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# Deadlift Biomechanics across Multiple Sets in Resistance Trained Males

Daniel Scherrer[1], Brandon Nunley[2], Jeffrey D. Eggleston[3] & John R. Harry[4]

[1]Massey University of New Zealand, NZ, [2]University of Texas at Dallas, Dallas, TX USA, [3]University of Texas at El Paso, El Paso, TX USA, [4]Texas Tech University, Lubbock, TX, USA

*Corresponding Author: john.harry@ttu.edu*

## ABSTRACT

This study sought to determine whether the deadlift exercise using the 5-by-5 scheme can be performed at a commonly prescribed moderate-to-high load with consistent mechanical output among sets with respect to concentric and eccentric rate of force development [RFD], rate of force attenuation [RFA; i.e., the rate at which the application of force is reduced], total lower limb joint angular work, and the contributions of the individual joints to total lower limb angular work. Twelve resistance-trained males [21 ± 1 y; 1.8 ± 0.56 m; 89.1 ± 15.48 kg] completed five sets of five repetitions of deadlift exercise with a load corresponding to 8 out of 10 on the modified Borg rated perceived exertion (RPE) scale. Body and barbell kinematics [e.g., velocity] and force production [e.g., rate of force development] variables of interest were calculated and averaged across repeated sets. Repeated-measures analyses of variance [$\alpha = 0.05$] detected no significant differences [$p > 0.05$] for any variable. Results suggest deadlift exercise using the 5-by-5 scheme at an RPE of 8 can be performed without altered movement or force application across sets. Although these results are preliminary, it appears that deadlift exercise using the current loading scheme can be performed by resistance trained males without concern for movement or mechanical output changes across the five sets.

Keywords: Barbell Velocity; Joint Work; Rate of Force Development; Resistance Training.

## INTRODUCTION

The deadlift is a multi-joint exercise that places demands on lower extremity joints (4) and large muscle groups, such as the gluteals, hamstrings, quadriceps, and spinal erectors (8), and stimulates adaptations related to strength and hypertrophy (12). Accordingly, some argue that the deadlift exercise may be the most thorough test of overall strength (10). While the primary purpose of the deadlift may be to strengthen the musculature supporting and creating rotation about the lower back, hip and knee, secondary benefits can include a speculative increase of resilience to muscular injuries (18), enhanced vertical jump performance (22), and increased bone density and physical quality of life (1).

It was reported that loads of approximately 80-85% or more should be performed to produce beneficial adaptations in trained individuals (9). Such an intensity should be appropriate for five repetitions. This is because National Strength & Conditioning Association [NSCA] recommendations (8) state that five sets of five repetitions can be performed with a load equal to ~87% of the 1-repetition maximum [1RM]. Extrapolating from squat data, this intensity range likely coincides with a seven or eight out of ten on the modified Borg rating of perceived exertion (RPE) scale (23), leaving an estimated two repetitions in reserve when following the scale parameters (5), although the RPE to percent load relationship can vary. However, as cumulative load-volume with a 5x5 training structure increases during working sets of the deadlift, the technical quality of subsequent sets can become compromised due in part to increased demands on the neuro-musculo-skeletal system (21). Furthermore, compromises in biomechanical output, notably the amount of work done about the lower extremity joints, can contribute to potential changes in technical quality. Changes in the joints' contributions to the total work performed (i.e., organization of joint work) have potential to threaten the transferability of the deadlift to important sporting actions [e.g., jumping] over time. This can be attributed to how each joint tends to contribute a specific percentage of work during maximum effort sporting actions (16, 17), and training with substantially altered contributions could lead to adaptations where subpar contributions become an athlete's standard strategy.

Current literature lacks empirical evidence concerning whether performers display technical changes, mechanical output changes, or both as the cumulative load volume increases from set to set. Knowledge of the number of sets of a deadlift exercise that can be performed without altered technique, biomechanical output, or a combination of these factors, could help strength and conditioning professionals optimize training prescriptions to stimulate targeted adaptations. Therefore, the purpose of the current study was to detect and characterize any alterations in technical performance or mechanical output across sets associated with deadlift exercise using a scheme consisting of five sets of five repetitions and moderate-to-high loads in resistance trained men. It was hypothesized that [1] body and barbell kinematics and force production characteristics would be altered in later sets when compared to the first set, and that [2] different organizations of lower extremity joint work would occur in the later sets when compared to the first sets.

