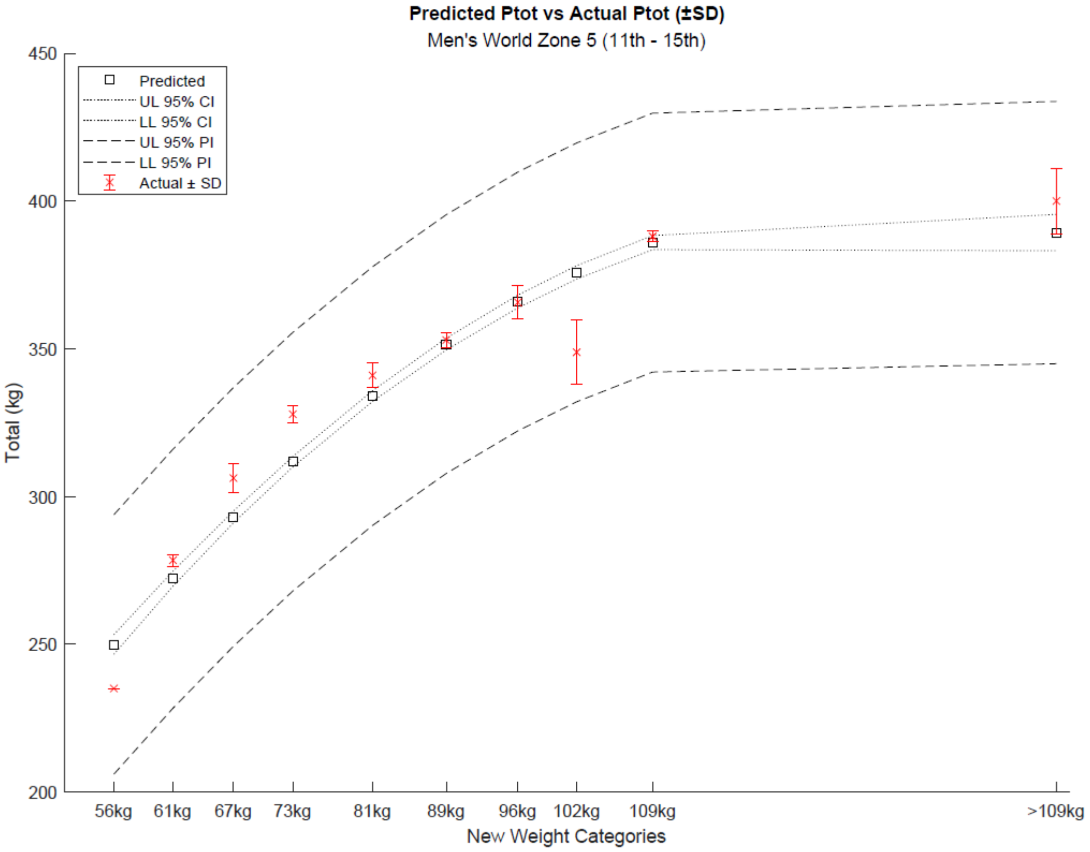
Appendix 2.9. World performance zones 1 to 5 prediction plots.



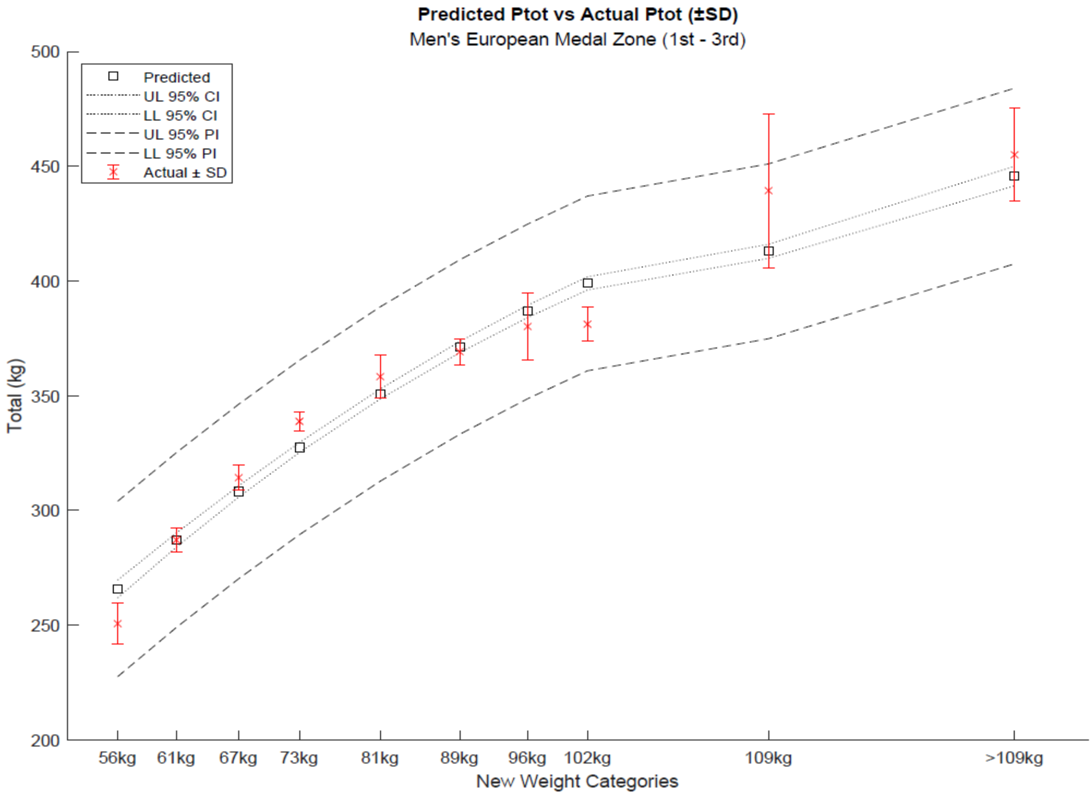


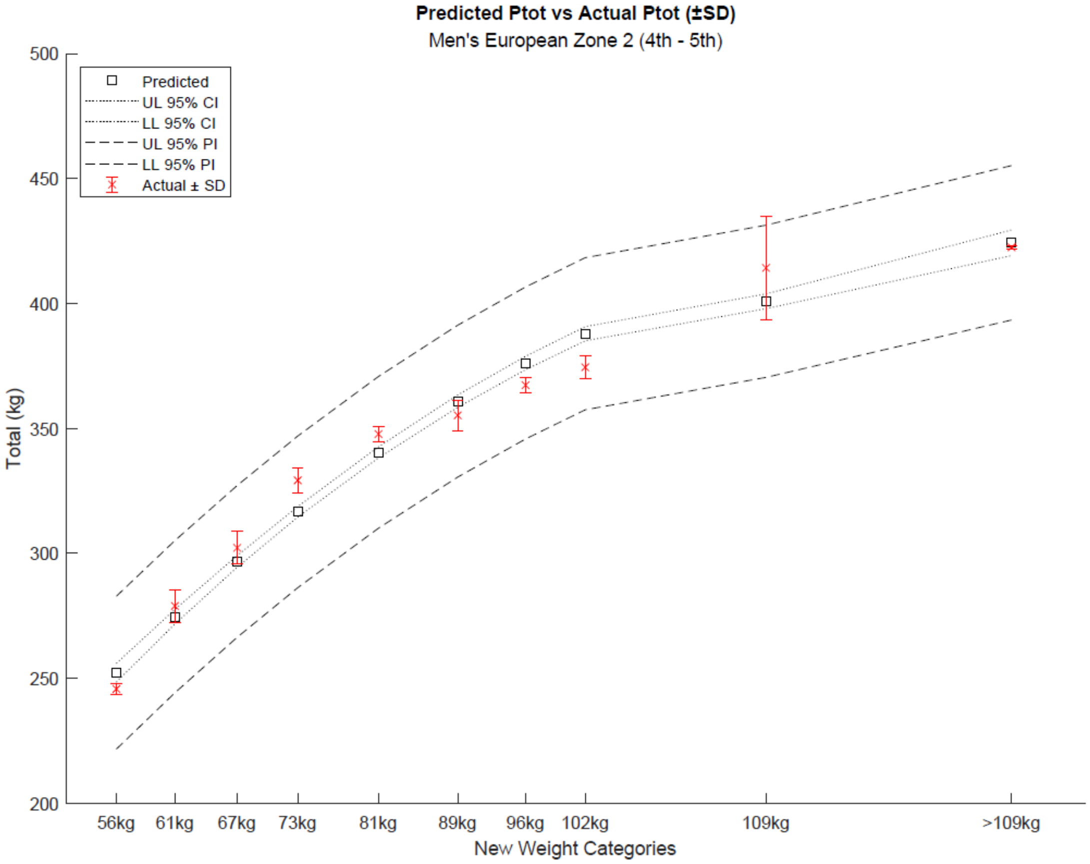

Predicted Ptot vs Actual Ptot (±SD)
Men's World Zone 3 (6th - 8th)
□ Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
450
400
350
300
250
200
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

