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Effect of Intra-Set Rest Periods on Back Squat Propulsive Impulse

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Abstract

Background: Cluster sets (CSs) maintain velocity and power in compound movements by employing similar propulsion strategies or maintaining impulse through different mechanisms. This study aimed to explore the effect of four CS conditions on back squat (BS) propulsion and provide models for estimating changes in propulsion based on repetition and set number. Methods: Twenty male participants (age = 28.3 ± 3.1 years, stature = 1.74 ± 8.21 m, body mass = 84.80 ± 7.80 kg, BS 1RM = 140.90 ± 24.20 kg) completed four data collection sessions. Each session consisted of three sets of five repetitions at 80% 1RM BS with three minutes of unloaded inter-set rest, using varying intra-set rest intervals. Experimental conditions included 0 s (TRAD), 10 s (CS10), 20 s (CS20), and 30 s (CS30) inter-repetition rest, randomly assigned to sessions in a counterbalanced order. Ground reaction force data were collected on dual force platforms sampling at 1000 Hz, from which net propulsive impulse (J_{PROP}), mean force (MF), and propulsion time (t_{PROP}) were calculated. Conditions and sets were analysed using a 4 × 3 (CONDITION*SET) repeated-measures ANOVA to assess differences between conditions and sets, and linear mixed models (LMMs) were used to provide regression equations for each dependent variable in each condition. Results: The ANOVA revealed no significant interactions for any dependent variable. No main effects of CONDITION or SET were observed for J_{PROP}. The main effects of CONDITION showed that MF was significantly lower in TRAD than CS20 (g = 0.757) and CS30 (g = 0.749). t_{PROP} was significantly higher in TRAD than CS20 (g = 0.437) and CS30 (g = 0.569). The main effects of SET showed that MF was significantly lower in S2 (g = 0.691) and S3 (g = 1.087) compared to S1. t_{PROP} was significantly higher in S2 (g = 0.866) and S3 (g = 1.179) compared to S1. LMMs for CS20 and CS30 revealed no significant effect (p > 0.05) between repetition or set number and dependent variables. Conclusions: The results suggest that CS20 and CS30 maintain J_{PROP} by limiting MF and t_{PROP} attenuation. This is less rest than that suggested by the previous literature, which may influence programming decisions during strength and power mesocycles to maximise training time and training density. LMMs provide accurate estimates of BS propulsive force attenuation when separating repetitions by up to 30 s, which may help practitioners optimise training load for long-term adaptations.

Keywords: inter-repetition rest; alternative set strategies; strength; conditioning

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1. Introduction

Cluster sets (CSs) are an alternative set strategy used in resistance training, characterised by the addition of pre-planned intra-set rest periods [1]. Typically, CS models add intra-set rest (e.g., 10, 20, or 30 s) between single or groups of repetitions while maintaining prescribed inter-set rest. This strategy facilitates improved power performance through more consistent movement velocity or increased number of repetitions [1–3]. CSs may be beneficial for muscular hypertrophy, strength, and power [1–3]. They may be particularly beneficial for experienced athletes, where CSs can be used as a tool to vary training prescription during strength and power phases [2].

Numerous studies have assessed the effect of CS strategies on lower limb power [4–7]. Overall, the results show that CSs maintain lower limb power for more repetitions than traditional sets (TSs) [3]. It is generally considered that power maintenance is primarily a result of velocity maintenance, with minimal change in force metrics [1,3]. For example, Tufano et al. [4] observed higher back squat (BS) velocity and power at 60% of one-repetition maximum (1RM) using CSs compared to TSs, when averaged across all repetitions. Furthermore, no difference in velocity or power was observed between CSs, while significant declines in velocity and power were noted in subsequent sets when performed traditionally. Similar results have been reported at heavier loads [5–7]. No difference in force metrics was observed between CS and TS conditions in these studies.

These studies all used 30 s inter-repetition rest (IRR) periods, demonstrating the efficacy of this CS model in maintaining lower limb performance. This interval duration coincides with the typical duration of phosphocreatine (PCr) replenishment, as 30 s facilitates the replenishment of a large portion of adenosine triphosphate (ATP) and PCr [8]. Limited studies have assessed the effect of <30 s IRR on lower limb velocity and power. Gonzalez-Hernandez et al. [9] and Girman et al. [10] observed BS velocity and power maintenance using 15 s IRR compared to TSs. However, these studies considered intensities of 10RM [9] and 55–75% 1RM [10]. Therefore, the effect of IRR periods <30 s at higher intensities remains unclear. Nevertheless, some studies have considered the effect of shorter IRR periods on the performance of other exercises. For example, Hardee et al. [11] found that both 20 s and 40 s IRR periods were sufficient to maintain power clean velocity and power, compared to TSs, citing adequate PCr resynthesis after 20 s as a possible mechanism for this observation. Indeed, the fast component of PCr resynthesis lasts 21–22 s, enabling a considerable portion of PCr to be recovered [12]. Power clean performance requires higher velocities and power compared to the slower, more compliant BS. Thus, the effect of <30 s IRR on higher-intensity squat prescriptions remains unclear but essential to distinguish, as the higher neuromuscular demand of higher-intensity prescriptions, combined with increased work and time under tension, may result in greater or more rapid PCr depletion than lower intensities. The ability to achieve similar performances with shorter IRRs may have implications for planning training duration, as many practitioners work in time-constrained environments.

