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Section: Original Investigation

Article Title: Divergent Performance Outcomes Following Resistance Training Using Repetition Maximums or Relative Intensity

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Abstract

Purpose: The purpose of our investigation was to compare repetition maximum (RM) to relative intensity using sets and repetitions (RI_{SR}) resistance training (RT) on measures of training load, vertical jump, and force production in well-trained lifters. **Methods:** Fifteen well-trained (isometric peak force= 4403.61$\pm$664.69 N, mean$\pm$SD) males underwent RT 3 d·wk^{-1} for 10-weeks in either an RM group (n=8) or RI_{SR} group (n=7). Weeks 8-10 consisted of a tapering period for both groups. The RM group achieved a relative maximum each day while the RI_{SR} group trained based on percentages. Testing at five time-points included unweighted (<1kg) and 20kg squat jumps (SJ), counter-movement jumps (CMJ), and isometric mid-thigh pulls (IMTP). Mixed design ANOVAs and effect size using Hedge's *g* were used to assess within and between-group alterations. **Results:** Moderate between-group effect sizes were observed for all SJ and CMJ conditions supporting the RI_{SR} group (g=0.76-1.07). A small between-group effect size supported RI_{SR} for allometrically-scaled isometric peak force (g=0.20). Large and moderate between-group effect sizes supported RI_{SR} for rate of force development from 0-50ms (g=1.25) and 0-100ms (g=0.89). Weekly volume load displacement was not different between groups ($p>0.05$), however training strain was statistically greater in the RM group ($p<0.05$). **Conclusions:** Overall, this study demonstrated that RI_{SR} training yielded greater improvements in vertical jump, rate of force development, and maximal strength compared to RM training, which may partly be explained by differences in the imposed training stress and the use of failure/non-failure training in a well-trained population.

Key Words: maximal strength, rate of force development, vertical jump, resistance training

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Introduction

Resistance training (RT) has repeatedly shown the capability to enhance physical performance characteristics such as maximal strength[1-4] and rate of force development (RFD).[5] Maximal strength and RFD are critically important for athletes, particularly in strength-power sports.[6,7] While RT has been shown to enhance these and other physical traits, exercise or training intensity seems to play a major role in facilitating these improvements.[8] Both high load/high force and low load/high velocity loading prescriptions have been shown to enhance jump performance.[9,10] However, a combination of high force and high velocity training may provide superior results.[1,9-12] Toji et al.[12] observed greater peak power output increases (52.9%) in the elbow flexors when varying heavy-and-light training loads (i.e. greater load ranges throughout study). Similarly, Cormie et al.[10] showed that the combination of "optimally" loaded jump squats with heavy squats were superior to only jump squat training in producing increases in peak jump power and height. These observations indicate that a broad range of loading is necessary for superior improvements in ballistic movements. Therefore, loading strategies should be carefully considered when designing RT programs for athletes requiring high rates of force development.

There are a number of prevalent strategies for load prescription in RT. Two popular strategies include using a percentage of a one-repetition maximum (%1RM)[1,2,13,14] or repetition maximum (RM) zones.[4,15] Proponents of RM zone training suggest it is superior to %1RM due to acute fluctuations in daily strength levels.[15] Therefore, by completing repetition maximums in training, it has been suggested that practitioners can account for these perturbations in strength levels and more accurately prescribe training loads.[15] Converse to RM zones, training programs based on %1RM (often referred to as relative intensity, RI) use mostly submaximal training intensities or percentages.[8,15] RI loading is a popular method for prescribing a more undulated

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training approach using heavy-and-light training days within each training week.[16,17] Further, due to fluctuations in 1RM values (e.g. due to daily fatigue levels), a variant of relative intensity loading has been developed (RI_{SR}) using percentages of set and repetition combination maximums instead of %1RM to prescribe training loads.[16] Using the RI_{SR} strategy, each set and repetition combination (e.g. 3x10 vs 3x5) has a specific 100% value, as opposed to constantly being related back to a 1RM. Proponents of RI_{SR} suggest that using submaximal training intensities and heavy-and-light training days results in better fatigue management and superior adaptations compared to RM training.[1,3,16,18]

Differences in physiological and performance changes between these two RT load prescription strategies have not been compared. Therefore, the purpose of our investigation was to compare RM to RI_{SR} training on measures of training load, vertical jump, and maximal strength in well-trained lifters. We hypothesized that the greater variations in training intensity and attention to fatigue management in RI_{SR} would result in superior performance changes compared to RM training.

Methods

Subjects

Fifteen well-trained males volunteered to participate in the study (age= 26.94±3.95 yrs, body mass= 86.21±12.07 kg, BMI= 27.07±3.08). All subjects were required to have at least one year of RT experience at a minimum frequency of 3 days/wk. Experience was confirmed based on a questionnaire and careful questioning by the investigators. Subjects were considered well-trained based on their baseline isometric mid-thigh pull peak force (IPF) (4403.61±664.69 N) and allometrically scaled isometric peak force (IPFa) (226.04±25.81 N/kg$^{0.67}$), which were similar or greater than previously reported values for collegiate athletes.[19-21] Subjects were ranked based on

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initial IPFa and matched pairs were randomly assigned into either a RI_{SR} group (RI_{SR}, n=7) or an RM zone group (RM, n=8). All subjects read and signed an informed consent document prior to participating in the study, as approved by the university's Institutional Review Board.