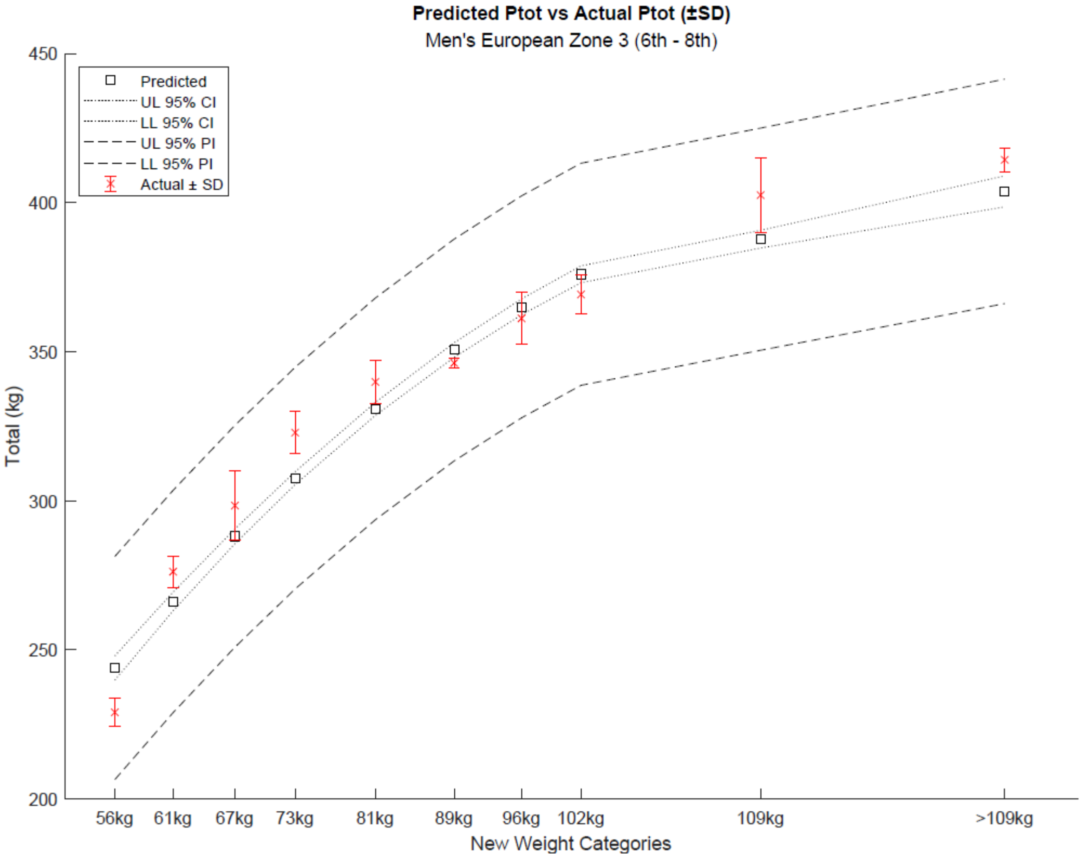

Predicted Ptot vs Actual Ptot (±SD)
Men's World Zone 4 (9th - 10th)
□ Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
450
400
350
300
250
200
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

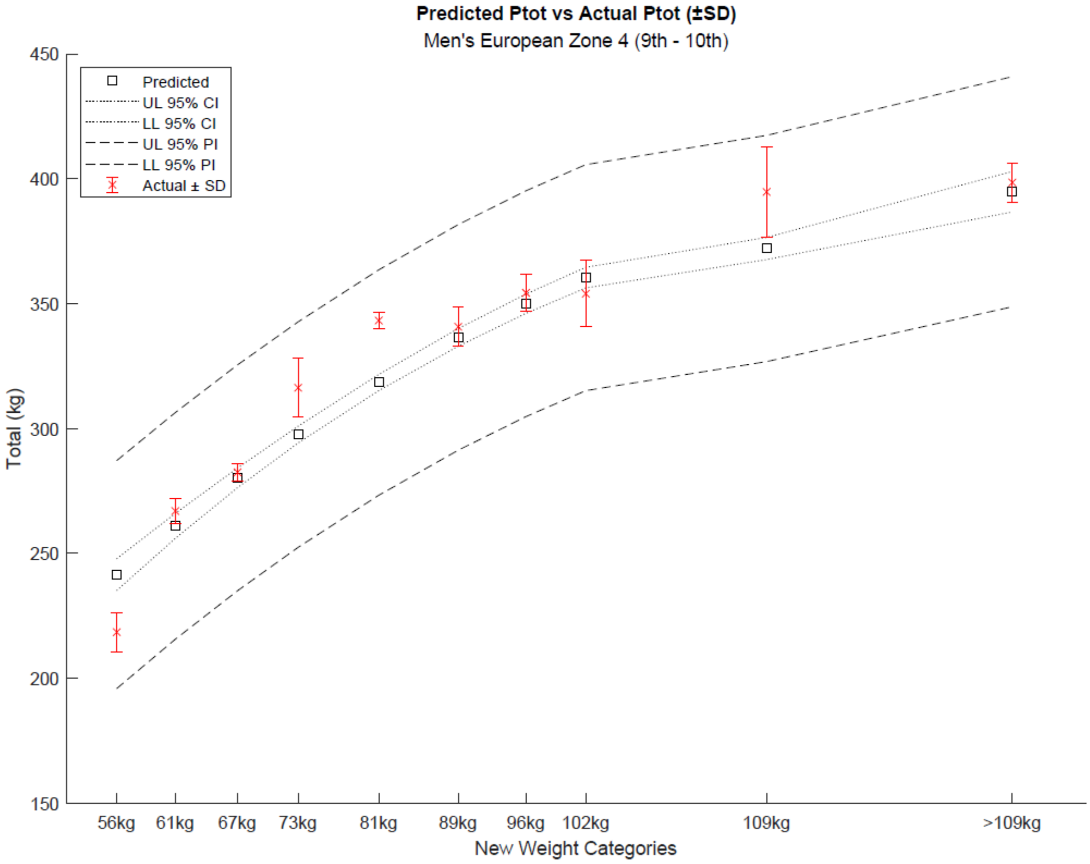

Predicted Ptot vs Actual Ptot (±SD)
Men's World Zone 5 (11th - 15th)
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
450
400
350
300
250
200
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

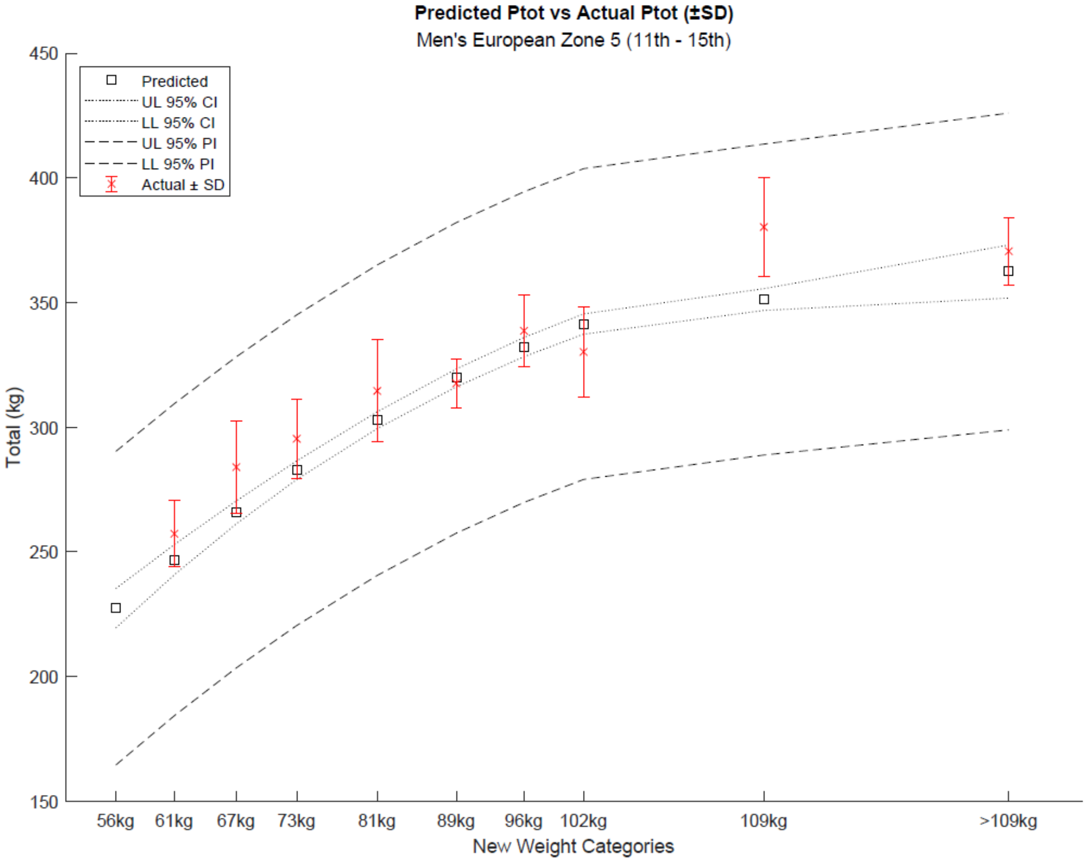
Appendix 2.10. European performance zones 1 to 5 prediction plots.






Predicted Ptot vs Actual Ptot (±SD)
Men's European Zone 3 (6th - 8th)
Total (kg)
450
400
350
300
250
200
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories


Predicted Ptot vs Actual Ptot (±SD)
Men's European Zone 4 (9th - 10th)
Total (kg)
450
400
350
300
250
200
150
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories



