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ORIGINAL ARTICLE

Relationship Between Kinetic and Kinematic Measures of the Countermovement Jump and National Weightlifting Performance

Shyam Chavda[1] · **Jason P. Lake**[2] · **Paul Comfort**[3] · **Chris Bishop**[1] · **Shaun A. Joffe**[4] · **Anthony N. Turner**[1]

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Abstract

Purpose The association between vertical jump and weightlifting performance have been well established often using discrete performance measures such as jump height or peak power which provides little insight into temporal strategies. The purpose of this investigation was to identify currently unassessed temporal countermovement jump metrics and their reliability and relationship to national weightlifting performance.

Methods A total of 42 national weightlifting athletes ($n = 30$ females and 12 males), were recruited for this study. Countermovement jump was measured using a force plate following a national and international competition. Vertical ground reaction force and time data were analyzed using a custom script where temporal metrics relating to specific phases of the jump were extracted. Snatch, Clean and Jerk and Total weightlifting performance was obtained following each competition. Reliability of jump metrics were determined using coefficient of variation and interclass correlation coefficient. A Spearman's Rho, non-parametric bivariate correlation was used to determine the relationship between the jump metrics and weightlifting performance.

Results 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.

Conclusion This novel finding suggests that practitioners may wish to use propulsive impulse as it may provide more insight into changes of force capabilities following training. Additionally, it may also be used as a talent identification tool given its strong relationship to performance.

Keywords Jumping · Force · Snatch · Clean

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 [17, 28]. 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 (Fig. 1). Temporal kinetics of the weightlifting pull typically display impulses (the area under the force time curve)

✉ Shyam Chavda
s.chavda@mdx.ac.uk

[1] London Sports Institute, Middlesex University, West Stand, Stone X Stadium, Greenlands Lane, London NW4 1RL, UK

[2] Chichester Institute of Sport, University of Chichester, College Lane, Chichester PO19 6PE, UK

[3] Directorate of Sport, Exercise and Physiotherapy, University of Salford, Salford, Greater Manchester, UK

[4] School of Sport, Health and Applied Sciences, St Marys University, Waldegrave Road, Twickenham, London TW1 4SX, UK