Training Programs

Following baseline testing, subjects completed resistance training 3 $d \cdot wk^{-1}$ for 10 weeks (Table 1). Resistance training was completed on Mondays, Wednesdays, and Fridays (Table 2) while a rudimentary sprint program was completed on Tuesdays and Thursdays. The sprint program consisted of 2-3 sets of three 20m sprints with 2 minutes of rest between repetitions and 4 minutes of rest between sets for both groups. The purpose of the sprint program was to provide a stimulus more like what a typical strength-power athlete would encounter. Where most RT studies only provide a stimulus on RT days, we attempted to more closely mimic training that occurs in the real world. Subjects in the study completed 100% of the training sessions. All training sessions were supervised by trained and certified strength and conditioning coaches (subject-to-coach ratio ranging from 1:7 to 1:8). Strength coaches were rotated periodically to reduce potential coaching bias. Both groups performed the same dynamic warm-up preceding each training session. The warm-up consisted of general calisthenics, multi-directional lunge movements, leg swings, squatting patterns, and build-up sprints. Additionally, subjects were encouraged to give maximal effort for all repetitions throughout each training session. All subjects trained within the same 3-hour window each day. Work was estimated by volume load displacement from all warm-up and working sets (VLd= sets · repetitions · vertical displacement)[18] and session rating of perceived exertion (sRPE)[22]. Vertical displacement was measured using a linear position transducer (Open Barbell, Brooklyn, NY, USA). To further interpret the workloads experienced during each group's RT, training monotony (TM) and training strain (TS) were calculated for each week using sRPE

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multiplied by session duration. TM was calculated by dividing the mean weekly sRPE by the standard deviation of the week; and TS was calculated as the product of the mean weekly sRPE and the TM score for the week.[23,24]

Both groups followed a block-periodized program consisting of three main phases: strength-endurance, maximum strength, and speed-strength.[18] This phase progression, which has been used similarly by other training studies,[1,17] was applied to both training groups. The final two-weeks of the intervention for both groups consisted of a tapering period. This taper immediately followed a functional overreach. For both groups, the tapering period included a reduced volume of training and also incorporated complex training where the main movements were combined with plyometric-type exercises. However, RI_{SR} training used mostly submaximal intensities (i.e. percentages of set-and-rep maximums), heavy-and-light training days within each week, and down-sets (where appropriate). The maximums for each set and repetition combination were: 100% was very heavy, 90-95% was heavy, 85-90% was moderately heavy, 80-85% was moderate, 75-80% was moderately light, 70-75% was light, and 65-70% was very light.[16,25] Heavy-and-light training days consisted of a specific intensity reduction from Day 1 to Day 3 in the RI_{SR} group: 10% for strength-endurance and overreach, 15% for maximum strength, and 20% for speed-strength (Table 1). Loads were adjusted weekly based on estimated set-rep bests within each set-rep combination (3x10, 3x5, 5x5, 3x3, 3x2).[16,26]

Unlike RI_{SR} training, the RM training group used maximal loads within each training session and RM zone prescription (3x8-12, 3x4-6, 5x4-6, 3x2-4, 3x1-3). The goal of the RM zone prescription was that each subject would reach muscular failure on the final set of the exercise, indicating a maximum had been achieved. If the failed set resulted in repetitions fewer than were prescribed, the load was subsequently reduced by a minimum of 2.5%. However, if the repetitions achieved surpassed the prescription, the load was increased by a minimum of 2.5%. All other factors not pertaining to the loading strategy (i.e. training times, rest intervals, training volumes, etc.) were controlled between groups to the best of our ability. Rest periods between RT sets were 3-5 minutes for both groups. Throughout the intervention, subjects were instructed to refrain from excess physical activity outside of training and on rest days. Subjects were also instructed to maintain their typical dietary habits throughout the intervention and to abstain from taking stimulants prior to any testing or training sessions.

Vertical Jump Assessments

Static jumps (SJ) and counter-movement jumps (CMJ) were assessed at five time-points as indicated in Table 1 using unweighted (<1kg) and weighted (20kg) conditions. Jump height (JH) and allometrically scaled peak power (PPa) were measured during each jump condition. All performance testing was completed 72-hours following the most recent training stimulus. Baseline testing was considered time point A and all other time points were in order: B, C, D, and E (where E is the post-test). Following a standardized dynamic warm-up,[27] each subject performed two warm-up SJs with a plastic pipe (<1kg) rested on the trapezius muscles just below the seventh cervical vertebrae. The plastic pipe was used to eliminate arm swing and to standardize testing conditions between subjects. Static jumps were performed from an internal knee angle of 90° measured using a goniometer. Following 50% and 75% effort warm-up jumps, two maximal-effort SJs were performed on dual-force plates (2x91cm x 45.5cm) sampling at 1000Hz (Rice Lake Weighing Systems, Rice Lake, WI). Following the SJs, CMJ testing was performed using identical procedures. Data were collected and processed using a LabView program (LabView 8.6, and 2010, National Instruments Co., Austin, TX). Sixty-seconds of rest were given between each jump trial and between jump types. Jump height was estimated from flight time as described previously.[28]

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The force-time trace was converted to an acceleration-time trace, which was then differentiated to obtain a velocity-time trace. Peak power was the maximal value obtained from the product of the velocity-time and force-time trace, and was allometrically scaled to account for differences in body mass. The mean of the two best trials within a 2-cm difference in JH was used for analysis. Additional trials were performed when the difference between two trials was greater than 2-cm. Reliability was assessed by intraclass correlation coefficients (ICC) and coefficient of variation (CV) for JH (ICC= 0.99, CV= 1.96%) and PPa (ICC= 0.92, CV= 2.24%).