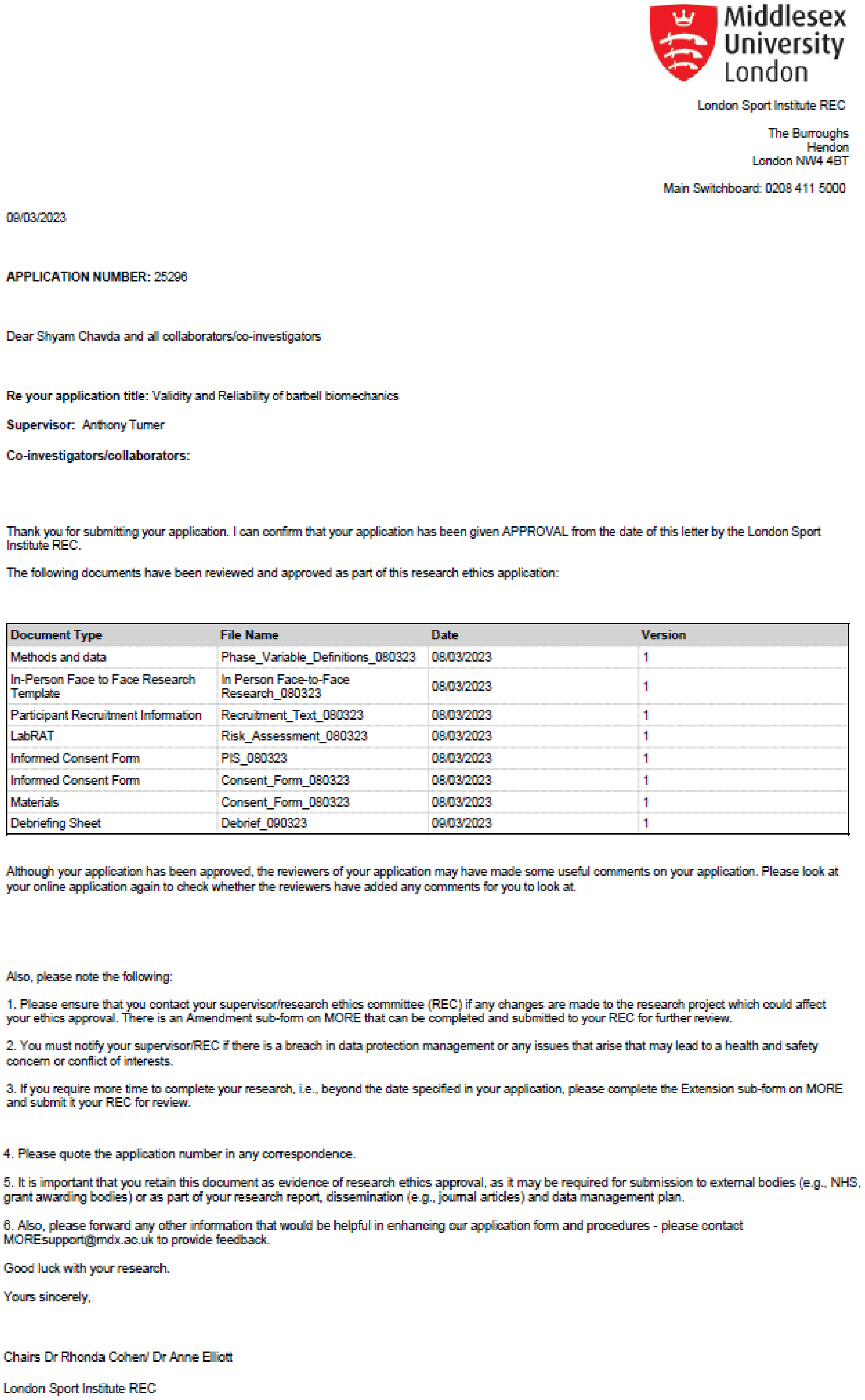
Predicted Ptot vs Actual Ptot (±SD)
Men's European Zone 5 (11th - 15th)
Predicted
UL 95% CI
LL 95% CI
UL 95% PI
LL 95% PI
Actual ± SD
Total (kg)
450
400
350
300
250
200
150
56kg
61kg
67kg
73kg
81kg
89kg
96kg
102kg
109kg
>109kg
New Weight Categories

Appendix 3.1. Scoping review quality scoring sheet.

Criteria No.	Item	Score
1	*Sample description* 1.1. Subject properties (i.e. age, height, weight, sex, maximum performance). 1.2. Definition of population and/or Competition (i.e. elite, , professional, Olympics, World Championships).	0-2
2	*Procedures described* 2.1. Detailed description of the test (i.e. exercise type, in or out of competition, loading conditions employed). 2.2. Number of trials/lifts analysed defined or attempt number stated.	0-2
3	*Instrumentation used and methods employed* 3.1. Configuration, sampling frequency and instrumentation description provided. 3.2. Method of lift phase, data extractions and analysis clearly described (i.e. filters used, onsets defined).	0-2
4	*Dependent variables defined* 4.1. Each variable or phase defined directly or referenced. 4.2. Associated calculations of variables presented/ referred to where necessary.	0-2
5	*Statistics appropriate* 5.1. Defined statistical test to explore hypothesis. 5.2. Descriptive in nature with or without additional statistics.	0-2
6	*Results detailed* 6.1. Measure of central tendency, frequency or individual data presented. 6.2. Relevant statistical information provided (i.e. frequency, relationships, differences).	0-2
7	*Conclusion* 7.1. Practical considerations and/or application provided. 7.2. Future direction and/or research outlined.	0-2
Total		0-14

NB. Each point was scored from 0-1, thus allocating each criteria a maximum of 2 points

Appendix 4.1. Ethical Approval Letter for study 3.



Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

09/03/2023

APPLICATION NUMBER: 25296

Dear Shyam Chavda and all collaborators/co-investigators

Re your application title: Validity and Reliability of barbell biomechanics

Supervisor: Anthony Turner

Co-investigators/collaborators:

Thank you for submitting your application. I can confirm that your application has been given APPROVAL from the date of this letter by the London Sport Institute REC.

The following documents have been reviewed and approved as part of this research ethics application:

Document Type	File Name	Date	Version
Methods and data	Phase_Variable_Definitions_080323	08/03/2023	1
In-Person Face to Face Research Template	In Person Face-to-Face Research_080323	08/03/2023	1
Participant Recruitment Information	Recruitment_Text_080323	08/03/2023	1
LabRAT	Risk_Assessment_080323	08/03/2023	1
Informed Consent Form	PIS_080323	08/03/2023	1
Informed Consent Form	Consent_Form_080323	08/03/2023	1
Materials	Consent_Form_080323	08/03/2023	1
Debriefing Sheet	Debrief_090323	09/03/2023	1

Although your application has been approved, the reviewers of your application may have made some useful comments on your application. Please look at your online application again to check whether the reviewers have added any comments for you to look at.

Also, please note the following:

1. Please ensure that you contact your supervisor/research ethics committee (REC) if any changes are made to the research project which could affect your ethics approval. There is an Amendment sub-form on MORE that can be completed and submitted to your REC for further review.

2. You must notify your supervisor/REC if there is a breach in data protection management or any issues that arise that may lead to a health and safety concern or conflict of interests.

3. If you require more time to complete your research, i.e., beyond the date specified in your application, please complete the Extension sub-form on MORE and submit it your REC for review.

4. Please quote the application number in any correspondence.

5. It is important that you retain this document as evidence of research ethics approval, as it may be required for submission to external bodies (e.g., NHS, grant awarding bodies) or as part of your research report, dissemination (e.g., journal articles) and data management plan.

6. Also, please forward any other information that would be helpful in enhancing our application form and procedures - please contact MOREsupport@mdx.ac.uk to provide feedback.

Good luck with your research.