## METHODS

Twelve resistance trained males volunteered to participate in this study. Descriptive data for participants' age, height, body mass, and RPE-intensity are provided in Table 1. This sample was determined according to an a priori sample size estimation using G*Power software (6). Due to a lack of relevant input data for the sample estimation, we conducted the estimation using a proposed effect size of 0.30, alpha [α] of 0.05, power [1-β] of 0.90, and a correlation among repeated measures of 0.70. Participants were included if they verbally confirmed the ability to perform a conventional deadlift with a load greater than 1.5 times body weight, had regularly participated in strength training at a frequency of two weekly sessions for at least two years, and were free of any injury/ailment that would impair their ability to perform the deadlift exercise at the prescribed load and volume while using their preferred technique strategy. Prior to completing the testing protocol, participants were provided with a description of the study protocol, and written informed consent was obtained as approved by the local Institutional Review Board at Texas Tech University in accordance with the Declaration of Helsinki.

Participants completed a single laboratory session. Firstly, demographic and anthropometric data [age, height, mass, etc.] were collected by the research team. Then, participants were asked to perform a warm-up consisting of approximately five minutes of cycling at a self-selected intensity followed by ~3 minutes of lower body calisthenic exercises [e.g., bodyweight squat and walking lunges] which was prescribed similarly across participants. Spherical 14-mm reflective markers were adhered bilaterally over the following locations using hypo-allergenic adhesive tape (Figure 1): acromion process, iliac crest, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial and lateral aspects of the knee joint, base of the second toe, the medial and lateral aspects of the elbow and wrist, medial and lateral malleoli. Individual markers were adhered over the C7 and T10 vertebrae, sternum-jugular notch, xiphoid process, and sacrum. Thermo-plastic shells with four non-collinear markers were secured bilaterally over the lateral, mid-segment aspects of the thigh, shank, upper arm, lower arm, and heel counter of the shoe using elastic wraps and hypoallergenic adhesive tape where appropriate. The participants then performed a dynamic warm up protocol with instructions to replicate their usual warm up process for this type of exercise. This included bodyweight squats, walking lunges, and low intensity barbell rows for some participants, and all participants finished the warm up performing familiarization repetitions of the deadlift exercise. We asked all participants to perform familiarization repetitions to both become accustomed to the laboratory environment and to ensure progressive loading up to the training weight. Specifically, participants would perform five repetitions at a self-selected load intended to

**Table 1.** Descriptive data for participants' age, height, mass, and deadlift intensity for an RPE of 8.

| Age (y) | Height (m) | Mass (kg) | RPE 8 Intensity (kg) |
|---|---|---|---|
| 21.3 ± 1.4 | 1.8 ± 0.6 | 89.1 ± 15.5 | 126 ± 28 |

*Notes – data are presented as the mean ± one standard deviation calculated across participants.*

be "very moderate" and representative of the load they would start with during a typical deadlift training session. Following completion of each set of five repetitions, a member of the research team asked the participants to verbally identify their RPE for the load of the completed set according to the Borg Category-Ratio [CR-10] scale (19). The RPE scale was presented to the participants similar to recent recommendations (11), as we verbally asked the participants as "How many more reps could you have completed at this load with a score of zero being representative of sitting still and a score of 10 being representative of maximal effort using your maximal physical capacity?". The process was repeated with increased loads [~10-20%] until a rating of 8 out of 10 on the Borg scale was identified by the participants. The load corresponding to the RPE of 8 was recorded and used for all experimental trials during the study. Briefly, the RPE corresponds to the number of repetitions in reserve during a resistance exercise set (19). Thus, at an RPE of 8, an individual should feel that they have two repetitions in reserve for the set (26).

