Intra- and inter-day reliability of weightlifting variables and correlation to performance during cleans

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ABSTRACT

The purpose of this investigation was to examine intra- and inter-day reliability of kinetic and kinematic variables assessed during the clean, assess their relationship to clean performance, and determine their suitability in weightlifting performance analysis. Eight competitive weightlifters performed 3 sets of single repetition cleans with 90% of their one-repetition maximum. Force-time data were collected via dual force plates with displacement-time data collected via 3-dimensional motion capture, on three separate occasions under the same testing conditions. Seventy kinetic and kinematic variables were analyzed for intra- and inter-day reliability using intraclass correlation coefficients (ICC) and the coefficient of variation (CV). Pearson's correlation coefficients were calculated to determine relationships between barbell and body kinematics and ground reaction forces and for correlations to be deemed as statistically significant, an alpha-level of $p \leq 0.005$ was set. Eleven variables were found to have 'good' to 'excellent' intra- and inter-day ICC (0.779-0.994 and 0.974-0.996, respectively) and CV (0.64-6.89% and 1.14-6.37%, respectively), with strong correlations (r = 0.880-0.988) to cleans performed at 90% 1RM. Average resultant force of the weighting 1 (W1) phase demonstrated the best intra- and inter-day reliability (ICC = 0.994 and 0.996 respectively), and very strong correlation (r = 0.981) to clean performance. Average bar power from point of lift off to peak bar height exhibited the highest correlation (r = 0.988) to clean performance. Additional reliable variables with strong correlations to clean performance were found, many of these occurred during or included the W1 phase, which suggests coaches should pay particular attention to the performance of the W1 phase.

Keywords: weightlifting performance, kinetics, kinematics, reliability

INTRODUCTION

Weightlifting pulling movements have previously been defined by vertical ground reaction force (vGRF) alongside changes in knee joint angles, and although system weight (body + barbell weight) does not actually change, they are generally categorized into three phases: weighting 1 (W1), unweighting (UW), and weighting 2 (W2) (9). These three phases have also been reported in other research using different terminology, but with similar definitions, as first pull, transition, and second pull, which approximately correspond to W1, UW, and W2 respectively (20, 23, 32). The pulling phases have been considered to be among the most important components in weightlifting (16-20, 32, 33), as the performance off these will determine whether a lifter may be able to successfully displace the barbell during a given lift. The W1 phase is noted by an increase in vGRF above system weight as the knee joints extend, the UW phase is marked by a decrease in vGRF as the knee joints flex, and lastly, the W2 phase is exhibited by a second increase in vGRF as the knee joints reach maximal extension (9). While all phases exhibit varying levels of force and power, W1 has been noted to be a knee-dominant movement where force must be exerted to overcome the inertia of the barbell, making it more of a strength-oriented phase. In comparison, W2 has been noted to be a hip-dominant movement that must occur quickly, making it more of a power-oriented phase (1, 14, 16, 18, 20, 28) .

A variety of reliable kinetic and kinematic variables of both barbell and system (body + barbell) have been reported to describe the pull and its specific elements, such as power, velocity, and barbell displacement (3, 8-20, 25, 27, 28, 29, 32). Additional reliable variables like peak force, peak power, and peak velocity are also frequently reported in the weightlifting literature (3, 7, 10, 20, 21, 27, 33, 34). Peak barbell height has also been of particular interest to researchers, as the primary objective in weightlifting is to displace a barbell from the floor to the shoulders (clean) or overhead position (snatch and jerk) (3, 4, 13, 32, 33), illustrating the potential importance of peak barbell height. However, Isaka et al. (26) and Nagao et al. (33) suggest that decreasing the distance between the maximum height of the barbell and the catch position (drop distance), rather than peak bar height, may be a more important factor for success in weightlifting. Thus, it may be suggested that variables like peak barbell height are important only insofar as they relate to the remainder of the system kinematics and additional reliable variables may exist that could be shown to have higher correlations to weightlifting performance.