Yours sincerely,

Chairs Dr Rhonda Cohen/ Dr Anne Elliott

London Sport Institute REC

Appendix 4.2. Matlab data extraction code.

```
%% Open .txt file of marker data
clear;
clc;

close all;

data=readmatrix('GK_Snatch2_85%_2.txt');                                   % opens
.txt file must change to name
t=readmatrix('time.txt');

%% Extract column data for all markers of interest

knee = rmmissing(data (1:end,2));                                                %
rmmissing gets rid of NaN
hip = rmmissing(data (1:end,3));
ankle = rmmissing(data (1:end,4));
LBx = rmmissing(data (1:end,5));
LBy = rmmissing(data (1:end,6));
LBz = rmmissing(data (1:end,7));
RBx = rmmissing(data (1:end,8));
RBy = rmmissing(data (1:end,9));
RBz = rmmissing(data (1:end,10));
barx = rmmissing((LBx+RBx)/2);
bary = rmmissing((LBy+LBy)/2);
barz = rmmissing((LBz+RBz)/2);

t= t(1:numel(barz));                                                     % changes
t array to the same length as the disp (in this case vertical disp)

%% Insert weight lifted
prompt = {'Enter Weight on Bar'};
title = 'input';
num_lines = 1;
def = {''};
answer = inputdlg(prompt,title,num_lines,def);

kg = str2num(answer{1});

%% Insert athlete height
prompt = {'Enter Athlete Height'};
title = 'input';
num_lines = 1;
def = {''};
answer = inputdlg(prompt,title,num_lines,def);

ht = str2num(answer{1});

%% Angle correction factor - this changes the angle to +'ve (and knee 180 = straight)
knee = knee*-1;
hip = hip*-1;
ankle = ankle*-1;



%% Define residual cut off for vertical and apply filter to positional data

% RAN in BIMECH TOOLBAR FOR NOW = 6Hz
```

```
%https://engineeredathletics.com/2020/08/31/determining-filter-cutoff-frequency-
with-residual-analysis-for-variable-biomechanics-applications/

%% Apply filter to data

co = 4;                                                                  % cut
off freq determined by res analysis in R on sample of 30 random of L/R bar Z
freq = 200;                                                           %capture
freq 200hz
filt_order = 4;                                                       % butter
worth filt (4th order)

[b,a]=butter(filt_order,co/(freq/2));                                 % filter
coeff
Vdisp = filtfilt(b,a,barz);                                            % apply
filter to vert disp
Hrzdisp = filtfilt(b,a,barx);                                          % apply
filter to hrz disp
kneeangle = filtfilt(b,a,knee);                                        % apply
filter to knee angle
hipangle = filtfilt(b,a,hip);                                          % apply
filter to hip angle
ankleangle = filtfilt(b,a,ankle);                                      % apply
filter to ankle angle

Hrzdisp=Hrzdisp*-1;                                                     %flips
+ve and -ve so -ve is away from lifter
%% Derivative of displacement data to obtain  velocity and acceleration

freq = 1/200;

% VERTICAL PROFILES

% VELOCITY - Vv is vertical velocity

Vv =diff(Vdisp)./diff(t);                                       %differentiate
disp to get velocity
Vv(numel(t))=0.001;                                                    % as Vv
is 1 cell short, this adds a 0 to match time length


% ACCELERATION - Vacc is vertical acceleration

Vacc =diff(Vv)./diff(t);                                        %differentiate
disp to get velocity
Vacc(numel(t))=0.001;                                                     % as
Vv is 1 cell short, this adds a 0 to match time length


% HORIZONTAL PROFILES

% VELOCITY - Hrzv is horizontal velocity

Hrzv =diff(Hrzdisp)./diff(t);                                   %differentiate
disp to get velocity
Hrzv(numel(t))=0.001;                                                     % as
Vv is 1 cell short, this adds a 0 to match time length
```

```
% ACCELERATION - Hrzacc is horizontal acceleration

Hrzacc =diff(Hrzv)./diff(t);                                        %differentiate
disp to get velocity
Hrzacc(numel(t))=0.001;                                                    % as Vv
is 1 cell short, this adds a 0 to match time length





%% START to CATCH
% Correct for Enode, which starts at 0.05m/s with disp 0'd.

enodeStartRow= find(Vv>=0.05,1);                                           % finds
ROW 0.05 enode start threshold in Vv
enodeStartValue=Vv(enodeStartRow);                                               %
provides exact start value
VdispEnode = Vdisp(enodeStartRow);                                               %
provides Vdisp value at 0.05 ms threshold
HdispEnode = Hrzdisp(enodeStartRow);                                             %
provides Hrzdisp value at 0.05 ms threshold

LiftOff=enodeStartRow;                                                           %
renamed for ease

% DEFINE END OF LIFT (CATCH)

waitfor(msgbox('Select after the catch'));                                 % gives
a message box telling you what to do
plot(Vdisp);                                                               % plots
vertical disp
hold on
plot(Vv);

[y1, ~]=ginput(2);                                                        % select
two points to read between

y1a=round(y1(1));
y1b=round(y1(2));


catchRow = find(Vv(y1a:y1b)<=0.05,1);                                  % finds ROW
of 0.05 threshold for the end of lift, but is the row between ginput points
enodeCatchRow = catchRow+y1a;                                               % adds
the row value from above to y1(1) (initial ginput marker 1)
enodeCatchRow = round(enodeCatchRow);                                      % round
value to whole number
vline(enodeCatchRow);
enodeCatchValue = Vv(enodeCatchRow);                                             %
provides exact catch value

Catch = enodeCatchRow;

close all
   %%
plot(Vdisp(LiftOff:Catch));                                                 % Plot
new cropped displacement
hold on
```

```
plot(Vv(LiftOff:Catch));


figure(2)
plot(Hrzdisp(LiftOff:Catch),Vdisp(LiftOff:Catch));




%% Correction for displacement being 0 when 0.05 threshold is met.

Vdisp = Vdisp-VdispEnode;
Hrzdisp = Hrzdisp-HdispEnode;

% Correction for displacement to normalise to axis

Vdisp = Vdisp-Vdisp(1);
Hrzdisp = Hrzdisp-Hrzdisp(1);


t= t(1:Catch);                                                                   %
changes t array to the same length as the disp (in this case vertical disp)
tCatch = t(end);

plot(Vdisp(LiftOff:Catch));                                                 % Plot
new cropped displacement
hold on
plot(Vv(LiftOff:Catch));
hold on
yyaxis right
plot(Hrzdisp(LiftOff:Catch));

figure(2)
plot(Hrzdisp(LiftOff:Catch),Vdisp(LiftOff:Catch));


%% WORK + F calculation

% WORK - Calculation of work change in ME. KE = mv2/2 and PE = mgh.
VworkKE = kg*Vv.^2/2;
VworkPE = kg*9.81*Vdisp;
Vwork = VworkKE+VworkPE;

% FORCE - this uses work*distance method
VF = Vwork./Vdisp;


% POWER - Fv Method
VP = VF.*Vv;                                                                     %
Calculation of power


% WORK - Calculation of work change in ME. KE = mv2/2 and PE = mgh.
HrzworkKE = kg*Hrzv.^2/2;
HrzworkPE = kg*9.81*Hrzdisp;
Hrzwork = HrzworkKE+HrzworkPE;

% FORCE - word*dist method
HF = Hrzwork./Hrzdisp;
```

```
% POWER - work/time method
HP = Hrzwork./tCatch;                                                      % 0.005
is the time from 200 hz freq


%% Crop ALL data to these defined points

t = t(LiftOff:Catch);
Vdisp = Vdisp(LiftOff:Catch);
Vv = Vv(LiftOff:Catch);
Vacc = Vacc(LiftOff:Catch);
Vwork = Vwork(LiftOff:Catch);
VF = VF(LiftOff:Catch);
VP = VP(LiftOff:Catch);
Hrzdisp = Hrzdisp(LiftOff:Catch);
Hrzv = Hrzv(LiftOff:Catch);
Hrzacc = Hrzacc(LiftOff:Catch);
Hrzwork = Hrzwork(LiftOff:Catch);
HF = HF(LiftOff:Catch);
HP = HP (LiftOff:Catch);
kneeangle = kneeangle(LiftOff:Catch);
hipangle = hipangle(LiftOff:Catch);
ankleangle = ankleangle(LiftOff:Catch);


%%
figure (1) % disp, velo, acc
sgtitle ('Displacement, Velocity & Acceleration (Vert to Hrz)');

subplot(6,1,1) % 6 rows, 1 columns, plot 1.
plot(t,Vdisp);


subplot(6,1,2) % 6 rows, 1 columns, plot 2.
plot(t,Vv);
hline(0,'k--')


subplot(6,1,3) % 6 rows, 1 columns, plot 3.
plot(t,Vacc);
hline(0,'k--')


subplot(6,1,4) % 6 rows, 1 columns, plot 4.
plot(t,Hrzdisp);
hline(0,'k--')


subplot(6,1,5) % 6 rows, 1 columns, plot 5.
plot(t,Hrzv);
hline(0,'k--')


subplot(6,1,6) %  6 rows, 1 columns, plot 6.
plot(t,Hrzacc);
hline(0,'k--')

vlinefunction();    % this give vert line cursors
```

```
figure (2) % Work, Force and Power
sgtitle ('Work, Force Power (Vert to Hrz)');

subplot(6,1,1) % 6 rows, 1 columns, plot 1.
plot(t,Vwork);


subplot(6,1,2) % 6 rows, 1 columns, plot 2.
plot(t,VF);
hline(0,'k--')


subplot(6,1,3) % 6 rows, 1 columns, plot 3.
plot(t,VP);
hline(0,'k--')


subplot(6,1,4) % 6 rows, 1 columns, plot 4.
plot(t,Hrzwork);
hline(0,'k--')


subplot(6,1,5) % 6 rows, 1 columns, plot 5.
plot(t,HF);
hline(0,'k--')


subplot(6,1,6) %  6 rows, 1 columns, plot 6.
plot(t,HP);
hline(0,'k--')

vlinefunction();

figure (3) % joint angles
sgtitle ('Knee, hip, ankle angle (deg)');

subplot(3,1,1) % 6 rows, 1 columns, plot 1.
plot(t,kneeangle);


subplot(3,1,2) % 6 rows, 1 columns, plot 2.
plot(t,hipangle);
hline(0,'k--')


subplot(3,1,3) % 6 rows, 1 columns, plot 3.
plot(t,ankleangle);
hline(0,'k--')

vlinefunction();
%% Phase Identification - this is to identify the phases of the lift.
% Sometimes there maybe issues if thresholds are not met, therefore double check
when an error occurs.
% I have set ginput for more freedom of selection but also to better own
% and view the data for EACH phase. This would enhance accuracy, but is
% suboptimal for auto analysis.
```

```
%PHASE ID

% FIRST PULL - LO to 1st Pull (Set to first peak knee extension)
waitfor(msgbox('Select between first peak knee extension'));
subplot(4,1,1)
plot(kneeangle);                                                            % plots
vertical velocity
ylabel('degrees')
subplot(4,1,2)
plot(hipangle);
ylabel('degrees')
subplot(4,1,3);
plot(ankleangle);
ylabel('degrees')
subplot(4,1,4);
plot(Vdisp);
ylabel('VDisp')
vlinefunction();