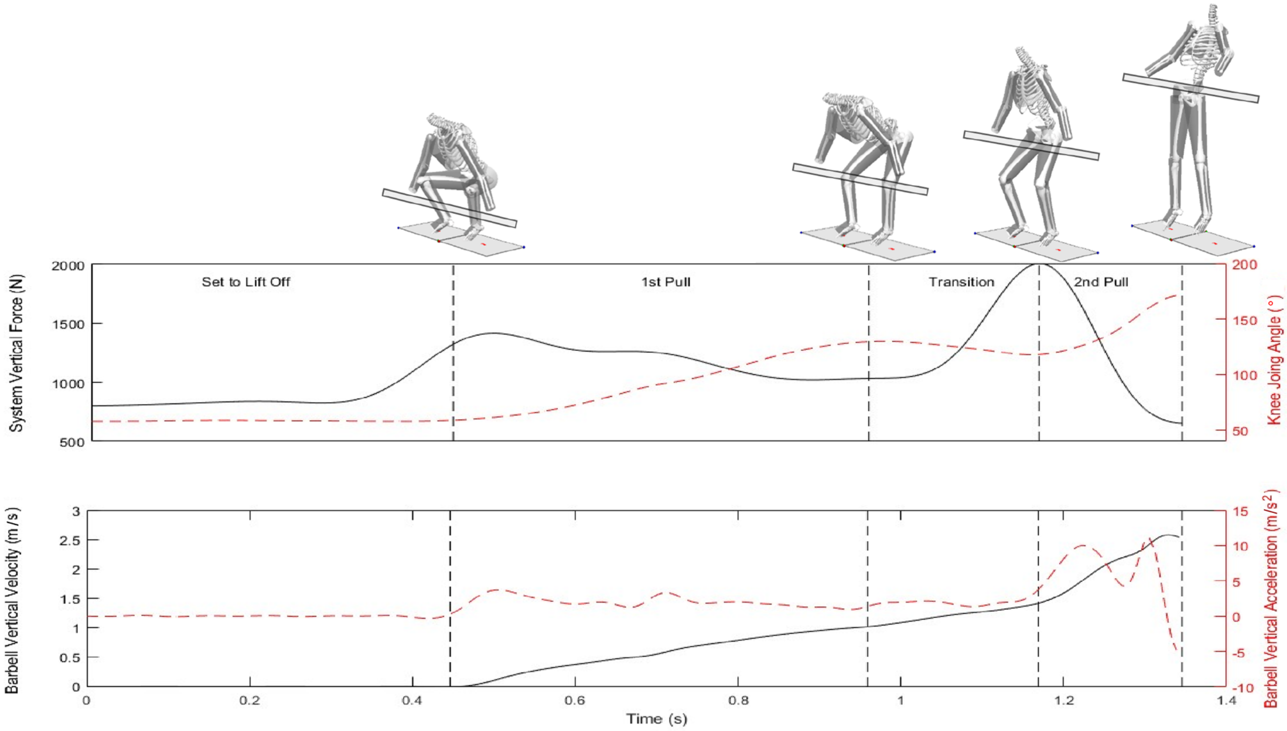


Fig. 1 System, joint and barbell kinetics and kinematic of the pull during a snatch

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 [13, 39], 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) [29, 34]. 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 [1, 13, 25]. 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) [9, 18]. 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 [3, 31, 35]. 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 [3]. 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.

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 [6, 20, 24, 27, 30, 41] as well as to monitor changes in weightlifting performance over time [23, 28]. This can help practitioners assess 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 [24], Khaled [30], and Kite & Spence [32] 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 [17, 20, 23, 27, 28, 41]. 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) [20, 23, 28]. 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 [17], 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 [12], 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 [6, 15, 20, 23, 28]. 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 [38]. Given that jump height is dictated by net impulse applied to the ground [46], 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 [6, 15, 20, 23, 24, 27, 28, 30, 32, 41], 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.

Methods

Experimental Approach to the Problem

To identify the relationship between WLp and CMJ kinetic and kinematics of national and international weightlifters CMJ, 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.

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. Weight category distribution is presented in the supplementary materials. All participants were over the age of 18 and provided consent during the sign up for the competition. Ethical approval was obtained via *Middlesex university, London Sport Institute Research Ethics Comittee* (Ethics Application #7811).

Methodology

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-h. 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 1000 Hz. Athletes were asked to stand as still as possible on the force plate, with arms akimbo, for a minimum of 1 s, before they were instructed to jump as high as possible whilst keeping their hands on their hips [8]. Once the athlete was ready, they were asked to perform 2 maximal CMJ's interspersed with ~ 1-min rest between trials. All raw force–time data were extracted for analysis in a custom spreadsheet [8]. Definitions of the extracted metrics can be found in in Table 1. Figure 2 is representative of a force and velocity–time and power-time curve with the unweighting, braking, and propulsion phases identified.

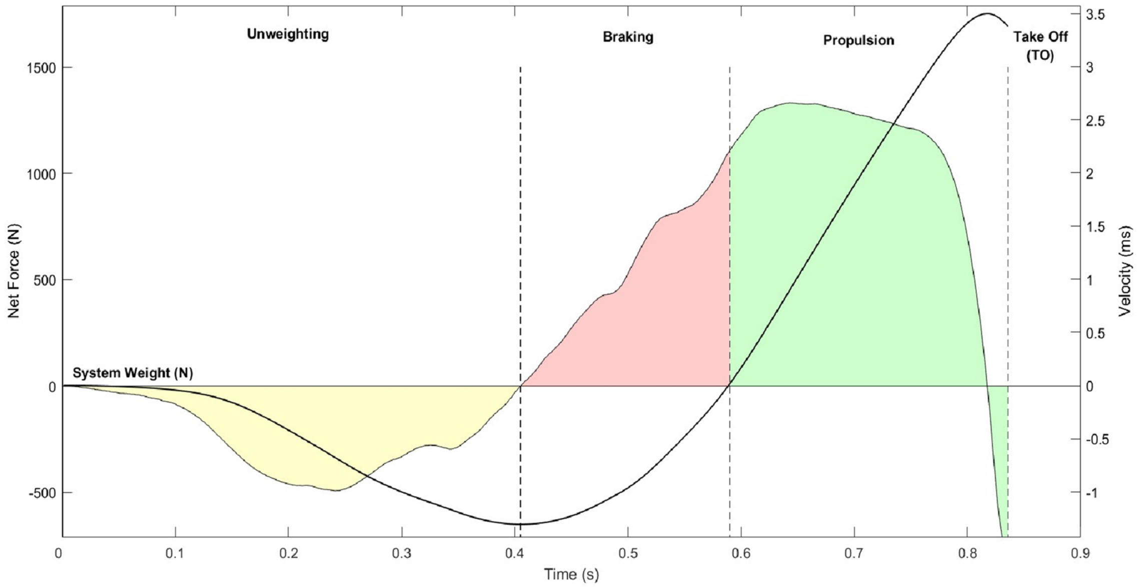
Competition Performance Competition performance was recorded as the heaviest successful SN and CJ, and therefore TOT. Official results were taken from the British Weightlifting website for each of the competitions (accessed: 26/01/2019 and 20/04/2019, respectively). Competition performance was taken as absolute ($^{\text{abs}}$WLp), relative to bodyweight ($^{\text{rel}}$WLp), relative to weight category ($^{\text{cat}}$WLP), and allometrically scaled ($^{\text{allo}}$WLp) to the exponent of 0.67 [2].