Studies have attempted to quantify and compare fatigue between TSs and alternative set strategies by examining percentage change [5,9,11]. Wagle et al. [5] reported that TSs resulted in a larger percentage decrease in mean velocity by repetition three and five (of five repetitions) compared to CSs. Similarly, Gonzalez-Hernandez et al. [9] observed greater percentage velocity loss after every five repetitions (of 30 total repetitions) using TSs compared to various CS conditions. While studies have quantified fatigue using percentage change, this has limited application in practice, as practitioners cannot predict performance attenuation during subsequent repetitions or sets. Such an approach may benefit practitioners by providing a tool to predict and monitor training load and quantify the acute effect of alternative set structures.

While studies have considered the effect of CSs on velocity metrics, they have overlooked how CSs affect the propulsion strategy through which propulsive force is applied. Propulsive force determines acceleration, with the duration of acceleration determining velocity based on the impulse–momentum relationship [13]. As system mass (the sum of body mass and external load) is constant, velocity is directly proportional to net propulsive impulse (J_{PROP}) [13]. J_{PROP} is calculated by integrating the force–time curve, with MF and propulsion time (t_{PROP}) being fundamental components. While it is clear that CSs maintain velocity (and therefore J_{PROP}) compared to TSs, it is unclear whether propulsive force is applied uniformly across repetitions or if the propulsion strategy changes. Indeed, previous research has been inconsistent, with no statistical difference (p = 0.249) [7] in force variables between alternative sets and TSs [7,14,15], while other research has demonstrated that later repetitions in CS protocols can generate higher mean force (MF) [16] and peak force [11] compared to TSs. Thus, it remains unclear how the strategy for applying propulsive force during CSs differs from that during TSs. This is critical to understand, as it has implications for the training phase, during which alternative set strategies may be used. Lower t_{PROP} suggests that peak velocity and power are reached more rapidly, meaning that more repetitions may be performed explosively. In this case, propulsive force is greater to maintain J_{PROP}. However, a higher t_{PROP} suggests that more time is spent accelerating the barbell, thereby supporting strength development. In this case, less propulsive force is applied to maintain J_{PROP}.

Therefore, this study has two aims. First, to elucidate the effect of multiple IRR periods up to 30 s on propulsive force application during BS. Second, to predict the performance of force–time metrics in subsequent repetitions and sets using linear mixed models (LMMs) to enhance the practical application of CS structures. We hypothesised that an IRR of less than 30 s would be sufficient to maintain J_{PROP} during BS.

2. Materials and Methods

2.1. Experimental Design

The BS was selected as it is considered an effective movement for developing lower limb propulsive force [7,17–20], with squat performance associated with progression or maintenance in sports performance [21,22]. Participants attended the facility on six separate occasions. The first session confirmed BS competency. The second session was used to assess participants' BS one-repetition maximum (1RM). The subsequent four sessions, used for data collection, consisted of one control and three experimental conditions allocated in a randomised, counterbalanced order. The conditions were the traditional loading (no IRR, [TRAD]) and three experimental CS conditions, 10 s, 20 s, and 30 s, unloaded IRR between repetitions (CS10, CS20, and CS30, respectively). Sessions were separated by seven days. All sessions were completed at the same time of day, at least two hours postprandial. A within-subject design assessed the effect of TRAD, CS10, CS20, and CS30 IRRs between BS repetitions on inter-set change in J_{PROP}, MF, and t_{PROP}.

2.2. Participants

An a priori sample size estimation was completed based on findings from a previous similar study [7]. The proposed intervention was expected to result in pairwise large main effects (ηp^2 = 0.400) in all variables examined. To detect such effects, the estimated sample size required for the research design used (with p = 0.05 and $1 - \beta$ = 0.8) was 10 participants.

Twenty male recreational athletes (age = 28 $\pm$ 3.1 years, body mass = 84.79 $\pm$ 7.60 kg, stature = 1.74 $\pm$ 8.21 m, BS 1RM = 140.90 $\pm$ 24.20 kg, body mass normalised 1RM = 1.66 $\pm$ 0.18) were recruited from local strength and conditioning facilities and sports teams. Recreational athletes were considered individuals who trained for general strength two to four times a week, with no focused strength and conditioning programme aligned to their sport or sports performance. Consistent with previous research, participants were required to have at least one year of strength and power training experience, relative strength in the BS >1.30 × body mass, and be injury-free for three months before data collection [7]. The study was ethically approved by the Institutional Review Board. After being informed of the risks and benefits of the study, participants completed and signed informed consent documents and physical activity readiness questionnaire forms (PAR-Q & You). Questions within the PAR-Q & You form are significantly related to matched questions in alternative PAR-Q forms (phi coefficients = 0.43–0.71, $p < 0.001$), suggesting agreement in responses between similar PAR-Q forms [23]. Participants were asked to refrain from exercise 48 h before data collection.