[y2, ~]=ginput(2);                                                         % select
two points to read between

FirstPull=min(kneeangle(y2(1):y2(2)));                                      % finds
max between two points selected
[row,~] =find(kneeangle==FirstPull);                                         % find
the row at which this occurs
FirstPullRow = row;                                                               %
defines LO row as variable
vline(FirstPullRow);


% Transition (First Pull end to most rear H Disp OR V and Hrz = 0 acc)

waitfor(msgbox('Select a range where most rear H Disp is'));              % gives
a message box telling you what to do
subplot(2,1,1)
smooth(Hrzdisp);
plot(Hrzdisp);                                                              % plots
vertical velocity
ylabel('Hrz Disp')
vlinefunction();

subplot(2,1,2)
plot(kneeangle);                                                            % plots
knee angle
ylabel('degrees')
hline(0,'k--');
hold on
yyaxis right
smooth(Vacc)
plot(Vacc)
ylabel('V acc')
hline(0,'k--');
vlinefunction();


[y3, ~]=ginput(2);                                      % select two points to read
between
```

```
Trans=max(Hrzdisp(y3(1):y3(2)));                    % finds max between two points
selected
[row,~] =find(Hrzdisp==Trans);                        % find the row at which this
occurs
TransRow = row;                                       % defines LO row as variable

vline(TransRow);



% 2nd pull (most rear H Disp to PVv)

SecondPull = max(Vv);                                % peak vert velo
SecondPullRow = find(Vv==SecondPull);                % row of PVv
vline (Vv);



% TO occurs between 2nd pull and receive

% Receive (PBH to min vV or 0 acc)
Receive = min(Vv(SecondPullRow:end));               % Receieve of bar
ReceiveRow = find(Vv==Receive);                      % Receieve row
vline(Receive);

figure(1);
plot(Vv);
ylabel('Vv')
hold on
yyaxis right
plot(Hrzdisp)
ylabel('Hrz Disp')
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
CatchAdjusted = Catch-(enodeStartRow-1);                                         %
adjusting the row number for the enode start and end
vline(CatchAdjusted);

vlinefunction();

% Catch (~0.05 for enode threshold) already defined. Adjustment made for
% start at 0.05 threshold. see note above

%% Normalising Hrz to 0

Hrzdisp = Hrzdisp-Hrzdisp(1);

%% ID plot of phases across kinematics and trajectory.

figure (1) % disp, velo, acc
sgtitle ('Displacement, Velocity & Acceleration (Vert to Hrz)');

%Knee angle
subplot(7,1,1) % 6 rows, 1 columns, plot 1.
smooth(kneeangle);
plot(kneeangle);
ylabel('Degrees');
```

```
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);


%Displacement
subplot(7,1,2) % 6 rows, 1 columns, plot 1.
smooth(Vdisp);
smooth(Hrzdisp);
plot(Vdisp);
ylabel('V Disp');
hold on
yyaxis right
plot(Hrzdisp);
ylabel('Hrz Disp');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);

%Velocity
subplot(7,1,3) % 6 rows, 1 columns, plot 2.
smooth(Vv);
smooth(Hrzv);
plot(Vv);
ylabel('Vv');
hold on
yyaxis right
plot(Hrzv);
ylabel('Hrz v');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);

%Acceleration
subplot(7,1,4) % 6 rows, 1 columns, plot 3.
smooth(Vacc);
smooth(Hrzacc);
plot(Vacc);
ylabel('V acc');
hold on
yyaxis right
plot(Hrzacc);
ylabel('Hrz acc');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);

% Work
subplot(7,1,5) % 6 rows, 1 columns, plot 1.
smooth(Vwork);
smooth(Hrzwork);
```

```
plot(Vwork);
ylabel('V work');
hold on
yyaxis right
plot(Hrzwork);
ylabel('Hrz Work');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);

% Force
subplot(7,1,6) % 6 rows, 1 columns, plot 2.
smooth(VF);
plot(VF);
ylabel('VF');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);


% Power
subplot(7,1,7) % 6 rows, 1 columns, plot 3.
smooth(VP);
plot(VP);
ylabel('VP');
vline(FirstPullRow);
vline(TransRow);
vline(SecondPullRow);
vline(ReceiveRow);
vline(CatchAdjusted);


vlinefunction();    % this give vert line cursors

% Trajectory plot + Phase POI

% location of each phase within the Hrz and Vert disp data
loc_FirstPull_x = Hrzdisp(FirstPullRow);                             % Location of
first pull in hrz disp
loc_FirstPull_y = Vdisp(FirstPullRow);                               % Location of
first pull in vert disp
loc_Trans_x = Hrzdisp(TransRow);                                     % Location of
transition in hrz disp
loc_Trans_y = Vdisp(TransRow);                                       % Location of
transition in vert disp
loc_SecondPull_x = Hrzdisp(SecondPullRow);                           % Location of
second pull in hrz disp
loc_SecondPull_y = Vdisp(SecondPullRow);                             % Location of
second pull in vert disp
loc_Receive_x = Hrzdisp(ReceiveRow);                                 % Location of
receive in hrz disp
loc_Receive_y = Vdisp(ReceiveRow);                                   % Location of
receive in vert disp
loc_Catch_x =Hrzdisp(CatchAdjusted);                                    % Location
of catch  in hrz disp
```

```
loc_Catch_y =Vdisp(CatchAdjusted);                                 % Location
of catch  in vert disp


% Plot
figure (2);
smooth(Hrzdisp);
smooth(Vdisp);
plot(Hrzdisp,Vdisp,'k','linewidth',1.5) % displays trajectory
vline(0,'r--'); % start intercept
ylabel (' y - Vertical Displacement (m)');
xlabel (' x - Horizontal Displacement (m)');
title = 'Bar Trajectory';
hold on
plot(loc_FirstPull_x,loc_FirstPull_y,'o-
','markerfacecolor','r','markeredgecolor','k') % POI of First Pull
hold on
plot(loc_Trans_x,loc_Trans_y,'o-','markerfacecolor','r','markeredgecolor','k')    %
POI of trans
hold on
plot(loc_SecondPull_x,loc_SecondPull_y,'o-
','markerfacecolor','r','markeredgecolor','k') % POI of second Pull
hold on
plot(loc_Receive_x,loc_Receive_y,'o-','markerfacecolor','r','markeredgecolor','k')
% POI of receieve Pull
hold on
plot(loc_Catch_x,loc_Catch_y,'o-','markerfacecolor','r','markeredgecolor','k')    %
POI of catch Pull



%% POI - points of interest. These are variables you are interested based on the
phases. Refer to Code_Definitions sheet

%SHYAM CHECK THE FROM AND TO IS ROW AND NOT JUST LIFTOFF OR TRANS (I.E.
%LIFTOFFROW, TRANSROW)

%FIRST PULL
VvEnd1 = Vv(FirstPullRow);                                                  % Vv
value at end of 1st pull
Vdisp1 = Vdisp(FirstPullRow);
Hdisp1 = Hrzdisp(FirstPullRow);
t1 = t(FirstPullRow);

% TRANSITION
VvEndTrans = Vv(TransRow);
VdispTrans = Vdisp(TransRow);
HdispTrans = Hrzdisp(TransRow);
tTrans = t(TransRow)-t1;
vLossTrans = VvEnd1 - VvEndTrans;
%

%SECOND PULL
VvEnd2 = Vv(SecondPullRow);                                                 % Vv
value at end of 2nd pull
VdispEnd2 = Vdisp(SecondPullRow);
HdispEnd2 = Hrzdisp(SecondPullRow);
t2 = t(SecondPullRow)-tTrans;
```

```
% PBH
VPBH = max(Vdisp);
VPBHRow = find(VPBH==Vdisp);
HPBH = Hrzdisp(VPBHRow);

% TO > RECEIVE
VdispReceive = Vdisp(ReceiveRow);
HdispReceive = Hrzdisp(ReceiveRow);
tReceieve = t(ReceiveRow)-t2;
Drop1 = VPBH - VdispReceive;


%CATCH
VdispCatch = Vdisp(CatchAdjusted);
HdispCatch = Hrzdisp(CatchAdjusted);
tCatch = t(CatchAdjusted)-tReceieve;
Drop2 = VdispCatch - VdispReceive;
Drop3 = VPBH-VdispCatch;

%% DISCRETE METRICS
HLoop1 = min(Hrzdisp(TransRow:VPBHRow));                                     %
NOTE: max disp away frpm athlete in mm change to min if neg or select range from
TransRown if all positive
HLoop2 = HdispTrans - HLoop1;                                             % Diff
btwn tran and most fwd. Change to - if all +ve value and + if a pos and neg value
HLoopRow = find(HLoop1==Hrzdisp);
VLoop = Vdisp(HLoopRow);

time = t(CatchAdjusted);

% POWER - Metrics of Power
AvgVP = mean(VP(2:SecondPullRow));
VPP = max(VP(10:end));
VPF = max(VF(10:end));


%% Put Variabes in table

% change all displacements to cm for comparison to enode

Hdisp1 = Hdisp1.*100;
Vdisp1 = Vdisp1.*100;
HdispTrans = HdispTrans.*100;
VdispTrans = VdispTrans.*100;
HdispEnd2 = HdispEnd2.*100;
VdispEnd2 = VdispEnd2.*100;
HPBH = HPBH.*100;
VPBH = VPBH.*100;
HdispReceive = HdispReceive.*100;
VdispReceive = VdispReceive.*100;
Drop1 = Drop1.*100;
HdispCatch = HdispCatch.*100;
VdispCatch = VdispCatch.*100;
Drop2 = Drop2.*100;
Drop3 = Drop3.*100;
HLoop1 = HLoop1.*100;
HLoop2 = HLoop2.*100;
VLoop = VLoop.*100;
```

```
varname={'VvPull1','xDisp1','zDisp1','t1','VvTrans','xDispTrans','zDispTrans','tTrans','vLossTrans',
'VvPull2','xDisp2','zDisp2','t2','xPBH','zPBH','xDispReceive','zDispReceive','tReceive','Drop1','xDispCatch','zDispCatch','tCatch','Drop2','Drop3','MaxFwd','xLoop',
'zLoop','time','AvgP','PP','PF'};

T1=table(VvEnd1,Hdisp1,Vdisp1,t1,VvEndTrans,HdispTrans,VdispTrans,tTrans,vLossTrans,VvEnd2,HdispEnd2,VdispEnd2,t2,HPBH,VPBH,HdispReceive,VdispReceive,tReceieve,Drop1,HdispCatch,VdispCatch,tCatch,Drop2,Drop3,HLoop1,HLoop2,VLoop,time,AvgVP,VPP,VPF,
'VariableNames',varname);


%% Efficiency Ratio

TotalWork = Vwork(1:VPBHRow)+Hrzwork(1:VPBHRow);

PullAvgWork = mean(TotalWork);
PullAvgWork1 = mean(TotalWork(1:FirstPullRow));
PullAvgWorkTran = mean(TotalWork(FirstPullRow:TransRow));
PullAvgWork2 = mean(TotalWork(TransRow:VPBHRow));

VPullWork = mean(Vwork(1:VPBHRow));
VPullAvgWork1 = mean(Vwork(1:FirstPullRow));
VPullAvgWorkTran = mean(Vwork(FirstPullRow:TransRow));
VPullAvgWork2 = mean(Vwork(TransRow:VPBHRow));

HrzPullWork = mean(Hrzwork(1:VPBHRow));
HrzPullAvgWork1 = mean(Hrzwork(1:FirstPullRow));
HrzPullAvgWorkTran = mean(Hrzwork(FirstPullRow:TransRow));
HrzPullAvgWork2 = mean(Hrzwork(TransRow:VPBHRow));

ER1 = VPullAvgWork1./PullAvgWork1.*100;
ERT =VPullAvgWorkTran./PullAvgWorkTran.*100;
ER2 =VPullAvgWork2./PullAvgWork2.*100;
ERPull = VPullWork./PullAvgWork.*100;

varname={'PullAvgWork','VPullWork','HrzPullWork','ERPull','PullAvgWork1','VPullAvgWork1','HrzPullAvgWork1','ER1','PullAvgWorkTran','VPullAvgWorkTran','HrzPullAvgWorkTran','ERT','PullAvgWork2','VPullAvgWork2','HrzPullAvgWork2','ER2'};

T2=table(PullAvgWork,VPullWork,HrzPullWork,ERPull,PullAvgWork1,VPullAvgWork1,HrzPullAvgWork1,ER1,PullAvgWorkTran,VPullAvgWorkTran,HrzPullAvgWorkTran,ERT,PullAvgWork2,VPullAvgWork2,HrzPullAvgWork2,ER2,'VariableNames',varname);
```