Three-dimensional kinematic and ground reaction force [GRF] data were synchronously collected using a 12-camera motion capture system [Vantage v5 cameras; Vicon Motion Systems, Ltd., Oxford, UK] sampling at 200 Hz and two force platforms [OPT464508; Advanced Mechanical Technology, Inc., Watertown, MA, USA] mounted flush with the laboratory floor and sampling at 1000 Hz. Following a static calibration trial, the markers adhered to the iliac crest, anterior superior iliac spine, medial and lateral aspects of the knee joint, medial and lateral ankle, medial and lateral aspects of the wrist and elbow, and base of the second toe were removed, and the remaining markers were retained to track segmental motion. Participants completed a total of five sets of five repetitions at the pre-identified RPE-based load. Each set began with the participant grasping the barbell in a conventional deadlift position with each foot on a force platform. After a "go" command, participants began the five repetitions of the set. Each repetition required that participants achieve an erect, standing body position before bringing the barbell downward and resting briefly at the bottom of the movement for approximately one second. The movement speed of the deadlift repetitions was not controlled, although participants were asked to control the descent velocity of the barbell to ensure that variable extraction would be possible during the downward portion of the repetitions [i.e., participants could not drop the barbell or relax the involved musculature during the downward portion]. The research team visually monitored each repetition and set, and trials were repeated if the participant did not achieve an erect body position at the end of each repetition, hold a motionless position prior to the first repetition of each set, or both. Two participants were required to complete an additional set of five repetitions. Participants were provided with 2- to 5-minutes of rest between sets. Ecological validity was facilitated by replicating a normal strength training session with a broad inter-set rest time range and lack of strict technical instruction. For example, one participant might need three minutes rest to achieve adequate physiological restoration, while another participant might have needed three minutes and 30 seconds. Thus, we felt it was best to accommodate for such individualization. This would help to explain any observed changes by eliminating

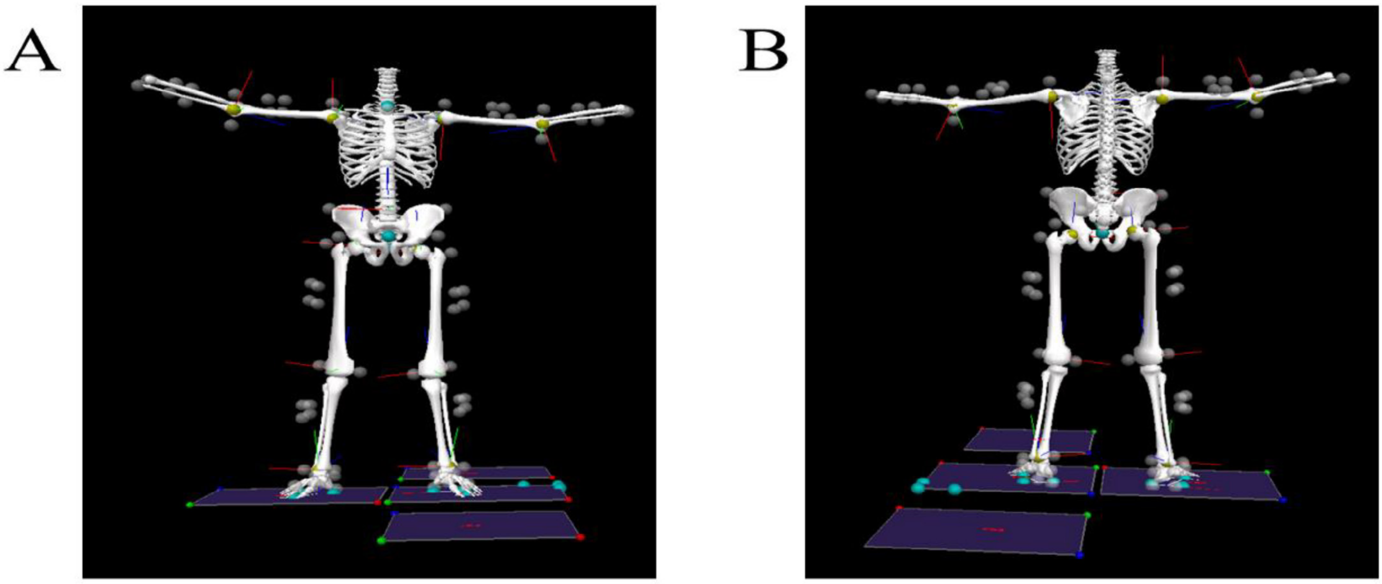


**Figure 1.** Anterior (A) and posterior (B) marker locations used for model calibration and segmental tracking.

the chance that any changes were due to restricting rest in some participants to a time period shorter than they required.