Many researchers have focused solely on variables during specific phases of the lift and during the performance of weightlifting derivatives (i.e., power snatches, clean pulls, etc.) that are initiated from a "hang" position, where the barbell is held at a position above knee level, thus excluding the W1 phase (8, 22, 34, 35). Suchomel et al. (34) investigated the effects different loads had on system peak power, peak velocity, and peak force during the hang power clean, and later went on to investigate the force-time characteristics of the hang high pull (35). Similarly, Comfort et al. (8) investigated the effect of load on barbell displacement, velocity, and peak power during the performance of midthigh clean pulls; noting that peak power, velocity, displacement, and impulse were shown to be highly reliable across all loads. These investigations help paint a substantial picture on the performance of weightlifting movements performed from the hang, which may be useful in sports performance, but by default, exclude the W1 phase seen in competitive weightlifting. Subsequently, these studies may miss important variables that may further explain optimal movements of the barbell and system in weightlifting.

Recently, James et al. (27) noted that the difficulty in investigating the entire pull derives from the inability to obtain the system weight, which is required to later calculate the pulling variables, prior to the initiation of the lift. System weight must be obtained with the lifter holding the barbell in a static position on force plates, while in contact with nothing else. Obtaining system weight during lifts that include the W1 phase, which typically begins with the barbell in contact with the floor, can be problematic as the barbell must first be lifted off the floor to obtain system weight and may lead to increased difficulty or additional fatigue to the lifter at higher loads. This was noted during the investigation by James et al. (27) who asked their subjects to hold the barbell at mid-shank level in order to obtain system weight before executing the lift from that level, and further noted that this could be a difficult position to maintain at higher loads. To date this is one of the few studies electing to specifically examine variables during the W1 phase of the pull.

Research investigating only particular portions of the weightlifting pull and pulling derivatives may aid researchers in their investigations by eliminating the need to design new methods for obtaining system weight prior to lifting the barbell from floor level; however, these investigations would often exclude a comprehensive, detailed examination of the W1 and UW phases. As weightlifting is a sport initiated from the floor, variables within the early phases of the pull may have an impact on how variables are expressed in subsequent phases and thus have an impact on overall weightlifting performance.

Determining what occurs during each individual phase and throughout the entire duration of the pull would facilitate a better understanding of what underpins optimal movement of the barbell and system. A detailed examination of the pull in its entirety to determine the intra- and inter-day reliability of force-time and displacement-time variables is warranted to provide a more detailed picture of performance, building upon the early work of Enoka (9, 10), Garhammer (11-15), and Hakkinen (23). Providing coaches with specific variables that occur during each of the three phases that are shown to be reliable measures of both intra- and inter-day performance would enable them to track and monitor performance on an acute, daily basis, as well as over longer training cycles. Furthermore, understanding which of these variables have a higher correlation with clean performance would enable coaches to design training programs to elicit specific improvements in overall clean performance. Therefore, this study aimed to investigate the number of reliable biomechanical variables that could be obtained during cleans from the floor, determine their reliability, and determine their correlation with clean performance. It is theorized that several variables that occur within the early phases of the pull will have a significant correlation to overall clean performance.

METHODS

Experimental Approach to the Problem

A repeated measures design was used to assess the intra- and inter-day reliability of kinetic and kinematic variables during cleans performed from the floor in eight competitive weightlifters. Subjects were deemed competitive according to their ability to achieve qualifying standards for regional and national competitions according to the standards set by British Weightlifting. Subjects performed cleans beginning with 50% of their predetermined clean and jerk one-repetition maximum (1RM) and increased by 10% increments up to 90% of their 1RM. Subjects were tested on three separate occasions over the course of a week to determine intra- and inter-day reliability with at least 24-hours of rest between testing sessions. Only the lifts performed with 90% 1RM were used for the current analysis.

Subjects

Subjects of this study consisted of 8 competitive weightlifters (female n = 4, male n = 4) competing at a regional to national level. The females were 29.5 ± 6.6 years of age, 166.9 ± 11.2 cm in height, 63.5 ± 8.4 kg in body mass, and with clean and jerk 1-repetition maximum of 65.3 ± 18.8 kg. The males were 22.3 ± 3.3 years of age, 177.9 ± 5.5 cm in height, 75.4 ± 11.2 kg in body mass, and with clean and jerk 1-repetition maximum of 104.0 ± 10.8 kg. Subjects were excluded if they were not competitive weightlifters or if they were currently injured. All subjects were informed of the benefits and risks of the investigation and completed informed consent prior to participation in the study. Ethics were submitted and approved by an institutional ethics committee (3537). Given the strict criteria for subject selection, a post-hoc power analysis was performed. Given the lowest correlation used for analysis was 0.870, and we used the conventional alpha level of $\leq$ 0.05, our sample size (n = 8) revealed a statistical power of 98%.