Appendix 4.3. R code filter cut off determination.

```
# packages used (no need to install each time!)

install.packages("remotes")

install.packages("signal")


# load packages in this order
```

```
library(biomechanics)
library(remotes)
library(signal)

# read in your data
# import dataset from text - top right

dat <- read.delim("30.txt", header = TRUE, skip = 4)

# run residual analysis, storing the output in a dataframe
res <- residual_analysis(dat$Z, cutoff_range = c(1, 20), sample_freq = 200,
              final_order = 4, interval = 0.1)

# cut off frequency
residual_cut(res, c(1, 20), interval = 0.1)

# read in your data
# import dataset from text - top right

dat <- read.delim("30.txt", header = TRUE, skip = 4)

# run residual analysis, storing the output in a dataframe
res <- residual_analysis(dat$Z.1, cutoff_range = c(1, 20), sample_freq = 200,
                   final_order = 4, interval = 0.1)

# cut off frequency
residual_cut(res, c(1, 20), interval = 0.1)
```

Appendix 5.1. Ethical Approval Letter for study 4.

Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

04/06/2019

APPLICATION NUMBER: 7811

Dear Shyam Chavda

Re your application title: KPI in Weightlifters

Supervisor:

Co-investigators/collaborators:

Thank you for submitting your application. I can confirm that your application has been given approval from the date of this letter by the London Sport Institute REC.

Although your application has been approved, the reviewers of your application may have made some useful comments on your application. Please look at your online application again to check whether the reviewers have added any comments for you to look at.

Also, please note the following:

1. Please ensure that you contact your supervisor/research ethics committee (REC) if any changes are made to the research project which could affect your ethics approval. There is an Amendment sub-form on MORE that can be completed and submitted to your REC for further review.

2. You must notify your supervisor/REC if there is a breach in data protection management or any issues that arise that may lead to a health and safety concern or conflict of interests.

3. If you require more time to complete your research, i.e., beyond the date specified in your application, please complete the Extension sub-form on MORE and submit it your REC for review.

4. Please quote the application number in any correspondence.

5. It is important that you retain this document as evidence of research ethics approval, as it may be required for submission to external bodies (e.g., NHS, grant awarding bodies) or as part of your research report, dissemination (e.g., journal articles) and data management plan.

6. Also, please forward any other information that would be helpful in enhancing our application form and procedures - please contact MOREsupport@mdx.ac.uk to provide feedback.

Good luck with your research.

Yours sincerely

Charlie Cole

Appendix 5.2. All women's Spearman Rho correlations with relative snatch performance measures (rs [95% CI]). Significant correlations presented in bold (p <0.004).

	^{rel}SN	^{cat}SN	^{allo}SN
JH	**0.581 [0.25 - 0.79]**	**0.597 [0.28 - 0.8]**	**0.528 [0.19 - 0.76]**
RSI^{mod}	0.287 [-0.09 - 0.59]	0.269 [-0.11 - 0.58]	0.144 [-0.23 - 0.48]
CMJ PF	-0.46 [-0.71 - -0.1]	-0.333 [-0.62 - 0.04]	-0.245 [-0.56 - 0.13]
CMJ ^{rel}PF	0.22 [-0.16 - 0.54]	0.168 [-0.21 - 0.5]	0.046 [-0.32 - 0.4]
CMJ ^{allo}PF	-0.016 [-0.38 - 0.34]	-0.005 [-0.37 - 0.35]	-0.054 [-0.4 - 0.32]
Braking impulse	-0.318 [-0.62 - 0.06]	-0.217 [-0.54 - 0.16]	-0.056 [-0.41 - 0.31]
Propulsive impulse	-0.434 [-0.69 - -0.07]	-0.342 [-0.63 - 0.03]	-0.015 [-0.38 - 0.34]
Propulsive impulse duration	-0.024 [-0.38 - 0.34]	0.001 [-0.36 - 0.36]	0.116 [-0.25 - 0.46]
AvgPropF	-0.439 [-0.7 - -0.08]	-0.316 [-0.62 - 0.06]	-0.201 [-0.53 - 0.18]
PP	**-0.573 [-0.78 - -0.24]**	-0.464 [-0.71 - -0.1]	-0.247 [-0.56 - 0.13]
^{rel}PP	0.36 [-0.01 - 0.64]	0.325 [-0.04 - 0.62]	0.216 [-0.16 - 0.54]
^{allo}PP	-0.071 [-0.42 - 0.3]	0.05 [-0.32 - 0.4]	0.085 [-0.28 - 0.44]
PropAvgP	-0.403 [-0.67 - -0.03]	-0.297 [-0.6 - 0.08]	-0.128 [-0.47 - 0.24]

Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.

Appendix 5.3. All women's Spearman Rho correlations with relative clean and jerk performance measures (rs [95% CI]). Significant correlations presented in **bold** (p <0.004).

	^{rel}CJ	**^{cat}CJ**	**^{allo}CJ**
JH	**0.578 [0.25 - 0.79]**	**0.603 [0.28 - 0.8]**	**0.550 [0.21 - 0.77]**
RSI^{mod}	0.337 [-0.03 - 0.63]	0.283 [-0.1 - 0.59]	0.241 [-0.14 - 0.56]
CMJ PF	-0.37 [-0.65 - 0]	-0.237 [-0.56 - 0.14]	-0.108 [-0.45 - 0.26]
CMJ ^{rel}PF	0.341 [-0.03 - 0.63]	0.247 [-0.13 - 0.56]	0.2 [-0.18 - 0.53]
CMJ ^{allo}PF	0.117 [-0.25 - 0.46]	0.095 [-0.27 - 0.45]	0.114 [-0.26 - 0.45]
Braking impulse	-0.358 [-0.64 - 0.01]	-0.207 [-0.53 - 0.17]	-0.009 [-0.37 - 0.35]
Propulsive impulse	-0.445 [-0.71 - -0.09]	-0.314 [-0.61 - 0.07]	-0.006 [-0.37 - 0.35]
Propulsive impulse duration	-0.137 [-0.48 - 0.23]	-0.047 [-0.4 - 0.32]	0.004 [-0.36 - 0.36]
AvgPropF	-0.419 [-0.69 - -0.05]	-0.307 [-0.61 - 0.07]	-0.139 [-0.48 - 0.23]
PP	**-0.573 [-0.78 - -0.24]**	-0.458 [-0.71 - -0.1]	-0.222 [-0.54 - 0.16]
^{rel}PP	0.404 [0.03 - 0.67]	0.338 [-0.03 - 0.63]	0.264 [-0.12 - 0.57]
^{allo}PP	-0.038 [-0.39 - 0.33]	0.074 [-0.3 - 0.42]	0.151 [-0.22 - 0.49]
PropAvgP	-0.384 [-0.66 - -0.01]	-0.272 [-0.58 - 0.11]	-0.054 [-0.4 - 0.32]

Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.

Appendix 5.4. All women's Spearman Rho correlations with relative total performance measures (rs [95% CI]). Significant correlations presented in **bold** (*p* <0.004).

	^{rel}Total	**^{cat}Total**	**^{allo}Total**
JH	**0.579 [0.25 - 0.79]**	**0.6 [0.28 - 0.8]**	**0.551 [0.21 - 0.77]**
RSI^{mod}	0.298 [-0.08 - 0.6]	0.267 [-0.11 - 0.58]	0.181 [-0.2 - 0.51]
CMJ PF	-0.438 [-0.70 - -0.08]	-0.297 [-0.60 - 0.08]	-0.168 [-0.5 - 0.21]
CMJ ^{rel}PF	0.286 [-0.09 - 0.59]	0.215 [-0.16 - 0.54]	0.146 [-0.22 - 0.49]
CMJ ^{allo}PF	0.047 [-0.32 - 0.4]	0.043 [-0.33 - 0.39]	0.049 [-0.32 - 0.4]
Braking impulse	-0.395 [-0.67 - -0.03]	-0.265 [-0.58 - 0.11]	-0.023 [-0.38 - 0.34]
Propulsive impulse	-0.479 [-0.73 - -0.12]	-0.362 [-0.64 - 0.01]	0.012 [-0.35 - 0.37]
Propulsive impulse duration	-0.105 [-0.45 - 0.26]	-0.054 [-0.4 - 0.32]	0.056 [-0.31 - 0.41]
AvgPropF	-0.455 [-0.71 - -0.1]	-0.323 [-0.62 - 0.06]	-0.177 [-0.51 - 0.2]
PP	**-0.603 [-0.80 - -0.28]**	-0.476 [-0.73 - -0.12]	-0.223 [-0.54 - 0.16]
^{rel}PP	0.39 [0.02 - 0.67]	0.349 [-0.02 - 0.64]	0.238 [-0.14 - 0.56]
^{allo}PP	-0.064 [-0.41 - 0.31]	0.068 [-0.30 - 0.42]	0.126 [-0.24 - 0.47]
PropAvgP	-0.421 [-0.69 - -0.05]	-0.296 [-0.6 - 0.08]	-0.08 [-0.43 - 0.29]

Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.

Appendix 5.5. All men's Spearman Rho correlations with relative snatch performance measures (rs [95% CI]). Significant correlations presented in **bold** (*p* <0.004).

	^{rel}SN	**^{cat}SN**	**^{allo}SN**
JH	0.622 [0.01 - 0.89]	0.729 [0.19 - 0.93]	0.675 [0.1 - 0.91]
CMJ PF	-0.228 [-0.71 - 0.41]	-0.35 [-0.78 - 0.3]	0.042 [-0.55 - 0.6]
CMJ ^{rel}PF	0.322 [-0.32 - 0.76]	0.228 [-0.41 - 0.71]	0.301 [-0.34 - 0.75]
CMJ ^{allo}PF	0.06 [-0.53 - 0.61]	-0.109 [-0.64 - 0.5]	0.175 [-0.45 - 0.68]
Braking impulse	-0.144 [-0.66 - 0.47]	-0.235 [-0.72 - 0.4]	0.133 [-0.48 - 0.66]
Propulsive impulse	-0.34 [-0.77 - 0.31]	-0.294 [-0.75 - 0.35]	-0.056 [-0.61 - 0.54]
Propulsive impulse duration	0.657 [0.07 - 0.91]	0.678 [0.1 - 0.91]	0.533 [-0.1 - 0.86]
AvgPropF	-0.68 [-0.91 - -0.1]	**-0.792 [-0.95 - -0.32]**	-0.42 [-0.81 - 0.23]
PP	-0.469 [-0.83 - 0.18]	-0.417 [-0.81 - 0.23]	-0.238 [-0.72 - 0.4]
^{rel}PP	-0.207 [-0.7 - 0.42]	-0.077 [-0.62 - 0.52]	-0.07 [-0.62 - 0.53]
^{allo}PP	-0.172 [-0.68 - 0.45]	-0.238 [-0.72 - 0.4]	0.021 [-0.56 - 0.59]
BrkAvgP	-0.179 [-0.69 - 0.44]	-0.203 [-0.7 - 0.43]	-0.182 [-0.69 - 0.44]
PropAvgP	-0.441 [-0.82 - 0.21]	-0.522 [-0.86 - 0.12]	-0.182 [-0.69 - 0.44]

Where, JH = jump height, RSI^{mod}= reactive strength index modified, PF = peak force, ^{rel}PF = relative peak force, ^{allo}PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power, ^{rel}PP = relative peak power, ^{allo}PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.