2.3. Procedures

2.3.1. Anthropometrics

Participants' stature and body mass were recorded before the first data collection session. Stature was measured to the nearest 0.01 m using a calibrated stadiometer (Seca 217, Seca, Birmingham, UK). Body mass was measured to the nearest 0.1 kg using calibrated weighing scales (Seca 899, Seca, Birmingham, UK).

2.3.2. One-Repetition Maximum Assessment

Upon arrival at the laboratory for the second session, participants completed a standardised dynamic warm-up before the 1RM test. Procedures for the 1RM test followed the process outlined by Haff [24]. Participants self-reported a 1RM BS, from which warm-up set loads were calculated. 1RM attempts were then completed, with sufficient rest between efforts, until participants could not complete a heavier repetition. All repetitions during the 1RM test and subsequent data collection were conducted using a 20 kg Olympic barbell, calibrated competition bumper plates, collars, and a squat rack (Werksan, Ankara, Turkey, provided by TechnoGym, Bracknell, UK). Participants typically reached 1RM within four attempts. A successful attempt was defined when participants' hip axis passed below the axis of the knee and returned to standing, keeping the feet flat on the floor throughout. An experienced strength and conditioning coach monitored all repetitions.

2.3.3. Experimental Procedures

All participants completed a dynamic warm-up for the data collection sessions, followed by the relevant (control or experimental) condition. All conditions included three sets of five BS repetitions performed at 80% 1RM with 180 s inter-set rest. The four conditions (TRAD, CS10, CS20, and CS30) were randomised in a counterbalanced order. Table 1 provides a summary of the experimental conditions. Participants were instructed to complete each repetition maximally and were motivated to do so during each repetition. Inter-repetition rest began when the barbell was placed safely in the squat rack, and participants were instructed to unrack the barbell immediately after the prescribed IRR had elapsed [7].

Table 1. Experimental conditions.

Condition	Sets	Repetitions	%1RM	IRR (s)	ISR (s)
TRAD	3	5	80	0	180
CS10	3	5	80	10	180
CS20	3	5	80	20	180
CS30	3	5	80	30	180

%1RM, percentage of one repetition maximum; IRR, inter-repetition rest; ISR, inter-set rest; TRAD, 0 s rest interval (control condition); CS10, 10 s rest interval; CS20, 20 s rest interval; CS30, 30 s rest interval.

Raw force–time data were collected using two force platforms (PS-2141, Pasco, Roseville, CA, USA) sampling at 1000 Hz. For every repetition, raw vertical ground reaction force (GRF) data from both force platforms were summated to provide total GRF (GRF_{TOTAL}). The signal was collected and processed via dedicated software (Pasco Capstone 2.0, Pasco, Roseville, CA, USA).

2.3.4. Data Processing

The impulse–momentum relationship and differentiation [25–27] were used to calculate instantaneous net GRF (F_i), instantaneous J_{PROP}, velocity (v_i), and acceleration (a_i) from GRF_{TOTAL} for each repetition.

The start and end of the propulsive phase were defined as v_i = 0 $m{\cdot}s^{-1}$ and a_i = 0 $m{\cdot}s^{-2}$ [26]. Dependent variables were calculated from the concentric phase of each repetition. Instantaneous net impulse was calculated using the trapezoid rule. The sum of all instantaneous net impulse data points within the propulsive phase was calculated to determine J_{PROP} [28]. MF was calculated as the mean of all F_i data points within the propulsive phase. t_{PROP} was calculated as the difference in time between the start and end of the propulsive phase. For each set, J_{PROP}, MF, and t_{PROP} were calculated as the mean of the five repetitions within the set.

2.4. Statistical Analyses

Within-subject reliability for each variable was assessed using the intra-class correlation (ICC3,1), which indicates the correlation and agreement between trials, and typical error, which indicates the error expected from one measurement to the next. These (and their 95% confidence intervals) were calculated between the first and second BS repetitions of the TRAD condition for all variables. 0.00–0.10, 0.11–0.30, 0.31–0.50, 0.51–0.70, 0.71–0.90, and 0.91–1.00 were classed as trivial, small, moderate, large, very large, and nearly perfect ICCs, respectively [29]. Coefficients of variation (CVs) were calculated for each set within each condition, and the mean of these values was calculated to establish the CVs for each condition. These were calculated using the first two repetitions of each set as the ratio of the standard deviation to the mean and presented as a percentage [30].

Variables were tested for normality using the Shapiro–Wilk test and visual inspection of Q-Q plots and were confirmed to be normally distributed. Differences between conditions and sets were examined using a 4 $\times$ 3 repeated-measures ANOVA. Holm's sequential Bonferroni stepwise adjustment was used for pairwise comparisons when a significant main effect or interaction was found, and the corrected values are reported. Sphericity was corrected according to recommendations by Blanca et al. [31]. The overall effect size was calculated using partial eta squared (ηp^2), where effect sizes of 0.01, 0.06, and 0.14 were considered small, medium, and large, respectively [32]. Bias-corrected pairwise effect sizes (Hedge's *g*) with 95% confidence intervals were also calculated when significance between pairs was found. Based on our sample of recreationally trained participants, effect sizes were defined as trivial (<0.35), small (0.35–0.80), moderate (0.81–1.50), and large (>1.50) [33].