Procedures

Each subject completed three testing sessions over the course of a week, completed at the same time of day, and with at least 24 hours rest between sessions. Subjects completed 8 minutes of a self-selected warm-up that was followed by a weightlifting specific warm-up with an empty barbell (15 kg for females, 20 kg for males; Eleiko, Halmstad, Sweden) and consisted of 10 overhead squats, 10 good mornings, 5 hang clean pulls, 5 front squats, 5 halted clean first pulls, and 5 cleans. All loads used during the testing sessions were based on the subject's self-reported 1RM clean and jerk, which was obtained within 2 weeks prior to the start of testing.

Each testing session consisted of 3 sets of 1 repetition cleans performed from the floor on dual force plates (Kistler 9286AA and BA, Winterhur, Switzerland) with loads beginning at 50% of the subject's 1RM CJ and each subsequent load was increased by 10% up to 90% of their 1RM. Subjects were given a 30 second inter-repetition rest between the cleans performed at each given load in which subjects stood off the force plates in a relaxed state and were then given 3 minutes rest between the different loads during which time they were seated in a chair. The inter-repetition rest was increased from 30 to 60 seconds during the 90% load. System weight was obtained prior to performing the lifts by asking the subjects to stand motionless on the force plates for 2 seconds followed by an additional 2 seconds while they held the loaded barbell at arm's length. To reduce the effect of fatigue while obtaining system weight, the barbell was passed to and from the subject (by experimenters) while standing on the force plates in a position they would normally adopt prior to initiating the lifting sequence.

Force data were recorded from dual force plates recording at 1000 Hz. Barbell kinematics were captured using CODA motion capture (Charnwood Dynamics, Rothley, UK) at 200 Hz, with active markers attached to each end of the barbell and motion synchronized with the force plates. A customized Microsoft Excel spreadsheet (Microsoft Office 365 2016, Version 16.15) was used to extrapolate and calculate dependent variables from the raw force-time data based on principles that have been applied during the analysis of countermovement jumps (5). Only the cleans performed with 90% were analyzed for this study and a total of 70 variables were analyzed. System weight was obtained during testing (see above) and was used in the variable calculations seen in Table 1. Net force was calculated by subtracting the system weight from the sum of the raw vertical force data from the two force plates. The phases of the lift (W1, UW, W2) were determined when system weight (body + barbell) was met by the vGRF along the duration of the lift, as was defined by Enoka (9), and can be seen in Figure 1. Lift off was defined as the point where vertical force reached +5 SD of system weight to create a robust criterion marking the initiation of the lift. All kinetic variables were determined from the GRF according to each of the three pulling phases as well as determining total pull impulse (TPI), peak force (PF), and barbell peak power (BPP). Barbell power data were calculated from work (force multiplied by displacement) divided by time for the entire pull and each of the three pulling phases, according to the principles set forth by Garhammer (15). System metrics were defined as those of the body + barbell combined.

The raw marker position (displacement-time) data were smoothed using a low pass Butterworth filter with a cut off frequency of 6 Hz as derived from previous weightlifting literature (6, 29). Velocity was calculated by differentiating displacement ($\boldsymbol{v} = \Delta x / \Delta t$ [m/s]), while acceleration calculated by differentiating velocity ($\boldsymbol{a} = \Delta \boldsymbol{v} / \Delta t$ [m/s^2]). Both were automatically calculated within the Odin X64 software (Charnwood Dynamics, Rothley, UK) and filtered at 4 Hz.