Appendix 5.6. All men's Spearman Rho correlations with relative clean and jerk performance measures (rs [95% CI]). Significant correlations presented in **bold** (*p* <0.004).

	^{rel}**CJ**	^{cat}**CJ**	^{allo}**CJ**
JH	0.695 [0.13 - 0.92]	0.732 [0.19 - 0.93]	0.606 [-0.01 - 0.89]
CMJ PF	-0.218 [-0.71 - 0.41]	-0.305 [-0.75 - 0.34]	0.218 [-0.41 - 0.71]
CMJ ^{rel}PF	0.536 [-0.1 - 0.86]	0.378 [-0.27 - 0.79]	0.655 [0.06 - 0.91]
CMJ ^{allo}PF	0.255 [-0.38 - 0.73]	0.064 [-0.53 - 0.62]	0.591 [-0.03 - 0.88]
Braking impulse	-0.327 [-0.77 - 0.32]	-0.319 [-0.76 - 0.33]	-0.145 [-0.67 - 0.47]
Propulsive impulse	-0.355 [-0.78 - 0.29]	-0.264 [-0.73 - 0.37]	-0.027 [-0.59 - 0.56]
Propulsive impulse duration	0.441 [-0.21 - 0.82]	0.442 [-0.21 - 0.82]	0.299 [-0.34 - 0.75]
AvgPropF	-0.536 [-0.86 - 0.1]	-0.638 [-0.9 - -0.04]	-0.218 [-0.71 - 0.41]
PP	-0.309 [-0.76 - 0.34]	-0.237 [-0.72 - 0.4]	-0.127 [-0.65 - 0.48]
^{rel}PP	0.136 [-0.48 - 0.66]	0.21 [-0.42 - 0.7]	0.182 [-0.44 - 0.69]
^{allo}PP	0.1 [-0.5 - 0.64]	-0.055 [-0.61 - 0.54]	0.245 [-0.39 - 0.72]
BrkAvgP	-0.164 [-0.68 - 0.46]	-0.269 [-0.74 - 0.37]	0.155 [-0.46 - 0.67]
PropAvgP	-0.336 [-0.77 - 0.31]	-0.415 [-0.81 - 0.23]	-0.064 [-0.62 - 0.53]

Where, JH = jump height, RSI^{mod}*= reactive strength index modified, PF = peak force,* ^{rel}*PF = relative peak force,* ^{allo}*PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power,* ^{rel}*PP = relative peak power,* ^{allo}*PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.*

Appendix 5.7. All men's Spearman Rho correlations with relative total performance measures (rs [95% CI]). Significant correlations presented in **bold** (*p* <0.004).

	^{rel}Total	**^{cat}Total**	**^{allo}Total**
JH	0.672 [0.09 - 0.91]	0.719 [0.17 - 0.93]	0.723 [0.18 - 0.93]
CMJ PF	-0.173 [-0.68 - 0.45]	-0.3 [-0.75 - 0.34]	0.109 [-0.5 - 0.64]
CMJ ^{rel}PF	0.455 [-0.19 - 0.83]	0.336 [-0.31 - 0.77]	0.536 [-0.1 - 0.86]
CMJ ^{allo}PF	0.236 [-0.4 - 0.72]	0.073 [-0.52 - 0.62]	0.427 [-0.22 - 0.81]
Braking impulse	-0.227 [-0.71 - 0.41]	-0.355 [-0.78 - 0.29]	-0.036 [-0.6 - 0.55]
Propulsive impulse	-0.282 [-0.74 - 0.36]	-0.309 [-0.76 - 0.34]	-0.027 [-0.59 - 0.56]
Propulsive impulse duration	0.51 [-0.13 - 0.85]	0.566 [-0.06 - 0.87]	0.538 [-0.1 - 0.86]
AvgPropF	-0.527 [-0.86 - 0.11]	-0.673 [-0.91 - -0.09]	-0.4 [-0.8 - 0.25]
PP	-0.264 [-0.73 - 0.37]	-0.273 [-0.74 - 0.37]	-0.209 [-0.7 - 0.42]
^{rel}PP	0.064 [-0.53 - 0.62]	0.118 [-0.49 - 0.65]	0.018 [-0.56 - 0.59]
^{allo}PP	0.082 [-0.52 - 0.63]	-0.036 [-0.6 - 0.55]	0.091 [-0.51 - 0.63]
BrkAvgP	-0.236 [-0.72 - 0.4]	-0.255 [-0.73 - 0.38]	-0.045 [-0.6 - 0.54]
PropAvgP	-0.291 [-0.75 - 0.35]	-0.409 [-0.81 - 0.24]	-0.227 [-0.71 - 0.41]

Where, JH = jump height, RSI^{mod}*= reactive strength index modified, PF = peak force,* ^{rel}*PF = relative peak force,* ^{allo}*PF = allometric peak force, AvgPropF = average Propulsive force, PP = peak power,* ^{rel}*PP = relative peak power,* ^{allo}*PP= allometric peak power, BrkAvgP = braking average power, PropAvgP = Propulsive average power.*

Appendix 6.1. Timeline of training blocks leading into the Olympics along with block length, session number per microcycle, gap between training blocks and notes of importance.

Block	Comp	Date	Start	End	Wks	# S	Gap	Notes
Block 1 – Comp 1	EngC 19	20/01/2019	12/11/2018	17/01/2019	9	4		* Testing (CMJ + IMTP)
Block 2 – GPP 1			28/01/2019	08/03/2019	6	4	2	
Block 3 – SSP 1	BU 19	14/04/2019	11/03/2019	12/04/2019	5	4	0	* Testing (CMJ + IMTP)
Block 4 - Comp 2	BIO 19	08/06/2019	22/04/2019	07/06/2019	7	4	1	* Testing (CMJ + IMTP) * Wrist & Elbow injury
Block 5 – GPP 2			01/07/2019	09/08/2019	6	4	3	* Wrist injury through 09-2019 - 12-2019
Block 6 – GPP 3	EGP 19		12/08/2019	01/11/2019	9	4	0	* Wrist recovery + recovery from Covid
Block 7 - GPP 4			13/01/2020	07/02/2020	4	5	10	
Block 8 - GPP 5			17/02/2020	13/03/2020	4	5	1	
Block 9 - GPP 6			06/04/2020	01/05/2020	4	5	3	* National Lockdown 1 (Mar - Jun)
Block 10 - GPP 7			18/05/2020	12/06/2020	4	5	2	* Rule of 6
Block 11 - GPP 8			03/08/2020	28/08/2020	4	5	7	* National Lockdown 1 lifted * Gyms reopen 25 July
Block 12 - GPP 9			31/08/2020	25/09/2020	4	5	0	* Tier system
Block 13 - GPP 10			16/11/2020	04/12/2020	3	5	7	* National Lockdown 2 (Nov)
Block 14 - SSP 2			07/12/2020	01/01/2021	4	5	0	* Tier system
Block 15 - SSP 3	EC 21	02/02/2021	11/01/2021	12/02/2021	5	5	1	* National Lockdown 3 (Jan - Mar) * Elite athlete exemption
Block 16- GPP 11			22/02/2021	12/03/2021	3	5	1	
Block 17 - SSP 4			15/03/2021	09/04/2021	4	5	0	
Block 18 - SSP 5			12/04/2021	08/05/2021	4	6	0	
Block 19 - SSP 6			10/05/2021	05/06/2021	4	6	0	
Block 20 - Comp 3			07/06/2021	03/07/2021	4	6	0	
Block 21 - Comp 4	BWC 21	07/07/2021	05/07/2021	17/07/2021	2	4-6	0	
Block 22 - Taper	OG 21	31/07/2021	19/07/2021	31/07/2021	2	4-6	0	

Where GPP = general preparatory phase, SSP = sport specific phase, EngC = English Championships, BU = British University Championships, BIO = British International Open (Tokyo Bronze qualifying event), EGP = English Grand Prix, BWC = British weightlifting Championships, OG = Olympic Games, Wks = weeks within training blocks (mesocycle), #S = number of sessions within each week (microcycle) and "Gap" is the number for weeks between each training block.

Appendix 6.2. Competitor information based on best achieved snatch and jerk, average increase between attempts, average success rate of three attempts and highest ever attempted load.