LMMs were used to evaluate the extent to which set and repetition could estimate J_{PROP}, MF, and t_{PROP} performance in each experimental condition. Experimental conditions were included as fixed effects. Individual participants were included as random effects. Repetition and set numbers were included as covariates. Coefficients of determination (R^2) and standard error (SE) were calculated to compare the fit of the LMMs.

All data are presented as mean $\pm$ SD unless otherwise stated. Significance was set at $p < 0.05$. All data were analysed using Jamovi (The Jamovi Project, Version 2.3.28, Sydney, Australia).

3. Results

3.1. Reliability

A nearly perfect ICC was calculated for J_{PROP} (ICC = 0.95 (0.89–0.98)). Very large ICCs were calculated for MF (ICC = 0.89 (0.76–0.95)) and t_{PROP} (ICC = 0.82 (0.64–0.92)). The typical error for J_{PROP}, MF, and t_{PROP} was calculated as 8.31 N·s (6.60–11.38), 11.29 N (8.96–15.47), and 0.06 s (0.05–0.08), respectively. CVs are presented in Table 2.

Table 2. Coefficients of variation. Data are presented as percentages with 95% confidence intervals.

Variable	Condition	Set 1	Set 2	Set 3	Overall
Propulsive Impulse (N·s)	TRAD	3.61 (1.59, 5.63)	2.99 (1.97, 4.00)	3.78 (1.94, 5.62)	3.46 (1.80, 5.12
	CS10	3.04 (1.84, 4.24)	4.07 (2.70, 5.43)	2.41 (1.44, 3.38)	3.17 (1.96, 4.38)
	CS20	4.30 (1.40, 7.20)	2.20 (1.41, 2.99)	3.99 (2.39, 5.60)	3.50 (1.52, 5.47)
	CS30	2.53 (1.52, 3.53)	3.02 (1.88, 4.17)	5.63 (3.01, 8.25)	3.73 (1.91, 5.55)
Mean Force (N)	TRAD	3.95 (2.50, 5.39)	4.70 (3.16, 6.25)	5.53 (4.02, 7.04)	4.73 (3.22, 6.23)
	CS10	5.59 (3.20, 7.98)	5.45 (3.64, 7.26)	4.61 (2.48, 6.74)	5.22 (3.12, 7.31)
	CS20	3.93 (2.81, 5.04)	5.81 (3.86, 7.77)	6.55 (4.31, 8.80)	5.43 (3.56, 7.30)
	CS30	3.87 (2.73, 5.00)	4.29 (2.54, 6.04)	5.97 (3.37, 8.57)	4.71 (2.78, 6.64)
Propulsion Time (s)	TRAD	5.68 (3.20, 8.16)	5.02 (3.10, 6.94)	4.21 (2.86, 5.57)	4.97 (3.01, 6.93)
	CS10	3.98 (2.27, 5.69)	4.91 (3.30, 6.51)	4.16 (2.47, 5.85)	4.35 (2.70, 6.00)
	CS20	4.99 (1.43, 8.54)	3.34 (1.69, 4.99)	5.62 (2.54, 8.71)	4.65 (1.79, 7.51)
	CS30	3.49 (2.35, 4.63)	3.86 (2.49, 5.23)	3.06 (2.05, 4.08)	3.47 (2.30, 4.64)

TRAD, 0 s rest interval (control condition); CS10, 10 s rest interval; CS20, 20 s rest interval; CS30, 30 s rest interval.

3.2. Repeated-Measures ANOVA

Descriptive statistics for all variables are presented in Table 3. For J_{PROP}, there was no significant interaction of CONDITION*SET (F3.163, 60.098 = 1.698, p = 0.175, ηp^2 = 0.082). There was no significant main effect of SET (F1.205, 22.891 = 0.866, p = 0.382, ηp^2 = 0.044) or CONDITION (F1.730, 32.862 = 1.089, p = 0.340, ηp^2 = 0.054).

For MF, there was no significant interaction of CONDITION*SET (F2.664, 50.625 = 2.088, p = 0.120, ηp^2 = 0.099). There was a significant main effect of SET (F2, 38 = 18.627, p < 0.001, ηp^2 = 0.495). Post hoc analysis showed that S1 was significantly larger than S2 (t19 = 3.152, p = 0.003, g = 0.691 (0.202–1.165)) and S3 (t19 = 4.959, p < 0.001, g = 1.087 (0.528–1.628)), and S2 was significantly larger than S3 (t19 = 4.044, p < 0.001, g = 0.886 (0.365–1.392)). There was also a significant main effect of CONDITION (F3, 57 = 5.529, p = 0.007, ηp^2 = 0.217). Post hoc analysis showed that TRAD was significantly lower than CS20 (t19 = −3.453, p = 0.016, g = 0.757 (0.258–1.241)) and CS30 (t19 = −3.416, p = 0.017, g = 0.749 (0.251–1.232)).