Table 1. Variable calculations

Variable	**Calculation**
Acceleration (a)	$\boldsymbol{a} = \frac{\boldsymbol{F}}{m}$
Velocity (V)	$\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t$ (using the trapezoid rule)
Displacement (s)	$\boldsymbol{s} = \frac{1}{2}(\boldsymbol{v} - \boldsymbol{u})t$ (using the trapezoid rule)
Power (P)	$P = \boldsymbol{FV}$
Impulse	Impulse = $\boldsymbol{F}\Delta t$ (using the trapezoid rule)
Resultant Force	$\sqrt{(\boldsymbol{F}z^2 + \boldsymbol{F}x^2)}$
$\boldsymbol{F}$ = force; m= system mass; $\boldsymbol{u}$ = initial velocity; t = time; $\boldsymbol{F}z$ = vertical force; x = horizontal force (forward-backward)	

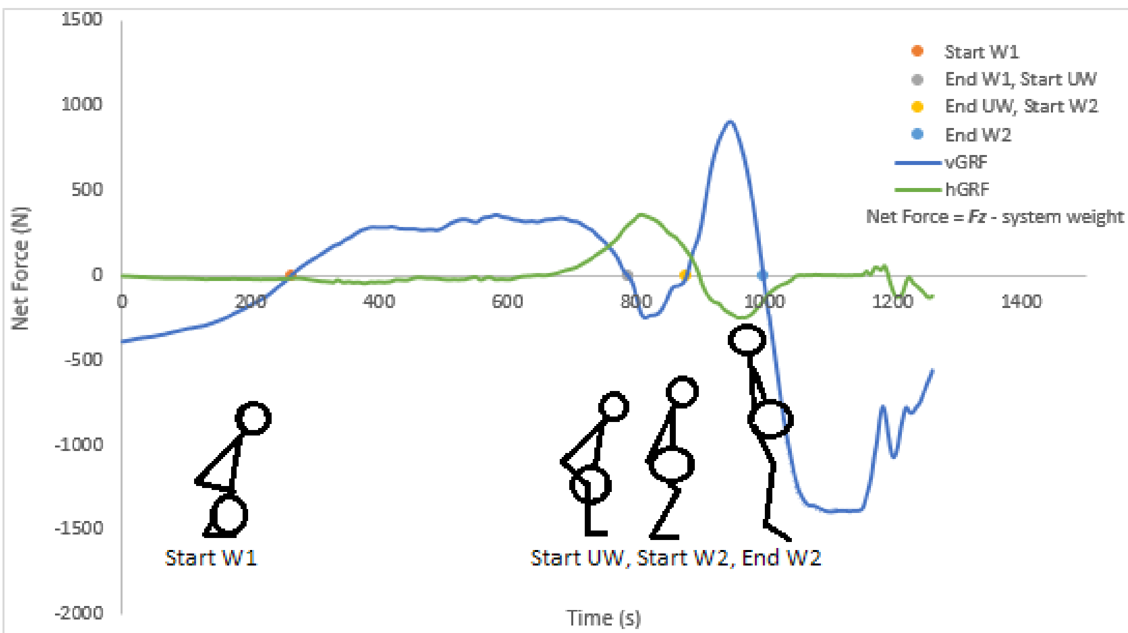

Figure 1. Force-Time Curve with Lift Phases

The raw marker position (displacement-time) data were smoothed using a low pass Butterworth filter with a cut off frequency of 6 Hz as derived from previous weightlifting literature (6, 29). Velocity was calculated by differentiating displacement ($\boldsymbol{v} = \Delta x / \Delta t$ [m/s]), while acceleration calculated by differentiating velocity ($\boldsymbol{a} = \Delta \boldsymbol{v} / \Delta t$ [m/s^2]). Both were automatically calculated within the Odin X64 software (Charnwood Dynamics, Rothley, UK) and filtered at 4 Hz. The two barbell markers' vertical data coordinates were averaged and later processed through a customized Excel spreadsheet to calculate peak bar height (PBH) as can be seen in Figure 2 and barbell peak power (BPP).