	Best	Opener	1 to 2	2 to 3	1 to 3	Success %	Highest Attempted
BLR	180	161	165	168	169	72%	184
CAN	181	169	175	179	178	72%	187
CUB	165	153	159	162	159	75%	165
GEO	181	170	173	177	178	83%	181
GHA	153	142	146	149	149	78%	153
GRE	163	155	158	160	160	67%	163
JPN	165	155	161	163	160	56%	170
KGZ	171	160	166	170	167	67%	176
KOR	162	150	156	159	159	52%	167
PLE	141	122	127	131	130	61%	145
POL	165	150	155	158	157	44%	169
QAT	178	170	175	177	174	50%	181
TPE	175	162	165	168	167	56%	175
VEN	175	161	166	168	165	77%	175

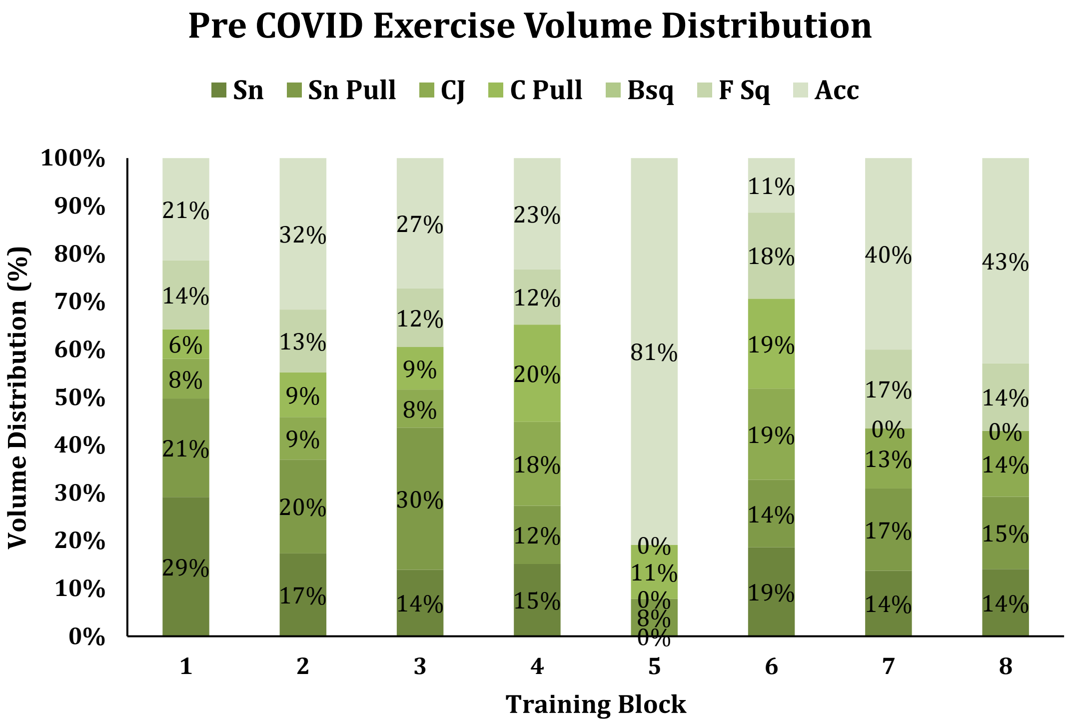
	Best	Opener	1 to 2	2 to 3	1 to 3	Success %	Highest Attempted
BLR	222	195	199	205	205	78%	222
CAN	210	202	204	208	210	61%	215
CUB	206	193	195	197	201	63%	206
GEO	215	201	207	213	213	78%	221
GHA	185	173	176	178	182	83%	185
GRE	197	186	190	193	195	72%	201
JPN	208	194	200	208	208	67%	217
KGZ	212	194	200	204	204	71%	219
KOR	207	193	199	201	199	78%	209
PLE	171	148	154	158	159	50%	176
POL	206	183	189	194	195	73%	206
QAT	228	214	220	224	225	63%	232
TPE	200	190	196	198	200	60%	205
VEN	211	198	202	204	204	54%	211

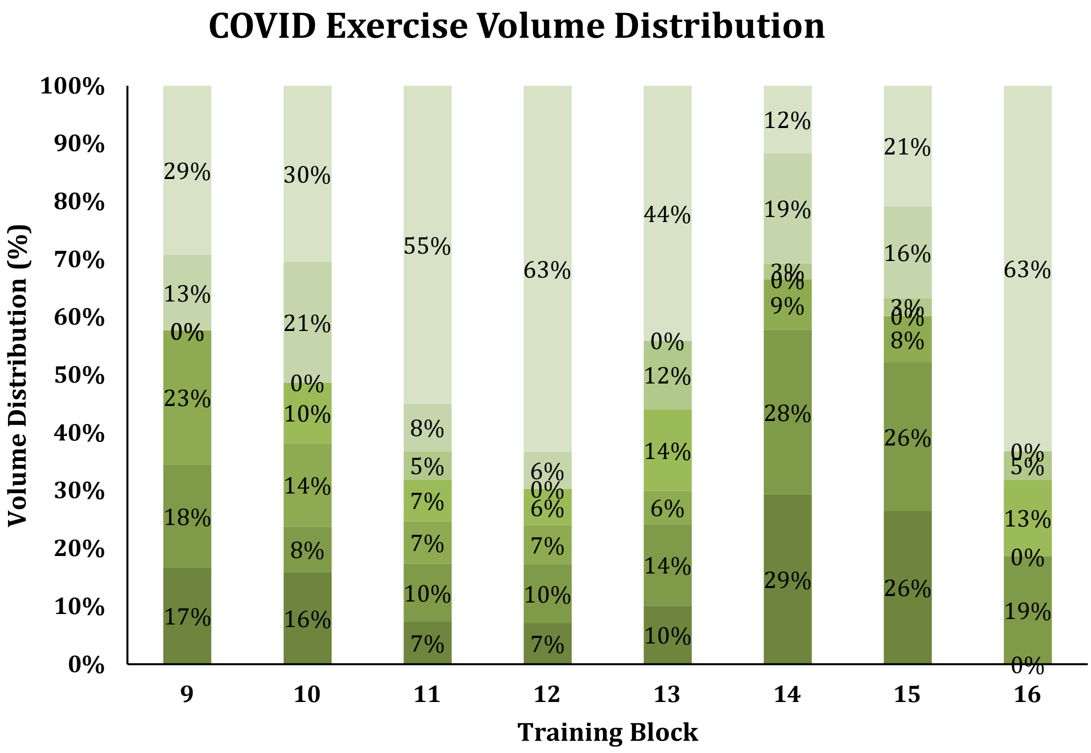
Appendix 6.3. Detailed breakdown of the athletes' competitions and success percentage, along with heaviest attempted load in the lead up to the Olympic Games.

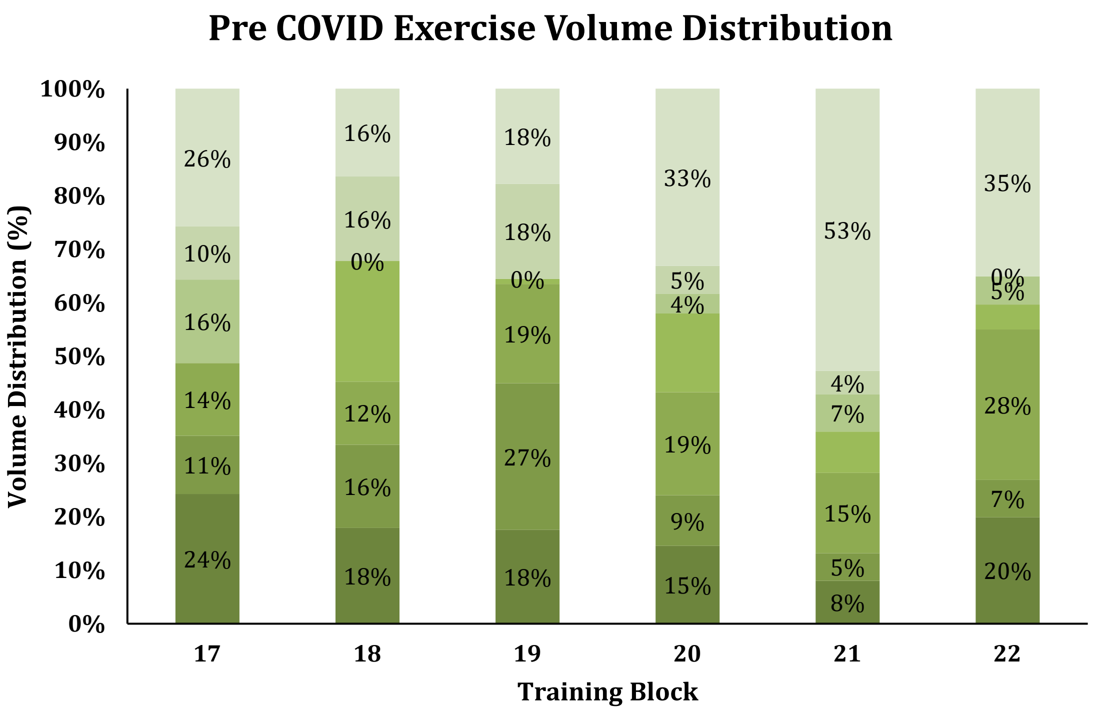
			Snatch Attempts				Attempt Difference (%)			Success (abs/%)		CJ Attempts				Attempt Difference (%)			Success (abs/%)			Heaviest Attempt	
Competition	**Cat.**	**BW**	**1**	**2**	**3**	**Best**	**1-2**	**2-3**	**1-3**			**1**	**2**	**3**	**Best**	**1-2**	**2-3**	**1-3**			**Total**	**Sn.**	**CJ.**
EC 19	96	95	141	**150**	150	150	6%	0%	6%	2	67%	**180**	180	190	190	0%	5%	5%	2	67%	340	150	190
BUCS 19	102	100.6	150	155	160	160	3%	3%	6%	3	100%	**190**	190	200	200	0%	5%	5%	2	67%	360	160	200
BIO 19	102	100.2	145	150	161	161	3%	7%	10%	3	100%	185	195	**205**	195	5%	5%	10%	2	67%	356	161	205
EGP 19	96	95.3	**150**	150	155	155	0%	3%	3%	2	67%	185	**195**	**195**	185	5%	0%	5%	1	33%	340	155	195
EC 21	102	97.9	150	**160**	**160**	150	6%	0%	6%	1	33%	180	190	**202**	190	5%	6%	11%	2	67%	340	160	202
BC 21	96	95.6	150	**155**	160	160	3%	3%	6%	2	67%	**180**	190	-	190	5%	-	-	1	50%	350	160	190

Where Cat. is weight category, BW is bodyweight in kilograms, abs is absolute, Sn. Is snatch and CJ is clean and jerk. Red filled boxes display missed lift, green filled boxes display heaviest successful lift and yellow filled boxes is the total achieved. Competition codes are presented as; EC = English Championship, BUCS = British University and College Sports Championship, BIO = British International Open, EGP = English Grand Prix and BC = British Championship.

Appendix 6.4. Volume distribution.






Pre COVID Exercise Volume Distribution
Volume Distribution (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
26%
10%
16%
14%
11%
24%
16%
16%
0%
12%
16%
18%
18%
18%
0%
19%
27%
18%
33%
5%
4%
19%
9%
15%
53%
4%
7%
15%
5%
8%
35%
0%
5%
28%
7%
20%
17
18
19
20
21
22
Training Block