Table 3. Dependent variable descriptive statistics. Data are presented as mean ± SD.

Variable	Condition	Set 1	Set 2	Set 3
Propulsive Impulse (N·s)	TRAD	232.86 ± 36.27	225.97 ± 41.55	224.78 ± 46.09
	CS10	238.91 ± 44.50	239.63 ± 46.17	239.03 ± 46.17
	CS20	241.53 ± 46.56	239.07 ± 50.84	237.11 ± 49.35
	CS30	232.93 ± 43.43	235.66 ± 44.41	235.37 ± 43.81
Mean Force (N)	TRAD	216.99 ± 27.67	205.68 ± 31.71	194.43 ± 31.46
	CS10	224.33 ± 37.74	219.10 ± 39.71	216.75 ± 43.41
	CS20	236.59 ± 36.13	228.06 ± 39.33	218.84 ± 43.36
	CS30	231.30 ± 41.95	228.20 ± 42.55	221.14 ± 44.51
Propulsion Time (s)	TRAD	1.08 ± 0.14	1.12 ± 0.18	1.17 ± 0.21
	CS10	1.08 ± 0.13	0.11 ± 0.15	1.12 ± 0.17
	CS20	1.02 ± 0.13	1.05 ± 0.15	1.10 ± 0.19
	CS30	1.02 ± 0.14	1.05 ± 0.17	1.08 ± 0.19

TRAD, 0 s rest interval (control condition); CS10, 10 s rest interval; CS20, 20 s rest interval; CS30, 30 s rest interval.

t_{PROP} showed no significant interaction of CONDITION*SET (F3.545, 67.363 = 1.042, p = 0.387, ηp^2 = 0.052). There was a significant main effect of SET (F1.428, 27.137 = 23.832, p < 0.001, ηp^2 = 0.556). Post hoc analysis showed that S1 was significantly lower than S2 (t19 = −3.926, p < 0.001, g = 0.866 (0.349–1.367)) and S3 (t19 = −5.401 p < 0.001, g = 1.179 (0.601–1.738)), and S2 was significantly lower than S3 (t19 = −4.386, p < 0.001, g = 0.943 (0.412–1.457)). There was also a significant main effect of CONDITION (F2.215, 42.091 = 4.044, p = 0.021, ηp^2 = 0.176). Post hoc analysis showed that TRAD was significantly higher than CS20 (t19 = 2.030, p = 0.028, g = 0.437 (0.020–0.901)) and CS30 (t19 = 2.615, p = 0.009, g = 0.569 (0.097–1.029)), and CS10 was significantly higher than CS20 (t19 = 2.141, p = 0.0.023, g = 0.454 (0.004–0.901)) and CS30 (t19 = 2.278, p = 0.017, g = 0.503 (0.039–0.955)).

3.3. Linear Mixed Models

LMM parameter estimates and fit information can be observed in Table 4, and regression results are reported in Table 5. The J_{PROP} results showed that y-intercepts were significant for TRAD ($t_{24.171}$ = 24.946, p < 0.001), CS10 ($t_{21.097}$ = 22.443, p < 0.001), CS20 ($t_{21.697}$ = 22.104, p < 0.001), and CS30 ($t_{22.428}$ = 23.327, p < 0.001). The repetition model results showed significant relationships between J_{prop} and REP for TRAD ($t_{278.000}$ = −2.916, p = 0.029) and CS10 ($t_{278.000}$ = −2.452, p = 0.015). No relationship was found between J_{PROP} and REP for CS20 ($t_{278.000}$ = −0.647, p = 0.518) and CS30 ($t_{278.000}$ = −1.724, p = 0.086). The set model results showed significant relationships between J_{PROP} and SET for TRAD ($t_{278.000}$ = −3.283, p < 0.001) and CS10 ($t_{278.000}$ = 0.061, p = 0.952). No relationship was found between J_{PROP} and SET for CS20 ($t_{278.000}$ = −2.084, p = 0.038) and CS30 ($t_{278.000}$ = −1.133, p = 0.260).

The MF results showed that y-intercepts were significant for TRAD ($t_{29.421}$ = 36.242, p < 0.001), CS10 ($t_{25.039}$ = 26.466, p < 0.001), CS20 ($t_{28.683}$ = 28.225, p < 0.001), and CS30 ($t_{22.985}$ = 24.808, p < 0.001). The repetition model results showed significant relationships between MF and REP for TRAD ($t_{278.000}$ = −16.287, p < 0.001), CS10 ($t_{278.000}$ = −10.776, p < 0.001), CS20 ($t_{278.000}$ = −4.807, p < 0.001), and CS30 ($t_{278.000}$ = −5.333, p < 0.001). The set model results showed significant relationships between MF and SET for TRAD ($t_{278.000}$ = −9.255, p < 0.001), CS10 ($t_{278.000}$ = −5.930, p < 0.001), CS20 ($t_{278.000}$ = −2.926, p = 0.004), and CS30 ($t_{278.000}$ = −4.462, p < 0.001).