Data were processed in the Visual3D software suite [version 6; C-Motion, Inc., Germantown, MD]. A kinematic model was built from the raw marker trajectories to include the trunk, pelvis, thigh, leg, foot, upper arm, and lower arm segments bilaterally as appropriate. The model included a trunk defined by the markers adhered over the iliac crests, C7 and T10 vertebrae, sternum-jugular notch, xiphoid process. In addition, the CODA pelvis was used to represent the pelvis segment, while hip joint centers were identified as 25% of the inter-trochanteric distance (4), and all other joint centers were identified as the midpoint between the medial and lateral markers adhered over the joint center. Raw kinematic and GRF data were filtered using a fourth-order, bi-directional, low pass, Butterworth digital filter with cutoff frequencies of 2 Hz and 50 Hz, respectively. These cutoff frequencies were determined by inspecting the frequency content averaged across five sets of five deadlift repetitions of raw pilot data using a Fast Fourier Transform, and visually identifying the frequency under which the majority of the signal was contained (i.e., where the signal amplitude leveled out at zero), similar to previous work (13). The filtered data from the two force platforms were then summed together to create a vertical GRF acting at the total body center of mass. The average vertical center of mass velocity of the right and left forearm segments was calculated and used to estimate average barbell velocity. This approach was used due to pilot testing, which determined that relying only on reflective markers was unsuccessful when trying to track the barbell as a rigid segment as required in a biomechanical analysis. A Cardan [X-Y-Z] rotation sequence was used to calculate the three-dimensional angular positions of the trunk segment and the hip, knee, and ankle joints, where X represents the medial-lateral axis, Y represents the anterior- posterior axis, and the Z represents the longitudinal axis. Joint angles were defined as the angle of the distal segment relative to the proximal segment, and the trunk angle was defined relative to the laboratory coordinate system. The right-hand rule was used for rotational polarity. Joint angles were extracted at the start of the concentric and eccentric phase as well as at the time of the peak vertical GRF magnitudes in each phase.

Newtonian inverse dynamics procedures were used to calculate net internal joint moments for the hip, knee, and ankle joints, with moments resolved in the coordinate system of the proximal segment and scaled to participant body mass. Joint angular powers were calculated as the dot product of the net joint moments and joint angular velocities, with joint angular velocities calculated as the derivative of the joint angular positions with respect to time. The net sum of joint angular powers about the hip, knee, and ankle joints was calculated and used to define concentric and eccentric phases of each repetition, similar to how these phases are defined during countermovement jumping (13). This is because the net sum of joint power defines the total amount of work (positive: concentric; negative: eccentric) done about the joints, indicating the type of muscle action dominating the involved musculature. Specifically, the concentric phase of each repetition was defined as the time when the net sum of joint power was positive, while the eccentric phase was defined as the time when the net sum of joint power was negative (Figure 2). Each joint's angular power curves were integrated with respect to time during the concentric and eccentric phases to obtain joint angular work. The percent contributions of each joint to the total angular work performed by the lower extremity was calculated as the absolute value of each joint's angular work divided by the absolute sum of angular work performed about the hip, knee, and ankle joints (16). From the vertical GRF mentioned previously, average rates of force development (RFD) and attenuation (RFA) were calculated as the positive and negative changes of vertical GRF divided the changes of time, respectively, within the concentric and eccentric phases (Figure 2), with the phases defined in detail later. These RFD and RFA values were scaled to body weight (BW/s) for analysis and presentation of results.

Mean and standard deviation values were calculated across participants for each repetition. One-way repeated-measures analyses of variance (ANOVA) were used to determine whether a statistically significant difference was present among the five repetitions, using a 5% probability level ($\alpha = 0.05$). Dependent t-tests were used for post-hoc multiple comparisons in the event a difference was detected in the omnibus ANOVA test, with Bonferroni corrections applied for multiple comparisons. Pairwise comparisons were conducted for each repetition relative to the first repetition. To report the magnitude or meaningfulness of the set-to-set mean differences, Cohen's *d* effect sizes for repeated measures were calculated.