Isometric Mid-Thigh Pull Assessments

Isometric peak force (IPF), allometrically scaled IPF (IPFa), and rate of force development (RFD) were assessed from isometric mid-thigh pulls (IMTP) performed at each testing time point. Specifically, RFD from 0-50ms (RFD50), from 0-100ms (RFD100), from 0-150ms (RFD150), and from 0-200ms (RFD200) were considered. Following a standardized warm-up,[27] each subject was positioned in a custom-built power rack with an affixed bar. Subject internal knee and hip angles were measured manually using a goniometer and were required to be 130±5° and 150±5°, respectively. Each power rack contained dual force plates (2 x 91cm x 45.5 cm) sampling at 1000 Hz (Rice Lake Weighing Systems, Rice Lake, WI). Subjects were secured to the bar using straps and athletic tape to eliminate grip strength as a confounding variable during testing. Prior to maximal effort trials, a 50% and a 75% warm-up effort was completed, separated by sixty seconds of rest. Three minutes of rest was given following the final warm-up effort. Each subject completed two maximal-effort IMTP trials and were instructed to "pull as fast and as hard" as they could. Additional trials were completed if the IPF differed between trials >250N or if there was a >200N counter-movement in any trial. Verbal encouragement was provided during every IMTP effort. Three minutes of rest were given between trials. Kinetic data were processed using a commercially

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available software (ForceDecks, NMP Technologies Ltd., London, UK). Within-subject, between-trial reliability assessed by ICC and within-subject CV were as follows: IPF (ICC= 0.95, CV= 2.83%), IPFa (ICC= 0.95, CV= 2.83%), RFD50 (ICC= 0.74, CV= 24.16%), RFD100 (ICC= 0.81, CV= 21.24%), RFD150 (ICC= 0.83, CV= 16.55%), RFD200 (ICC= 0.83, CV= 12.01%). The two IMTP trials were averaged together for statistical analysis.

Statistical Analysis

After verifying that there were no between group differences for SJ, CMJ, and IMTP ($p>0.05$) at baseline, a 2x5 (group x time) mixed-design analysis of variance (ANOVA) was conducted. Additionally, VLd, TM, and TS were compared using a 2x10 (group x time) mixed ANOVA. Homogeneity of variance using Levene's test and Mauchly's test of sphericity were calculated prior to performing ANOVA tests. Alpha level was set at $p\leq0.05$. Significant main effects were followed by post-hoc tests using a Holm-Bonferroni adjustment. Specific interest was given to post-hoc tests between the A and E (pre-to-post) time points and the D to E (before and after the taper). These points of interest were chosen due to the importance of both 1) the changes from baseline to post study, and 2) the changes associated with a taper period, which has been shown to be an important aspect of training.[29-31] Statistical analyses were performed on a commercially available statistics software (JASP version 0.8.1.1) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA). To assess practical significance, effect size using Hedge's *g* was calculated for pre-post measures.[32] Within-group effect sizes were calculated using pre-and post mean and standard deviation values for each group. Between-group effect sizes were calculated using change scores between groups. 90% confidence intervals were calculated for each of these effects. Effect size magnitude was assessed using the following scale: 0.0-0.2 (trivial); 0.2-0.6 (small); 0.6-1.2 (moderate); 1.2-2.0 (large); 2.0-4.0 (very large); 4.0-∞ (nearly perfect).[33]

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Results

ANOVA revealed a statistically significant interaction effect for VLd ($p<0.001$), and TS ($p=0.005$); a significant main effect for time was observed for TM ($p=0.033$). Further analysis revealed simple time effects for VLd ($p<0.001$) and TS ($p<0.001$) in both groups. Post hoc testing revealed statistically greater TS for the RM group in weeks 3-10, but not for VLd or TM (Figures 1 and 2). Body mass and BMI resulted in statistically significant main effects for time ($p<0.001$).

Unweighted SJH yielded a statistically significant main effect for time ($p=0.006$). Post hoc analysis revealed statistically significant increases for the RI_{SR} group from A-to-E ($p=0.009$) and from D-to-E ($p=0.023$), but not for the RM group ($p>0.05$) (Figure 3). A significant interaction ($p=0.046$) was observed for SJH with 20kg. Simple main time effects were observed for RI_{SR} ($p=0.021$) and for RM ($p=0.036$). The RI_{SR} group improved significantly in SJH 20kg from A-to-E ($p=0.012$) and from D-to-E ($p=0.014$), while the RM group only improved from D-to-E ($p=0.003$). Significant interaction effects occurred for both CMJH conditions ($p=0.006$ and $p<0.001$, respectively). Simple main effects for time were significant only for RM CMJH 20kg ($p=0.001$). Post-hoc comparisons revealed no statistically significant differences between groups at any time point for unweighted CMJH ($p>0.05$) while for CMJH at 20kg a difference was observed at time point D ($p=0.033$) (Figure 3). Additionally, the RM group significantly improved CMJH 20kg only between D-and-E ($p=0.031$). Between-group effect magnitudes supported the RI_{SR} group for all measures of JH with moderate effects ($g= 0.76$–1.07) (Table 3).

Allometrically scaled peak power revealed statistical main effects for time at unweighted SJ and 20kg SJ conditions ($p<0.001$ and $p=0.02$, respectively). The RI_{SR} group statistically increased unweighted SJ PPa from A-to-E ($p=0.003$) and from D-to-E ($p=0.026$), while no statistical change was present for RM ($p>0.05$). The RI_{SR} group also statistically increased 20kg

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SJ PPa from A-to-E (p=0.024). A significant interaction effect (p=0.024) was observed for 20kg CMJ PPa, with post-hoc tests revealing a significant between-group difference at the D time point (p=0.045). For all scaled peak power measures, both within- and between-group effect magnitudes supported the RI_{SR} group (Table 3).