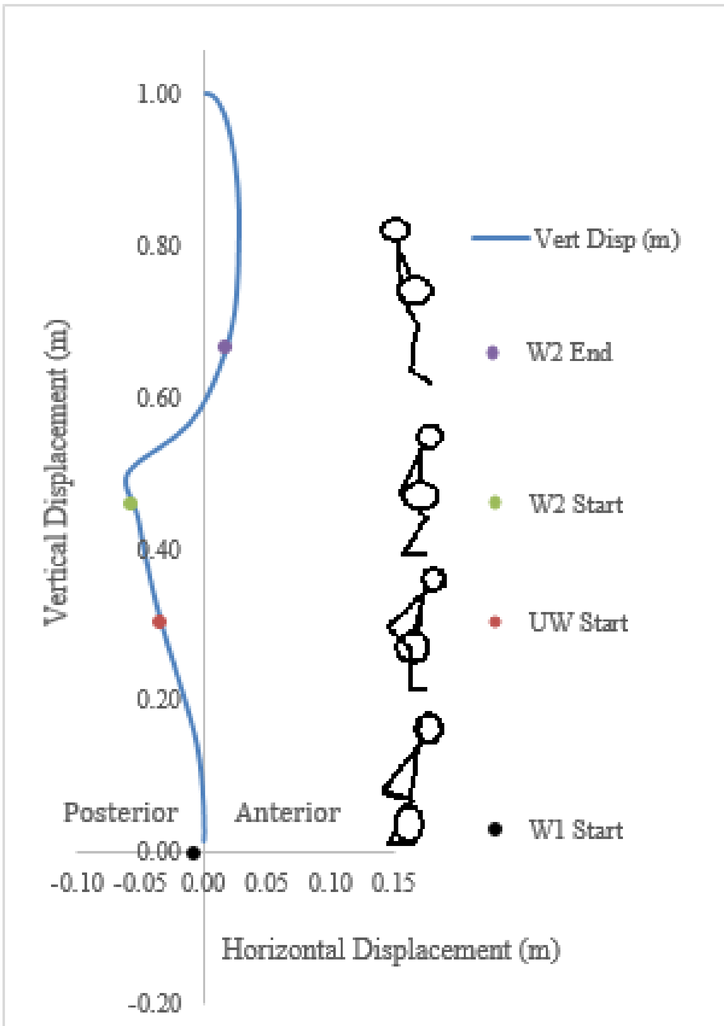

Figure 2. Barbell Displacement with Lift Phases

Statistical Analyses

All statistical analyses were performed in SPSS 24.0 (IBM Corp, Armonk, NY). All variables were tested for normality using Shapiro-Wilk test and all variables were normally distributed. Reliability was tested using the coefficient of variation (CV) with 95% confidence intervals (CI), a 2-way random effects intraclass correlation coefficient (ICC) with 95% CI, and standard error of measurement (SEM). The ICCs were analyzed as both single measures and average measures. Single measures ICC was used for intra- and inter-day best, and average measures was used for inter-day average. Reliability scores were categorized as acceptable and retained for further analysis if the CV was ≤10% (36). Reliability scores were further categorized as "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 and Li (30). Only the variables that exhibited high levels of reliability (CV ≤ 10%, lower bound ICC ≥ 0.750) for both intra- and inter-day were retained for further statistical analysis. Pearson's correlation coefficients were calculated with 95% CI utilizing Fisher *z*-transformation to determine associations between each variable and cleans performed at 90% 1RM (Table 2). Variables exhibiting a Pearson's *r*-value between 0.5-0.7 were considered to have a moderate correlation, 0.7-0.9 a strong correlation, and values above 0.9 a very strong correlation with values approaching 1.0 to be considered near perfect correlations (2). Lastly, variables whose ICCs were ranked as "good to excellent" and were shown to have a meaningful correlation to clean performance were assessed for multicollinearity by utilizing a Pearson's correlation coefficient matrix to determine whether these variables also had correlations to each other and thus may be reporting similar information (Table 3). To guard against Type II errors consequent to multiple comparisons, the conventional alpha-level of 0.05 was divided by the number of comparisons made (n = 11); therefore, a Bonferroni correction factor was applied.

Consequently, in this study for correlations to be deemed as statistically significant, an alpha-level of $p \leq 0.005$ was set.

RESULTS

Sixteen of the 70 variables analyzed were found to have good to excellent intra- and inter-day ICC (0.779-0.994 and 0.969-0.996 respectively) and CV (0.64-6.42 and 1.14-6.37 respectively) values (30, 36). Utilizing the Pearson's correlation coefficients (r = 0.5-1.0 at $p < 0.005$), these 16 variables were also shown to have strong correlations (r = 0.880-0.988) to cleans performed at 90% 1RM. From these 16 variables, bar work variables that were used to calculate bar power variables were then excluded because they are derived from the same force and displacement data and represented duplicate data. The resulting variables were further assessed for multicollinearity, which can be seen in Table 3. This system of filtering resulted in a total of 11 variables exhibiting "good to excellent" ICC with a CV of ≤10% for both intra-day and inter-day reliability measures and with correlations to clean performance as reported in Table 2.