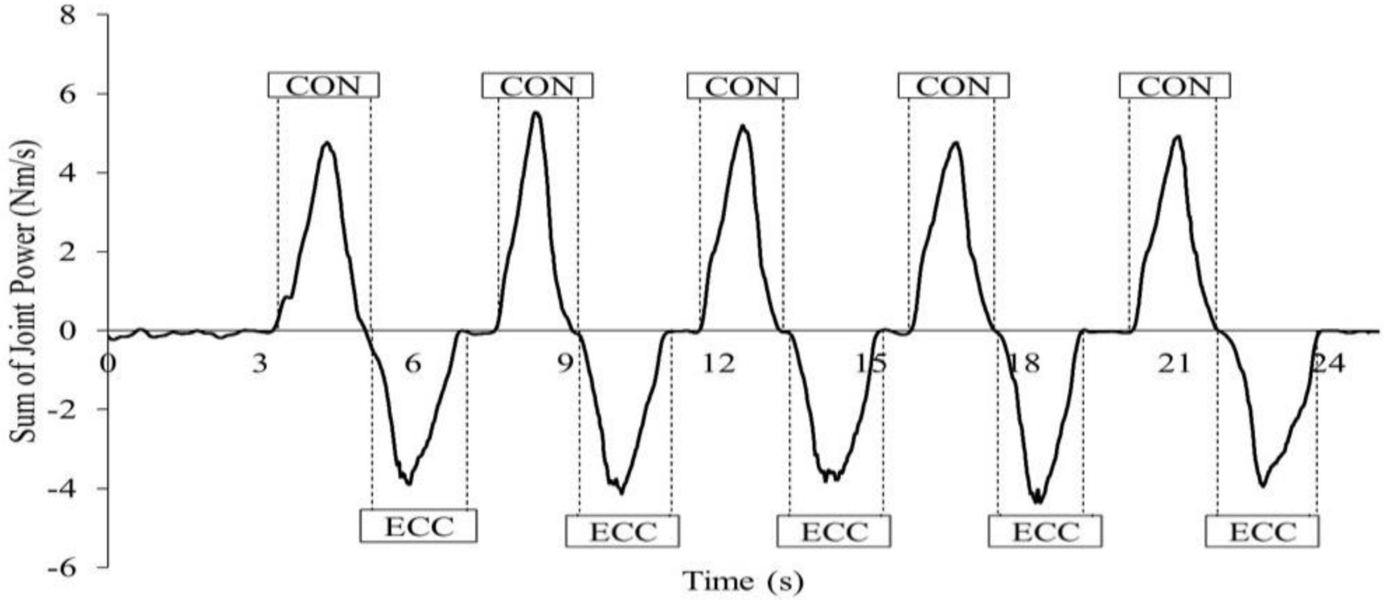


**Figure 2.** Exemplar representation of the joint power-based concentric and eccentric phases across repetitions.
*Notes – CON: concentric phases; ECC: eccentric phase.*