Statistically significant main effects for time were observed for IPF and IPFa (p<0.001). Statistically significant increases in IPF and IPFa were observed from A-to-E for the RI_{SR} group only (p<0.001). A statistically significant interaction (p=0.049) was observed for RFD50. A statistically significant decrease in RFD50 from A-to-E was observed for the RM group only (p=0.018), with no other statistical changes for either group (p>0.05) (Figure 4). A statistically significant time main effect was observed for RFD100 (p=0.014). A statistically significant decrease in RFD100 from A-to-E was observed in the RM group only (p=0.014). Both within- and between-group effect magnitudes supported the RI_{SR} group for all IMTP variables.

Discussion

The purpose of our investigation was to compare RM to RI_{SR} training on measures of training load, vertical jump, and maximal strength in well trained lifters. The main findings of the study were, 1) In support of our hypothesis, the RI_{SR} training group achieved superior improvements in vertical jump height and peak power outputs compared to the RM group throughout the intervention. 2) While both groups improved maximal strength, as measured by IPF and IPFa, only the RI_{SR} group reached statistical significance and showed larger effect sizes. Interestingly, the RM group statistically decreased RFD50 throughout the intervention. 3) Work, estimated as VLd, was similar throughout the intervention with the exception of a single day. 4) TS was consistently greater for RM compared to RI_{SR}. Further inspection of the within- and between-group effect magnitudes (Table 3) revealed virtually all performance variables within the

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current study supported the RI_{SR} group. Our findings suggest that RI_{SR} training may be advantageous compared to training with RM zones for athletes who aim to improve jumping performance and force production capabilities.

While the work completed by each group was similar across the intervention (Figure 1), the imposed stress demands differed. For example, the TS was significantly greater in the RM group compared to the RI_{SR} group throughout the majority of the intervention (Figure 2). As TS is a measure of the total stress imposed on an individual,[23] this demonstrates that the RM group was exposed to high levels of training stress even given the similar external workloads (VLd). By contrast, the RI_{SR} group had comparatively low TS scores, most likely as a function of heavy-and-light training days during each week. The greater TS observed in the RM group likely contributed to their inability to increase performance to the degree of the RI_{SR} group. This concept is not new, as high levels of monotony and strain have been suggested to impair adaptation and may potentially contribute to poor fatigue management and overtraining.[23,24] These findings demonstrate that differences in imposed training stress between training programs can impact performance outcomes despite similarities in total work completed.

Greater SJH and SJ PPa improvements were observed in the RI_{SR} group compared to the RM group. A possible mechanism may point to enhanced type II muscle fiber content and cross-sectional area in the RI_{SR} group, as positive relationships have been observed previously between SJ performance and type II fiber content and size.[34,35] CMJ performances were also superior in the RI_{SR} group from pre-to-post, suggesting favorable enhancements in stretch-shortening cycle (SSC) function. In contrast, the decreases in CMJH in both loads for the RM group indicate impaired SSC function likely resulting from the residual fatigue of repeated training to failure. In support of this, Moran-Navarro et al.[36] recently demonstrated that performing bench press and back squats

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to failure delays recovery of CMJ performance by up to 24-48 hours post-exercise.[36] Therefore, RI_{SR} training may stimulate greater CMJ performance improvements than RM training by permitting shorter recovery times between training sessions.

Both maximal strength and RFD can be impacted by fatigue.[37] Previous research has shown increases in maximal strength following RM training.[4,38] This is supported by our results, as both groups increased IPF and IPFa (RI_{SR} g= 1.05–1.26, RM g= 0.83–0.98), while only the RI_{SR} group reached a statistically significant increase ($p<0.001$). Rate of force development seems to have greater sensitivity to fatigue compared to maximal strength,[39] possibly due to neural factors. Indeed, early RFD measures (25-75ms) have been linked to motor unit discharge rates.[7] The statistically significant reductions in early RFD observed in the RM group (RFD50 $p=0.018$, RFD100 $p=0.014$) seem to suggest impaired neural drive. These findings may have major implications for athletes, as RFD is critically important for performing time-sensitive tasks in sport.[5,7] Therefore, RM training may result in inferior training adaptations to RI_{SR} training, particularly as it relates to rapid force production.

A taper was prescribed for both groups between time points D-and-E. The taper consisted of reduced volume, relatively high intensity, and more explosive exercises (e.g. down-sets of ballistic med ball throws for both groups).[29,40,41] An interesting observation was a noticeable increase in performance following the taper, regardless of group. These data are particularly intriguing as the "D" and "E" time points were only separated by two weeks. This agrees with a recent recommendation that tapers to improve maximal strength should last from 1-4 weeks.[41] Although RM training also benefited from a taper, this does not obviate the inferior performance adaptations observed throughout the intervention. Even with a taper, the RM group was unable to return to their baseline values for several variables (CMJH and early RFD). These findings

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demonstrate an impaired ability to fully recover in the RM group despite reduced training, which is indicative of non-functional overreaching.[42] Further, these depressed performance variables observed in the RM group provide further support for RI_{SR} as an efficacious training strategy. However, these data suggest regardless of training strategy, a taper should be used when optimal performances are the goal.