Table 4. Linear mixed-model results. Parameter estimates and fit for repetition and set model regression analysis. Coefficients of determination and standard error values for the y-intercept, repetition model gradient and set model gradient are presented for each variable.

Variable	Condition	R^2	Standard Error		
			c	m_{rep}	m_{set}
Propulsive Impulse (N·s)	TRAD	0.85	9.65	0.71	1.23
	CS10	0.91	11.08	0.61	1.06
	CS20	0.93	10.83	0.53	0.93
	CS30	0.89	10.09	0.62	1.08
Mean Force (N)	TRAD	0.80	7.25	0.70	1.22
	CS10	0.84	9.51	0.75	1.29
	CS20	0.76	9.14	0.86	1.50
	CS30	0.88	9.98	0.66	1.14
Propulsion time (s)	TRAD	0.79	0.04	0.00	0.01 (0.030–0.058)
	CS10	0.76	0.04	0.00	0.01
	CS20	0.75	0.04	0.00	0.01
	CS30	0.86	0.04	0.00	0.01

R^2; coefficient of determination; c, y-intercept; m_{rep}, repetition model gradient of the straight line; m_{set}, set model gradient of the straight line; TRAD, 0 s rest interval (control condition); CS10, 10 s rest interval; CS20, 20 s rest interval; CS30, 30 s rest interval.

Table 5. Linear mixed-model results. Regression analysis for repetition and set models. Y-intercept, repetition model gradient and set model gradient are presented for each variable. 95% confidence intervals are included in brackets.

Variable	Condition	c	m_{rep}	m_{set}
Propulsive Impulse (N·s)	TRAD	240.63 (221.73, 259.53)	−1.56 (−2.95, −0.17)	−4.04 (−6.45, −1.63)
	CS10	244.85 (223.14, 266.56)	−0.40 (−1.60, 0.81)	−2.21 (−4.30, 0.13)
	CS20	243.01 (221.79, 264.23)	−1.31 (−2.36, −0.26)	−0.06 (−1.76, 1.87)
	CS30	235.43 (215.65, 255.21)	−1.07 (−2.29, 0.15)	−1.22 (−0.89, 3.33)
Mean Force (N)	TRAD	262.65 (248.45, 276.86)	−11.46 (−12.84, −10.08)	−11.28 (−13.67, −8.89)
	CS10	251.50 (233.15, 270.44)	−8.05 (−9.52, −6.59)	−3.80 (−6.32, −1.25)
	CS20	258.04 (240.12, 275.96)	−4.15 (−5.85, −2.46)	−8.88 (−11.81, −5.94)
	CS30	247.56 (228.00, 267.11)	−3.51 (−4.79, −2.22)	−5.08 (−7.31, −2.85)
Propulsion Time (s)	TRAD	0.87 (0.79, 0.96)	0.06 (0.05, 0.06)	0.04 (0.03, 0.06)
	CS10	0.95 (0.88, 1.03)	0.03 (0.03, 0.04)	0.02 (0.01, 0.04)
	CS20	0.94 (0.87, 1.01)	0.02 (0.01, 0.02)	0.04 (0.03–0.05)
	CS30	0.95 (0.88, 1.03)	0.01 (0.01, 0.02)	0.03 (0.02, 0.04)

c, y-intercept; m_{rep}, repetition model gradient of the straight line; m_{set}, set model gradient of the straight line; TRAD, 0 s rest interval (control condition); CS10, 10 s rest interval; CS20, 20 s rest interval; CS30, 30 s rest interval.

The t_{PROP} results showed that y-intercepts were significant for TRAD ($t_{28.707} = 20.340$, $p < 0.001$), CS10 ($t_{29.424} = 25.905$, $p < 0.001$), CS20 ($t_{29.513} = 24.817$, $p < 0.001$), and CS30 ($t_{23.773} = 24.929$, $p < 0.001$). The repetition model results showed significant relationships between t_{PROP} and REP for TRAD ($t_{278.000} = 13.612$, $p < 0.001$), CS10 ($t_{278.000} = 9.476$, $p < 0.001$), CS20 ($t_{278.000} = 3.975$, $p < 0.001$), and CS30 ($t_{278.000} = 4.277$, $p < 0.001$). The set model results showed significant relationships between t_{PROP} and SET for TRAD ($t_{278.000} = 6.241$, $p < 0.001$), CS10 ($t_{278.000} = 3.760$, $p < 0.001$), CS20 ($t_{278.000} = 6.126$, $p < 0.001$), and CS30 ($t_{278.000} = 6.866$, $p < 0.001$).

4. Discussion

This study aimed to elucidate the effect of alternative set strategies on BS propulsive force application and use LMMs to assess set and repetition performance attenuation. It is the first study to assess the effect of various IRR periods on BS propulsion strategies using components of J_{PROP}. Additionally, this study uniquely evaluates the possible effect of IRR on propulsive force in BS by considering each set and repetition individually using LMMs. This approach enables practitioners to consider repetition-to-repetition changes in propulsive force application when prescribing lower body strength training.