It has previously been indicated that allometric scaling is an effect way to normalise performance measures relating to strength by eliminating the effect of body size [11]. The curve linear relationship that exists between body mass and weight lifted [2] 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 [7] 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 [26]. Challis [7] 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 [20, 23, 28]. In the present study, allometric scaling of the dependent and independent variables will provide indication into relationships between WLp and various kinetic and kinematic surrogates whilst removing the effect of body mass.

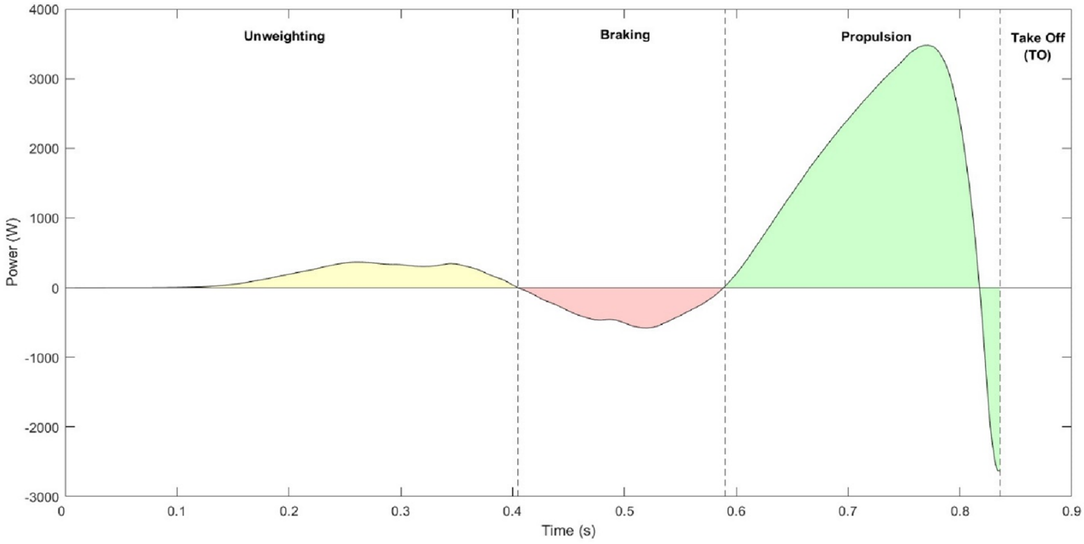
The rationale for scaling WLp relative to weight category is a novel method of scaling. It negates the issue that exists with ratio scaling to bodyweight. Athletes within the same weightclass could display different absolute results which dictate performance outcome (i.e., achieving a medal or higher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

Table 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$^{\text{mod}}$	-	Jump height/time to take off
Peak force	PF	N	Peak net propulsive force value
Relative peak force	$^{\text{rel}}$PF	N/kg	Peak net force value/athletes body mass
Allometric peak force	$^{\text{allo}}$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	$^{\text{rel}}$PP	W/kg	Peak power value/athletes body mass
Allometric peak power	$^{\text{allo}}$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



a – Force- and velocity- time curve of the countermovement jump.



b – Power - time curve of the countermovement jump.

Fig. 2 **a** Force-and velocity- time curve of the countermovement jump. **b** Power—time curve of the countermovement jump

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.