Table 2. Intra- and inter-day reliability of weightlifting variables.

		Intra-day			Inter-day (average)			Correlation with 90% Clean (kg)
	Variable	**ICC (95% CI)**	**CV% (95% CI)**	**SEM**	**ICC (95% CI)**	**CV% (95% CI)**	**SEM**	**Pearson's R (95% CI)**
Temporal Force	**W1 Vertical Impulse**	0.932 (0.779 – 0.987)	5.53 (2.82 – 8.24)	11.59	0.995 (0984 – 0.999)	4.12 (2.10 – 6.13)	2.97	0.907 (0.561 – 0.983)
	W1 Average vGRF	0.952 (0.837 – 0.991)	6.42 (3.27 – 9.56)	21.48	0.993 (0.978 – 0.998)	6.10 (3.11 – 9.09)	7.90	0.880 (0.462 – 0.978)
	W1 Average Resultant Force	0.998 (0.994 – 1.000)	0.64 (0.33 – 0.95)	17.96	0.999 (0.996 – 1.000)	1.14 (0.58 – 1.70)	12.68	0.981 (0.895 – 0.997)
	UW Average Resultant Force	0.984 (0.946 – 0.997)	2.56 (1.31 – 3.82)	35.78	0.997 (0.986 – 0.999)	1.94 (0.99 – 2.90)	15.35	0.910 (0.572 – 0.984)
	W2 Average Resultant Force	0.980 (0.929 – 0.996)	1.95 (0.99 – 2.90)	62.44	0.995 (0.983 – 0.999)	1.63 (0.83 – 2.43)	28.45	0.905 (0.553 – 0.983)
Bar Power	**Peak Power**	0.990 (0.962 – 0.998)	2.86 (1.46 – 4.26)	61.05	0.997 (0.990 – 0.999)	2.69 (1.37 – 4.00)	32.51	0.940 (0.697 – 0.989)
	Average Power – Lift Off to W1 End	0.990 (0.965 – 0.998)	4.60 (2.35 – 6.86)	26.80	0.994 (0.974 – 0.999)	6.37 (3.25 – 9.49)	20.92	0.957 (0.775 – 0.992)
	Average Power – W1 & UW	0.994 (0.980 – 0.999)	3.38 (1.72 – 5.03)	21.31	0.995 (0.984 – 0.999)	5.23 (2.67 – 7.80)	19.72	0.946 (0.724 – 0.990)

	Average Power – Lift Off to Most Rear	0.993 (0.974 – 0.999)	3.22 (1.64 – 4.80)	22.31	0.995 (0.982 – 0.999)	5.23 (2.67 – 7.80	18.98	0.926 (0.637 – 0.987)
	Average Power – Lift Off to PBH	0.989 (0.962 – 0.998)	2.99 (1.52 – 4.45)	27.25	0.996 (0.988 – 0.999)	3.58 (1.83 – 5.33)	16.69	0.988 (0.933 – 0.998)
	Average Power – UW to PBH	0.973 (0.907 – 0.955)	3.48 (1.78 – 5.19)	40.70	0.997 (0.989 – 0.999)	2.53 (1.29 – 3.77)	13.90	0.988 (0.993 – 0.998)

ICC = Intraclass coefficient correlation, CI = Confidence interval, CV = Coefficient of variation, SEM = Standard error of measurement, W1 = Weighting 1, vGRF = Vertical ground reaction force, UW = Unweighting, W2 = Weighting 2, PBH = Peak bar height.