The repeated-measures ANOVA results revealed no interaction of CONDITION*SET and no main effect of CONDITION or SET for J_{PROP}, suggesting no difference in overall propulsive force generation between sets with any experimental condition compared to TSs. However, the main effects of CONDITION and SET were found for the components that determine J_{PROP}, MF, and t_{PROP}. While CS10 was insufficient to show any changes in MF or t_{PROP}, the post hoc analysis showed that MF was higher for CS20 and CS30, and t_{PROP} was significantly lower for CS20 and CS30, compared to TRAD. These results suggest that while overall propulsive performance remained unchanged, $\geq$20 s IRR may alter BS propulsion by maintaining higher MF and minimising increases in t_{PROP}, resulting in greater acceleration to similar velocities. Furthermore, CS20 may be as effective as CS30 in terms of maintaining performance across multiple sets; this is an important finding with practical implications for improving training density and maximising training efficiency (time), given that IRR can be reduced to 20 s without any performance loss or impacting the training goals.

Linear mixed-model analysis provides further information for these observations (Table 5). The J_{PROP} results revealed significant negative relationships between REP and SET and TRAD and CS10. No relationships were observed between REP or SET and CS20 or CS30. The MF results showed significant negative relationships between REP and SET and all four conditions. Thus, as the number of sets and repetitions increases, MF attenuates, regardless of set strategy. However, larger REP and SET t-values for TRAD and CS10 show a steeper decline in MF compared to CS20 and CS30. Likewise, the t_{PROP} results showed significant positive relationships between REP and SET and all four conditions. Larger REP and SET t-values were observed for TRAD and CS10, showing a steeper increase in t_{PROP} compared to CS20 and CS30. Thus, while no difference in J_{PROP} was observed, this provides evidence that CS20 and CS30 may maintain J_{PROP} more effectively than less or no IRR by better maintaining higher MF and lower t_{PROP}. Furthermore, the combination of LMM p-values and R^2 values (Table 4) suggests that the models appropriately fit the data and can accurately estimate J_{PROP}, MF, and t_{PROP} performance based on REP and SET.

To date, studies have shown that 30 s IRR can maintain BS velocity and power [4,5,7,15,16,34,35]. However, this study has expanded on these results by showing that although velocity metrics are maintained using CSs, propulsive force generation may be altered. The present results show that CS20 and CS30 maintain J_{PROP}, and therefore velocity, by limiting MF attenuation and preventing longer t_{PROP}. Furthermore, the analysis of multiple IRR periods has shown that less IRR than previously thought may be used to maintain performance. While the results agree that CS30 may maintain BS performance, neither the ANOVA nor the LMM results revealed a difference between CS20 and CS30 for any metric. Therefore, shorter IRR periods may effectively maintain BS performance, enhancing training density and efficiency, without reduction in performance or impacting training goals.

Other studies have shown the success of $\leq$20 s IRR for maintaining lower body propulsion [9,11]. Gonzalez-Hernandez et al. [9] found that 15 s IRR maintained BS mean propulsive velocity. Participants used lower BS loads (10RM, 80.4 $\pm$ 13.1 kg, equivalent to relative strength of ~1.00 $\times$ body mass or ~75% 1RM) than those in the present study. Even if performed with maximal intent, the low absolute and relative BS load may not result in maximal motor unit recruitment. The propulsive force required for the success of individual repetitions may not reach the recruitment threshold of larger, fast-twitch motor units [36].

Furthermore, a correlation has been established between type II motor unit recruitment and strength levels [37]. The low relative strength levels may further suggest an inability to recruit higher-threshold motor units. As lower-threshold motor units are more resistant to fatigue, less rest may be required to maintain optimal performance. Participants in the present study had greater relative strength. The results suggest that when prescribing higher loads, CS20 may be the minimum amount of rest required for sufficient recovery between repetitions to maintain performance, as there was no difference between the TRAD and CS10 conditions. Hardee et al. [11] observed performance maintenance of power cleans when prescribing 20 s IRR. Power-based exercises, such as the power clean, require greater acceleration to achieve faster mean and peak velocities for success [38]. Therefore, they are typically performed at lower loads than BS [39], which may result in less metabolite accumulation compared to slower, heavier, and more compliant compound movements. The combined results of the present study and Hardee et al. [11] suggest that a 20 s IRR period may be sufficient to maintain higher velocities in power-based movements, where t_{PROP} and metabolite accumulation are significantly lower, and in strength-based exercises, where the inverse is true.