Table 2 Women and Men's absolute and relative performance data ($n=42$)

Variable	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
$^{\text{rel}}$SN	1.16 ± 0.19	[1.09–1.23]	0.04
$^{\text{rel}}$CJ	1.43 ± 0.24	[1.34–1.53]	0.05
$^{\text{rel}}$TOT	2.59 ± 0.44	[2.43–2.76]	0.08
$^{\text{cat}}$SN	1.16 ± 0.18	[1.09–1.22]	0.03
$^{\text{cat}}$CJ	1.44 ± 0.22	[1.35–1.52]	0.04
$^{\text{cat}}$TOT	2.60 ± 0.40	[2.45–2.75]	0.07
$^{\text{allo}}$SN	5.06 ± 0.64	[4.82–5.30]	0.12
$^{\text{allo}}$CJ	6.26 ± 0.81	[5.95–6.57]	0.15
$^{\text{allo}}$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
$^{\text{rel}}$SN	1.42 ± 0.20	[1.29–1.55]	0.06
$^{\text{rel}}$CJ	1.78 ± 0.26	[1.60–1.96]	0.08
$^{\text{rel}}$TOT	3.20 ± 0.47	[2.89–3.52]	0.14
$^{\text{cat}}$SN	1.42 ± 0.16	[1.32–1.52]	0.05
$^{\text{cat}}$CJ	1.80 ± 0.21	[1.66–1.94]	0.06
$^{\text{cat}}$TOT	3.24 ± 0.35	[3.00–3.48]	0.11
$^{\text{allo}}$SN	6.96 ± 0.72	[6.50–7.42]	0.21
$^{\text{allo}}$CJ	8.72 ± 0.94	[8.09–9.35]	0.28
$^{\text{allo}}$TOT	15.68 ± 1.63	[14.58–16.77]	0.49

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

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 [36] and with known differences in WLp between sexes [41], 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% [45]. 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 [33]. 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*" [22].

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 [37]. 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 $1\text{-}(1\text{-}\alpha)^n$, 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) [14]. 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.

Results

All data are presented as mean ± SD with 95% CI (mean ± SD [95% CI]). Women's and men's height, mass, and weightlifting performance data can be seen in Table 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

Table 3 Women's physical and performance characteristics reliability

Variable	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 to − 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**

All measures in bold denote excellent reliability

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

Table 4 Men's physical and performance characteristics reliability

Variable	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**

All measures in bold denote excellent reliability

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

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, RSI^{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 Tables 3 and 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, with correlation to relative weightlifting performance measures supplied in supplementary materials.

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.

Reliability

The use of kinetic data derived from a CMJ allows performance scientists and coaches a more extensive assessment of neuromuscular ability [44] with many of these metrics shown to have excellent sensitivity to change [10]. 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

Table 5 All women and men's Spearman Rho correlations with absolute total performance (r_s [95% CI])

Variable	^{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]

Significant correlations presented in bold

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 men (Tables 3 and 4). 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 [4]. These are further explored in the discussion of relationships.

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 [17], 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 [17] 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 [5] ($r = 0.510$, $P < 0.01$). Although, this was conducted on physical education students, it was later purported [15], 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 [40]. 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) [36]. 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 [29], 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 [29]. Secondly, higher performing weightlifters tend to display lower amortization phases between the dip and drive phase of the jerk [19, 29]. While the present study did not directly investigate measures of SSC ability, Kauhanen [29] 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 [6, 20, 23, 28, 42].

Power outputs produced in jump tests are thought to be similar to those produced in the pull phase of the SN and CJ [16]. Previous researchers have reported *strong* to *near perfect* relationships ($r = 0.60$–0.93) between PP and ^{abs}WLp [6, 20]. 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 [6]. 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 [2] 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 [6, 32], but not others [43]. 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 [38]. 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 ± 0.35 s) due to greater centre of mass displacement [21], 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 (15) 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. 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. [23] that loaded squat jumps maybe superior to unloaded jumps in identifying fatigue in trained individuals. Therefore, to summarise, future studies may wish to explore the current findings and its utility in monitoring training adaptations longitudinally along with loaded jump performances.

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.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors did not receive support from any organization for the submitted work.

Ethical Approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of withheld for anonymity.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent to Publish Participant consent was obtained outlining that their data will be analysed anonymously within a larger data set, with the results of the study having the potential to be published.

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