Table 3. Multicollinearity – Correlation Matrix

	W1 Vertical Impulse	W1 Average vGRF	W1 Average Resultant Force	UW Average Resultant Force	W2 Average Resultant Force	Peak Power	Average Power - Lift Off to W1 End	Average Power - W1 & UW	Average Power - Lift Off to Most Rear	Average Power - Lift Off to PBH	Average Power - UW to PBH	Clean
W1 Vertical Impulse	1.000											
W1 Average vGRF	0.989	1.000										
W1 Average Resultant Force	0.942	0.909	1.000									
UW Average Resultant Force	0.723	0.679	0.908	1.000								
W2 Average Resultant Force	0.867	0.803	0.964	0.917	1.000							
Peak Power	0.890	0.827	0.955	0.857	0.939	1.000						
Average Power - Lift Off to W1 End	0.863	0.870	0.932	0.885	0.833	0.840	1.000					
Average Power - W1 & UW	0.852	0.865	0.916	0.876	0.813	0.817	0.994	1.000				
Average Power - Lift Off to Most Rear	0.822	0.838	0.895	0.876	0.798	0.784	0.988	0.996	1.000			
Average Power - Lift Off to PBH	0.890	0.875	0.974	0.935	0.910	0.905	0.983	0.979	0.968	1.000		
Average Power - UW to PBH	0.894	0.865	0.985	0.949	0.945	0.940	0.945	0.940	0.923	0.988	1.000	
Clean	0.903	0.882	0.978	0.911	0.910	0.933	0.961	0.948	0.922	0.985	0.983	1.000

W1 = Weighting 1, vGRF = Vertical ground reaction force, UW = Unweighting, W2 = Weighting 2, PBH = Peak bar height.

Temporal Force

Five of the dependent temporal force variables showed good to excellent reliability (CV ≤ 10%, ICC ≥ 0.750) (Table 2). Of these variables, W1 average resultant force (see Table 1) had the highest intra- and inter-day reliability, lowest variance, and the highest, nearly perfect, correlation to the performance of the 90% clean (Table 2).

Bar Power

There were six reliable bar power variables (Table 2). Average bar power from lift off until the end of the UW phase (W1 & UW) had the highest intra-day reliability (ICC = 0.994), whereas bar peak power and average power of UW to PBH had the highest inter-day reliabilities (ICC = 0.997 and 0.997). Peak power had the lowest intra-day variance (CV% = 2.86) and average power UW to PBH had the lowest inter-day variance (CV% = 2.53). Average power for lift off to PBH and for UW to PBH both exhibited the highest correlations to the clean, each exhibiting a nearly perfect correlation.

DISCUSSION

Eleven of the 70 variables analyzed were found to have good to excellent intra- and inter-day reliability (lower bound ICC ≥ 0.750, CV ≤ 10%) and strong correlation to cleans performed at 90% 1RM as can be seen in Table 2. The variables with the greatest reliability and correlation to the clean from the two categories (temporal force and bar power) were W1 average resultant force, average bar power lift off to PBH, and average bar power UW to PBH. Furthermore, seven of the 11 variables included the W1 phase of the pull. This would suggest that clean performance at loads approaching maximal effort are largely determined by the performance of W1.

Previously, researchers have noted that the W1 phase is primarily characterized as a strength-based phase or more specifically, as the ability to exert force (1, 14, 16, 18, 20, 28). Of the five temporal force variables, three occurred during the W1 phase of the lift (W1 vertical impulse, W1 average vGRF, W1 average resultant force) where W1 average resultant force was shown to have the best intra- and inter-day reliability of all variables, as well as having the strongest correlation with clean performance (Table 2). The average resultant force, as defined in Table 1, captures the result of the combined application of vertical and horizontal force components. Previous investigations into weightlifting have noted that successful weightlifting performance is determined by displacing the barbell vertically while minimizing horizontal displacement, which is affected according to the direction of vertical and horizontal force application throughout the movement (2, 4, 13, 19, 24). The results of this investigation indicate that both the direction of force application and the magnitude are of particular importance during the pull as evidenced by the reliability of the average resultant force in all three phases, especially the W1 phase. It may therefore be suggested that programming exercises aimed at improving force generating capabilities, especially in movements initiated from the floor, would be of great benefit while also monitoring and ensuring appropriate technical performance of the pull. It can also be suggested that exercises like a squat or pull, which address force generating capabilities, would be easy for coaches to monitor as those exercises are regularly used in training programs.