The results of this study may be explained mechanistically by discussing the process of peripheral fatigue accumulation and subsequent recovery. The primary mechanism associated with CS efficacy is the reduction in peripheral fatigue, which subsequently maintains barbell velocity [3]. Continuous high-load repetitions result in peripheral fatigue. This compounds as more repetitions are completed [40]. Dynamic muscular contractions deplete ATP within 1 s [41]. ATP is then replenished using the phosphagen energy system. PCr resphorylates ATP for up to 12 s before also depleting [42]. If muscular contractions continue, ATP is rephosphorylated through anaerobic glycolysis. However, the byproducts of anaerobic glycolysis (hydrogen ions and inorganic phosphate) result in an acidic, suboptimal metabolic environment that hinders efficient muscular contractions. The accumulation of these metabolites has been repeatedly implicated in reduced muscle fibre contractile potential and subsequent rapid force production [2,3,43,44]. Upon the cessation of muscular contractions, ATP is replenished in two phases. Harries et al. [12] found a surge in PCr and subsequent ATP resynthesis within 21 s post-contraction, followed by continued resynthesis at a slower rate, with full resynthesis taking at least 170 s. Our results show that 10 s IRR is not sufficient to allow for adequate ATP-PCr replenishment, but 20 s IRR may be sufficient to allow for partial replenishment of the phosphagen energy system. Additionally, this could aid in clearing accumulated metabolites [10], resulting in a more consistent explosive propulsion strategy observed between sets and repetitions during CS20 and CS30 conditions compared to the decline seen during TRAD and CS10 conditions.

However, as this study only considered mechanical variables, this remains speculative. Future studies should consider combining this with biochemical or neuromuscular testing to empirically elucidate the mechanisms associated with changes in performance.

The limitations of the current study include the ability to generalise the results to athletic populations. Previous studies have reported positive CS outcomes on the performance of more experienced athletes [6,7,15,45]. Therefore, although the present study suggests a positive CS effect on propulsive force, sample homogeneity and participant training experience may affect the applicability of the findings in more experienced athletes, who may exhibit higher strength levels [46], and faster recovery [47], than recreational populations. Furthermore, as the present study focused on a male population, the effect of CS protocols on BS performance in female populations remains unclear. While ICCs and CVs (Table 2) suggest that movement was consistent between participants, sets, and conditions and are similar to previous research [28], standard deviations (Table 3) are larger than those in other similar studies [4,15]. This may have resulted in smaller effect sizes than those detectable with the present sample size. Therefore, future research should consider larger sample sizes to facilitate the detection of more subtle effects. We recommend that future studies consider using both LMMs and ANOVAs to confirm whether the IRR periods used in the present study have the same effect magnitude in more experienced athletes. Furthermore, as the same intensity and inter-set interval were used within conditions, future studies should examine the interplay between different loads and inter-set rest intervals to more comprehensively elucidate the practical efficacy of CSs in different training contexts. Lastly, longitudinal studies are needed to elucidate the most effective prescriptions for long-term adaptation and performance enhancement in specific groups of athletes.

The current findings may guide the implementation of alternative set strategies within macrocycles. Earlier mesocycles, where general physical preparedness is typically the primary aim, may employ TS structures or CS strategies using <20 s intra-set rest, allowing athletes to spend more time generating force [7,48]. In later mesocycles, when compound exercises are more likely to be completed with maximal intent to increase strength–speed and power qualities, CS20 may allow athletes to accelerate the barbell more consistently for more repetitions and sets throughout a training session. This may be particularly beneficial in sports like football or sprinting that require the maintenance of propulsive force and force–time metrics during high-intensity bouts. As CS20 and CS30 were equally effective, CS20 may be prescribed to enhance training density and maximise training time, which is often limited in many team sports. Furthermore, LMMs serve as an effective means for quantifying changes in propulsive force during high-load BS. The predictive accuracy of the LMMs can assist practitioners in optimising periodisation and training load for long-term adaptations. This may be beneficial in many team sport scenarios where dense competition schedules and high multi-modal training load can result in chronic fatigue accumulation, limited adaptation, and injury.

5. Conclusions

This study aimed to elucidate the effect of multiple IRR periods on BS propulsive force application and use LMMs to predict the change in BS propulsive force as repetitions and sets progress. The results of this study support our hypothesis by showing that 20 s IRR may maintain BS propulsive force application and subsequent velocity, and LMMs exhibited that set and repetition propulsion metrics can be accurately forecasted. The combined statistical approach contributes to a more holistic and practical understanding of the acute training stimulus of different CS conditions on BS propulsion. The results may have practical implications for coaches and practitioners for maximising training time and training density during strength and power mesocycles. Furthermore, LMMs may provide a tool for predicting and monitoring workload and balancing fatigue with chronic adaptations, which may be particularly beneficial for sports with dense competition schedules or training schedules with high workloads. Due to the limited generalisability of the results, practitioners are recommended to consider the present findings in the context of the populations they train.

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Abbreviations

The following abbreviations are used in this manuscript:

1RM	One-repetition maximum
ATP	Adenosine triphosphate
BS	Back squat
CSs	Cluster sets
CV	Coefficient of variation
GRF	Ground reaction force
ICC	Intra-class correlation coefficient
IRR	Inter-repetition rest
J_{PROP}	Propulsive impulse
LMMs	Linear mixed models
MF	Mean force
PCr	Phosphocreatine
t_{PROP}	Propulsion time
TSs	Traditional sets

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