Practical Applications

This investigation revealed potentially deleterious effects of RT to failure in well-trained populations. Compared to the relative simplicity of training to failure to adjust training loads, using more complex methods of load adjustment (i.e. RI_{SR}) may provide additional benefits in the form of improved fatigue management and optimal performance adaptations. Coaches and athletes should consider managing training loads in a similar fashion to how the RI_{SR} group trained, allowing athletes to train further away from their maximums and vary intensities when necessary. It should be noted that there was relatively high between-subject variability in RFD measures (Table 3). Readers should consider the variable nature of RFD measurements when interpreting these performance results.Sample size was limited due primarily to other, more invasive tests performed on this same cohort (i.e. muscle biopsies). We recognize the limitations associated with small sample sizes, and this should be considered when interpreting the results of the study. However, in a well-trained subject pool, the sample size seemed adequate.

Conclusion

Overall, this study demonstrated that RI_{SR} training resulted in consistently greater improvements in vertical jump and force production capabilities compared to RM training, which may partly be explained by the differences in the imposed stress and design of RT workloads

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between groups. Further, the similar workloads but drastically different TS experienced between groups highlight the importance of tactics within the training process. Although RM training resulted in an increase in maximal strength, the obvious impairments to vertical jump and early RFD performance bring into question the efficacy of training to failure in populations where optimal performance enhancement is the goal, such as in competitive athletes. Practitioners should consider the use of RI_{SR} training with the inclusion of adequately varied training stimuli, such as heavy-and-light training days and a variety of high force and velocity outputs.

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Conflict of Interest

The authors of this manuscript have no conflicts of interest.

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References

1. Harris GR, Stone MH, O'Bryant HS, Proulx CM, Johnson RL. Short-term performance effects of high power, high force, or combined weight-training methods. *J Strength Cond Res.* 2000;14(1):14-20.

2. Hoffman JR, Ratamess NA, Klatt M, et al. Comparison between different off-season resistance training programs in division III american college football players. *J Strength Cond Res.* 2009;23(1):11-19.

3. Stone MH, Potteiger JA, Pierce KC, et al. Comparison of the effects of three different weight-training programs on the one repetition maximum squat. *J Strength Cond Res.* 2000;14(3):332-337.

4. Campos GE, Luecke TJ, Wendeln HK, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur J Appl Physiol.* 2002;88(1-2):50-60.

5. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985).* 2002;93(4):1318-1326.

6. Suchomel TJ, Nimphius S, Stone MH. The Importance of Muscular Strength in Athletic Performance. *Sports Med.* 2016;46(10):1419-1449.

7. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol.* 2016;116(6):1091-1116.

8. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. *Sports Med.* 2004;34(10):663-679.

9. Tricoli V, Lamas L, Carnevale R, Ugrinowitsch C. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *J Strength Cond Res.* 2005;19(2):433-437.

10. Cormie P, McCaulley GO, McBride JM. Power versus strength-power jump squat training: influence on the load-power relationship. *Med Sci Sports Exerc.* 2007;39(6):996-1003.

11. Toji H, Suei K, Kaneko M. Effects of combined training loads on relations among force, velocity, and power development. *Can J of Appl Physiol.* 1997;22(4):328-336.

12. Toji H, Kaneko M. Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res.* 2004;18(4):792-795.

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13. Christou M, Smilios I, Sotiropoulos K, Volaklis K, Pilianidis T, Tokmakidis SP. Effects of resistance training on the physical capacities of adolescent soccer players. *J Strength Cond Res.* 2006;20(4):783-791.

14. Fink J, Kikuchi N, Yoshida S, Terada K, Nakazato K. Impact of high versus low fixed loads and non-linear training loads on muscle hypertrophy, strength and force development. *Springerplus.* 2016;5(1):698.

15. Tan B. Manipulating resistance training program variables to optimize maximum strength in men: A review. *J Strength Cond Res.* 1999;13(3):289-304.

16. DeWeese BH, Hornsby G, Stone M, Stone MH. The training process: Planning for strength-power training in track and field. Part 2: Practical and applied aspects. *J Sport Health Sci.* 2015;4(4):318-324.

17. Painter KB, Haff GG, Ramsey MW, et al. Strength gains: Block versus daily undulating periodization weight training among track and field athletes. *Int J Sport Physiol.* 2012;7(2):161-169.

18. DeWeese BH, Hornsby G, Stone M, Stone MH. The training process: Planning for strength-power training in track and field. Part 1: Theoretical aspects. *J Sport Health Sci.* 2015;4(4):308-317.

19. Kawamori N, Rossi SJ, Justice BD, et al. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J Strength Cond Res.* 2006;20(3):483-491.

20. Thomas C, Comfort P, Chiang CY, Jones PA. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. *J Trainol.* 2015;4(1):6-10.

21. McGuigan MR, Winchester JB. The relationship between isometric and dynamic strength in college football players. *J Sports Sci Med.* 2008;7(1):101-105.

22. Day ML, McGuigan MR, Brice G, Foster C. Monitoring exercise intensity during resistance training using the session RPE scale. *J Strength Cond Res.* 2004;18(2):353-358.

23. Foster C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc.* 1998;30(7):1164-1168.

24. McGuigan MR, Foster C. A new approach to monitoring resistance training. *Strength Cond J.* 2004;26(6):42-47.

25. Stone MH, Stone ME, Sands WA. *Principles and practice of resistance training.* Champagne, IL: Human Kinetics; 2007.

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26. DeWeese B, Sams M, Serrano A. Sliding toward Sochi—part 1: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach.* 2014;1(3):30-42.

27. Kraska JM, Ramsey MW, Haff GG, et al. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sport Physiol.* 2009;4(4):461-473.