There were six bar power variables where five of the six measured average bar power over different phases and four of the variables included the W1 phase (lift off to W1 end, W1 &

UW, lift off to most rear, lift off to PBH). The highest intra-day reliability was shown in average power from lift off until the end of UW (W1 and UW), whereas the highest inter-day reliability was shown to be peak power and average power of UW to PBH (Table 2). This was similar to findings by Comfort et al. (8) who also reported high reliability for peak power (r = 0.981), but it should be noted that this was during the performance of a mid-thigh clean pull and not a full lift from the floor. The findings of the current study showing the high reliability of peak power as an indicator of performance further supports other current weightlifting literature that frequently reports peak power (7, 10, 20, 21, 27, 33, 34). Average power of UW to PBH had the highest correlation to clean performance alongside average power of lift off to PBH, both exhibiting a correlation of r = 0.988. It should be noted that these two variables are also highly correlated to each other (Table 3) as one represents the entirety of the pull and the other only a portion of the pull. From a practical standpoint, average power of lift off to PBH is easier for coaches to track and monitor through video analysis, as it is much easier to identify the two main points of the lift (lift off and PBH) as compared to determining the start of the UW phase to PBH. Research by Baumann et al. (4) investigating the performance of elite level weightlifters in competition has reported higher average bar power values from lift off until maximal barbell height in weightlifters who performed the best in the elite competition versus lifters who finished lower in the rankings. This seems to suggest that average power from lift off to PBH could be an indicator of potential successful weightlifting performance and, as the current study has demonstrated, would be an easy variable to monitor throughout training. When considering both intra- and inter-day reliability, two of the three variables showing the highest reliability included the W1 phase (average power from lift off until end of UW and peak power) as did one of the two variables with the highest correlation to clean performance (average power of lift off to PBH). This would again illustrate the importance of the W1 phase during the performance of cleans. Additionally, it should be noted that five of the six bar power variables represent an average power which can be suggested to be a better gauge of performance over time as a greater portion of the lift will be represented as compared to peak values that only represent an instantaneous portion of the lift.

Overall, it should be noted that all 11 of the variables reported in this study showed a lower bound ICC $\geq$ 0.750, which according to ICC rankings proposed by Koo and Li (30) falls within the category of having good to excellent reliability. Furthermore, all variables reported also had CV $\leq$10%. This would suggest that any of these variables would be reliable to use in clean performance assessment and monitoring. However, several of the variables would report similar findings (i.e., average power of lift off to PBH and average power from UW to PBH) and should be considered carefully when determining their usefulness in performance assessment and monitoring. When selecting between variables that report similar findings, it can be suggested that variables that contain easily identifiable components would be of greater value in a practical environment, as a coach will be more readily able to identify specific points of a lift such as point of lift off or peak bar height, than the point of onset of UW. Lastly, of all 11 variables reported, W1 average resultant force was the only variable to exhibit high intra- and inter-day reliability (CV $\leq$ 10%, lower bound ICC $\geq$ 0.750) alongside a high correlation to clean performance (Table 2). This would suggest that particular attention should be paid to the performance of the W1 phase, particularly the application of vertical and horizontal force components.

The results of this study illustrate that additional reliable variables with a high correlation to clean performance exist beyond those that are commonly reported in current literature. Many of these variables were noted to occur during or include the W1 phase of the pull, which is of particular importance in competitive weightlifting. Variables like W1 average resultant force and average bar power lift off to PBH may provide valuable insights into understanding the underpinnings of weightlifting movements from the ground up, as they capture force and power components during the W1 phase as well as throughout the duration of the pull. These variables may also provide new ways to improve weightlifting performance by providing reliable metrics to monitor performance on both an acute, daily level, as well as over the duration of a training cycle. Further research is needed to determine whether these variables are sensitive to change, how these changes affect the performance of subsequent phases, and how these variables may be manipulated to improve performance outcomes.

PRACTICAL APPLICATIONS

The findings of this study reveal a number of reliable variables within the W1 phase of the pull that have been shown to have correlations to and accurately reflect the performance of cleans. Coaches should pay particular attention to the technical performance of this phase as it may impact the performance of subsequent clean phases. Furthermore, as the W1 phase has been noted to be primarily a strength-based movement, therefore coaches should pay particular attention to exercises that increase force generating capabilities, especially exercises initiated from floor level such as clean pulls. Coaches should also consider using video analysis to monitor average power from point of lift off to PBH as these two points are easy to identify in video analysis and this variable was shown to be reliable, with a strong correlation to clean performance. The use of this reliability data will give coaches accurate, dependable variables that are correlated to clean performance and can be used to monitor intra- and inter-day performances. By monitoring technical performance alongside known reliable variables that assess force and power capabilities during the individual pulling phases and total pull, coaches will be better able to assess and monitor performance over time.

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