28. Linthorne NP. Analysis of standing vertical jumps using a force platform. *Am J Phys.* 2001;69(11):1198-1204.

29. Bazyler CD, Mizuguchi S, Harrison AP, et al. Changes in muscle architecture, explosive ability, and track and field throwing performance throughout a competitive season and after a taper. *J Strength Cond Res.* 2017;31(10):2785-2793.

30. Trappe S, Costill D, Thomas R. Effect of swim taper on whole muscle and single muscle fiber contractile properties. *Med Sci Sports Exerc.* 2000;32(12):48-56.

31. Murach K, Raue U, Wilkerson B, et al. Single muscle fiber gene expression with run taper. *PLoS One.* 2014;9(9):e108547.

32. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol.* 2013;4:863.

33. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-13.

34. Mero A, Jaakkola L, Komi PV. Relationships between muscle fibre characteristics and physical performance capacity in trained athletic boys. *J Sports Sci.* 1991;9(2):161-171.

35. Andersen LL, Tufekovic G, Zebis MK, et al. The effect of resistance training combined with timed ingestion of protein on muscle fiber size and muscle strength. *Metabolism.* 2005;54(2):151-156.

36. Moran-Navarro R, Perez CE, Mora-Rodriguez R, et al. Time course of recovery following resistance training leading or not to failure. *Eur J Appl Physiol.* 2017.

37. Chiu LZ, Fry AC, Schilling BK, Johnson EJ, Weiss LW. Neuromuscular fatigue and potentiation following two successive high intensity resistance exercise sessions. *Eur J Appl Physiol.* 2004;92(4-5):385-392.

38. Spineti J, Figueiredo T, de Salles BF, et al. Comparison between different periodization models on muscular strength and thickness in a muscle group increasing sequence. *Rev Bras Med Esporte.* 2013;19(4):280-286.

39. Hornsby W, Gentles J, MacDonald C, Mizuguchi S, Ramsey M, Stone M. Maximum strength, rate of force development, jump height, and peak power alterations in weightlifters across five months of training. *Sports.* 2017;5(4):78.

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40. Stone MH, Sanborn K, O'Bryant HS, et al. Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res.* 2003;17(4):739-745.

41. Pritchard H, Keogh J, Barnes M, McGuigan M. Effects and mechanisms of tapering in maximizing muscular strength. *Strength Cond J.* 2015;37(2):72-83.

42. Meeusen R, Duclos M, Foster C, et al. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc.* 2013;45(1):186-205.

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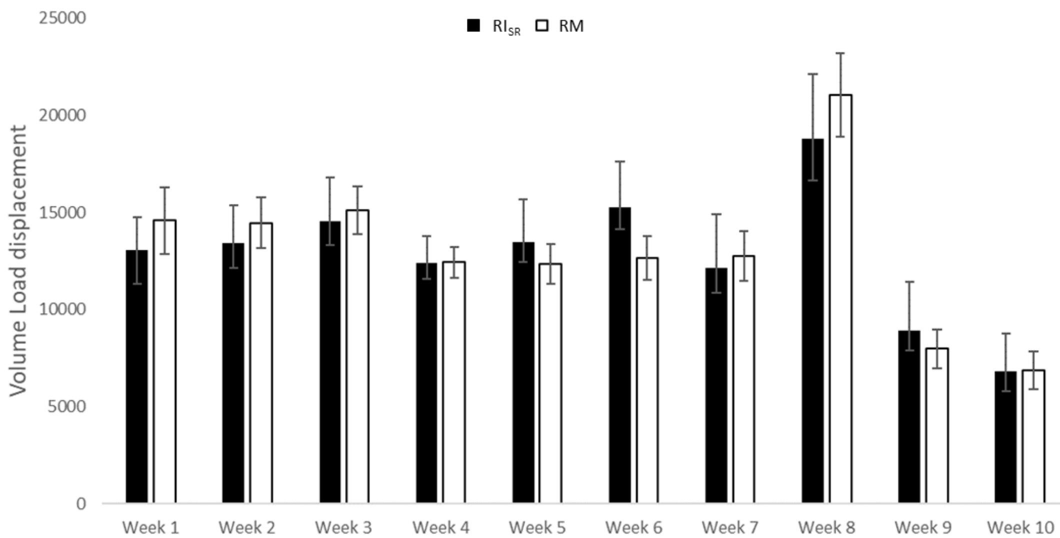

Figure 1. Weekly volume load displacement for relative intensity (RI) and repetition maximum (RM) groups were similar for all weeks ($p > 0.05$).

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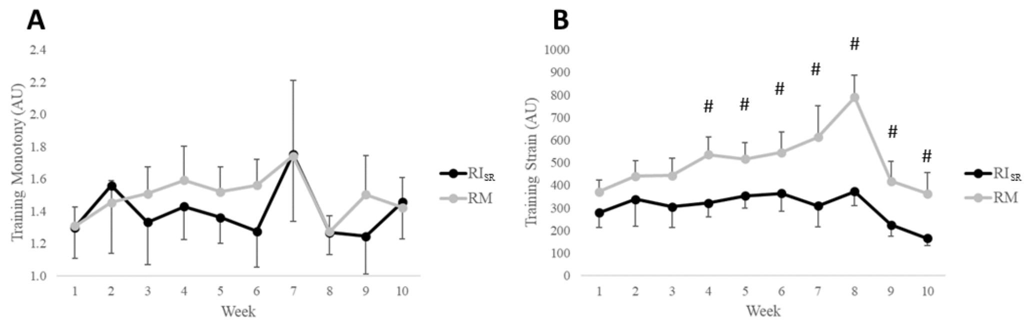

Figure 2. # = between-group difference at specific time-point. A) Training monotony and B) training strain were statistically higher for repetition maximum (RM) at week 3. These measures were also higher than relative intensity (RI) for all other weeks, although without statistical significance.

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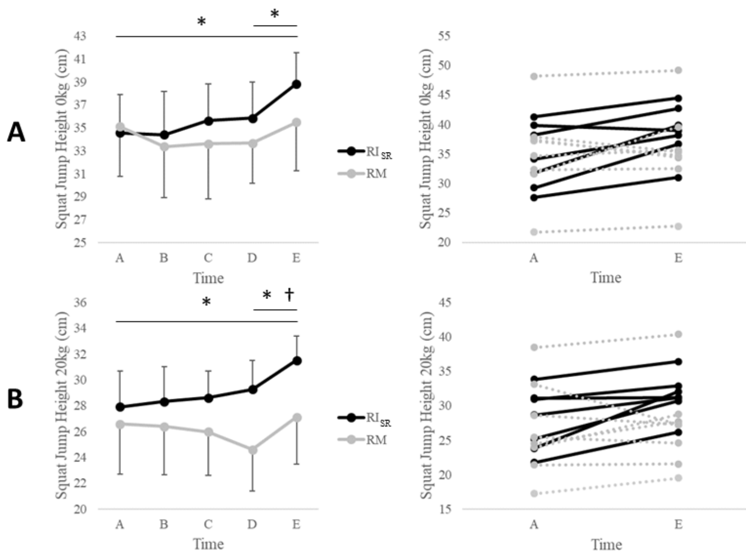

Figure 3. * = statistically significant change for relative intensity (RI) group only, † = statistically significant change for repetition maximum (RM) group only. Alterations in squat jump height for both unweighted (A) and 20kg (B) conditions. RI resulted in statistically significant increases in squat jump height from A-to-E and D-to-E while RM only increased squat JH significantly from D-to-E. Individual data are represented to the right of the group data.

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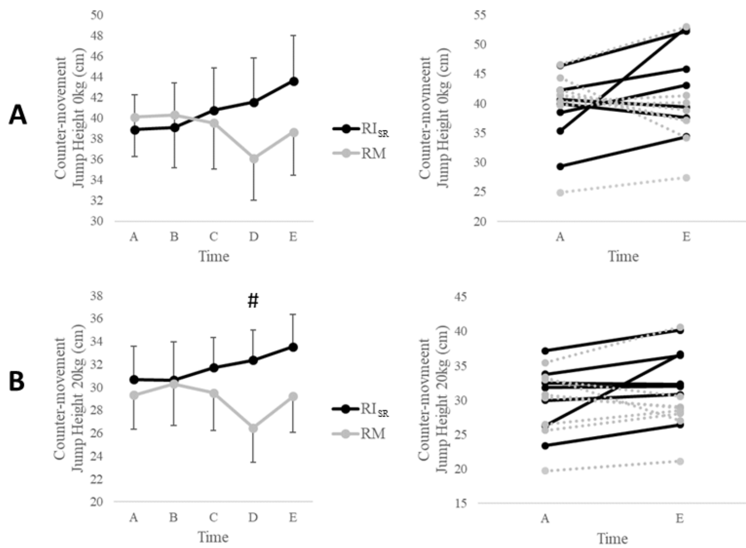

Figure 4. # = between-group difference at specific time-point. Alterations in counter-movement jump height for both unweighted (A) and 20kg (B) conditions. No within-group differences existed for counter-movement jump variables but there was a statistically significant between-group difference for 20kg counter-movement jump height at time point D. Individual data are represented to the right of the group data.

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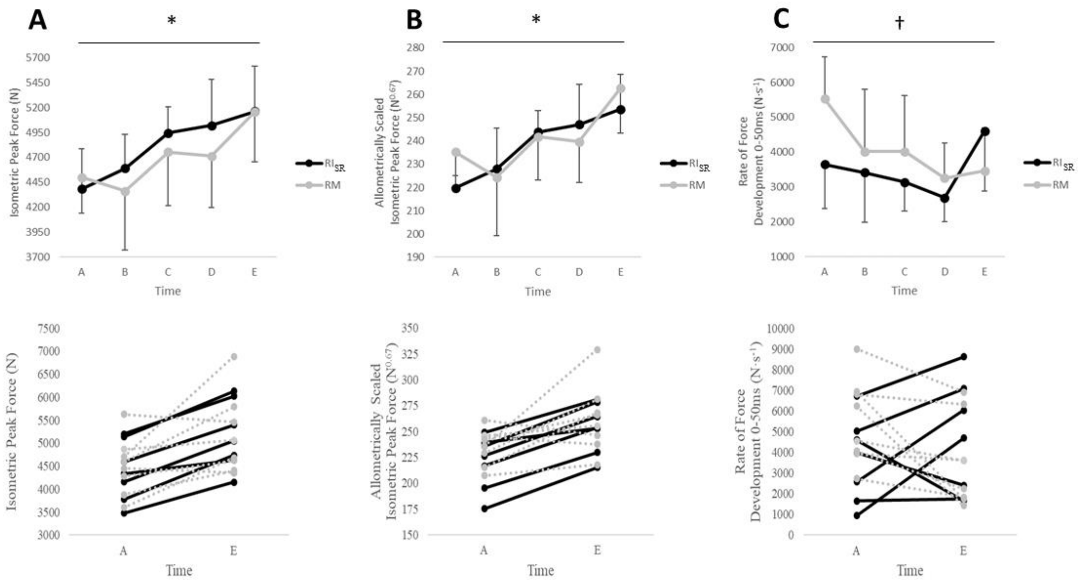

Figure 5. * = statistically significant change for relative intensity (RI) group only, † = statistically significant change for repetition maximum (RM) group only. RI resulted in statistically significant increases from A-to-E for A) isometric peak force and B) allometrically-scaled isometric peak force. RM resulted in a statistically significant decrease in C) rate of force development from 0-50ms. Individual data are represented below the group data.

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Table 1. Resistance Training Programs

Training Block	Week	(sets)x(reps)	RI_{SR} Day 1 and 2	RI_{SR} Day 3	RM Zone
(A) VJ and IMTP testing					
Strength-Endurance	1	3x10	80.0%	70.0%	3x8-12
	2	3x10	85.0%	75.0%	3x8-12
	3	3x10	90.0%	80.0%	3x8-12
(B) VJ and IMTP testing					
Max-Strength*	4	3x5	85.0%	70.0%	3x4-6
	5	3x5	87.5%	72.5%	3x4-6
	6	3x5	92.5%	75.0%	3x4-6
	7	3x5	80.0%	65.0%	3x4-6
(C) VJ and IMTP testing					
Overreach	8	5x5	85.0%	75.0%	5x4-6
(D) VJ and IMTP testing					
Speed-Strength	9	3x3	87.5%	67.5%	3x2-4
	10	3x2	85.0%	65.0%	3x1-3
(E) VJ and IMTP testing					

*Symbolizes down set at 60% of working weight (RI_{SR} only), RI_{SR}= relative intensity based on sets and repetitions, RM= repetition maximum, VJ= vertical jump, IMTP= isometric mid-thigh pull

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Table 2. Training Exercises for all subjects

Training Block	Day 1	Day 2	Day 3
Strength-Endurance	Back Squat, Overhead Press, Bench Press, DB Tricep Ext.	CG MTP, CG SLDL, BB Bent-Row, DB Bent Lateral Raise	Back Squat, Overhead Press, Bench Press, DB Tricep Ext.
Max-Strength	Back Squat, Push Press, Incline Bench Press, Wtd. Dips	CG MTP, Clean Pull, SG SLDL, Pull-Ups	Back Squat, Push Press, Incline Bench Press, Wtd. Dips
Overreach	Back Squat, Push Press, DB Step Up, Bench Press	CG CM Shrug, Clean Pull, CG SLDL, SA DB Bent-Row	Back Squat, Push Press, DB Step Up, Bench Press
Speed-Strength	Back Squat + Rocket Jump, Push Press, Bench Press + Med Ball Chest Pass	CG MTP, CG CM Shrug, Vertical Med Ball Toss	Back Squat + Rocket Jump, Push Press, Bench Press + Med Ball Chest Pass

*DB= dumbbell, CG= clean grip, MTP= mid-thigh pull, BB= barbell, Ext= extension, Wtd= weighted, SG= snatch grip, SLDL= stiff-legged deadlift, SA= single arm, CM= counter-movement

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Table 3. Effect size using Hedge's *g* and 90% Confidence Intervals for within-group and between-group effects

	Relative Intensity Effects			Repetition Maximum Effects			Between Group Effects
Variable	*g* ± CI	pre ± SD	post ± SD	*g* ± CI	pre ± SD	post ± SD	*g* ± CI
SJ 0kg JH	0.82±0.42	0.35±0.05	0.39±0.04	0.05±0.30	0.35±0.07	0.35±0.07	1.07±0.83
SJ 20kg JH	0.89±0.49	0.28±0.04	0.32±0.03	0.08±0.32	0.27±0.07	0.27±0.06	0.91±0.83
CMJ 0kg JH	0.69±0.70	0.39±0.05	0.44±0.07	-0.2±0.47	0.40±0.07	0.39±0.07	0.97±0.84
CMJ 20kg JH	0.58±0.54	0.31±0.05	0.34±0.05	-0.02±0.43	0.29±0.05	0.29±0.05	0.76±0.83
SJ 0kg PPa	0.96±0.39	246±25	270±20	0.21±0.26	229±45	239±42	0.81±0.82
SJ 20kg PPa	0.71±0.46	246±29	265±20	0.14±0.29	224±45	230±40	0.64±0.83
CMJ 0kg PPa	0.29±0.63	258±27	266±27	-0.01±0.35	240±35	240±42	0.35±0.84
CMJ 20kg PPa	0.20±0.48	254±30	260±22	0.08±0.33	231±35	234±35	0.15±0.83
IPF	1.05±0.23	4,382±648	5,161±733	0.83±0.67	4,500±621	5,159±864	0.18±0.81
IPFa	1.26±0.26	219±26	254±24	0.98±0.86	235±18	263±33	0.20±0.81
RFD50	0.37±0.72	3,646±2,034	4,613±2,768	-0.94±0.58	5,534±2,060	3,466±2,118	1.25±0.84
RFD100	0.12±0.68	7,778±4,061	8,374±5,068	-0.61±0.36	10,577±4,754	7,682±4,274	0.89±0.84
RFD150	-0.02±0.62	8,925±3,728	8,821±4,580	-0.34±0.39	9,982±2,865	8,743±3,922	0.31±0.84
RFD200	0.01±0.06	8,364±2,623	8,398±3,475	-0.19±0.94	8,813±1,681	8,307±3,058	0.13±0.82

**g*= Hedge's *g* effect size, CI= 90% confidence interval, SD= standard deviation, SJ= squat jump, CMJ= counter-movement jump, JH= jump height, PPa= allometrically-scaled peak power, IPF= isometric peak force, IPFa= allometrically-scaled isometric peak force, RFD= rate of force development

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