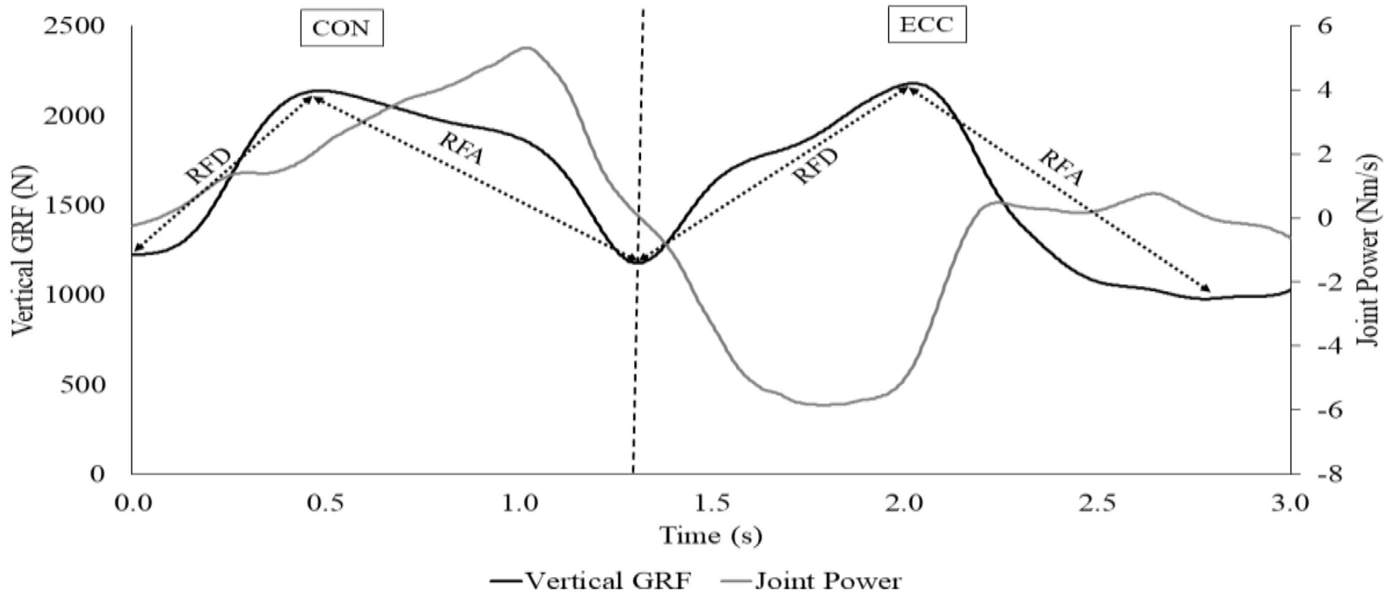


**Figure 3.** Exemplar representation of the concentric and eccentric rates of force development and attenuation during an isolated single repetition.
*Notes – CON: concentric phases; ECC: eccentric phase.*

## RESULTS

All descriptive data for the participants are provided in Table 1. Descriptive statistics for all concentric and eccentric phase variables across repetitions per set are presented in Tables 2 and 3, respectively. The ANOVA tests, shown in Table 4, did not detect any significant differences for any variable measured [$p > 0.05$]. Similarly, no moderate- or large-magnitude differences were detected for any variable [ES < 0.6].

## DISCUSSION

The purpose of this study was to determine whether performance of the deadlift exercise using the "5-by-5" repetition scheme and moderate-to-high loads is associated with altered technical performance or mechanical output across sets. Contrary to our hypotheses, no significant differences were observed across sets for any variable of interest. Given that no guidelines exist currently in the literature for evaluating the kinetic stimulus achieved during the deadlift exercise, our results provide valuable foundational evidence from which follow-up research should be conducted to evaluate the cumulative deadlift stimulus and determine recommended programming limits for load volumes during deadlift training. While our rationale for conducting this study was dependent on the common use of this training prescription, the intensities may have been

**Table 2.** Descriptive statistics for all concentric phase variables across repetitions per set.

| Phase | Variable | Set 1 | | | Set 2 | | | Set 3 | | | Set 4 | | | Set 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV |
| Con | Joint Work Sum (N·m/kg) | 3.51 | 0.67 | 19 | 3.51 | 0.73 | 21 | 3.49 | 0.66 | 19 | 3.46 | 0.69 | 20 | 3.50 | 0.64 | 18 |
| | Hip Contribution | 0.90 | 0.08 | 9 | 0.90 | 0.08 | 9 | 0.90 | 0.07 | 8 | 0.90 | 0.06 | 7 | 0.90 | 0.07 | 8 |
| | Knee Contribution | 0.02 | 0.05 | 250 | 0.02 | 0.06 | 300 | 0.01 | 0.06 | 600 | 0.01 | 0.04 | 400 | 0.01 | 0.05 | 500 |
| | Ankle Contribution | 0.08 | 0.04 | 50 | 0.08 | 0.04 | 50 | 0.08 | 0.04 | 50 | 0.08 | 0.04 | 50 | 0.08 | 0.05 | 63 |
| | Starting Trunk Angle (°) | -77.99 | 8.55 | 11 | -78.38 | 8.08 | 10 | -78.84 | 7.32 | 9 | -78.81 | 6.68 | 8 | -78.93 | 7.01 | 9 |
| | Starting Hip Angle (°) | 98.83 | 12.90 | 13 | 100.51 | 13.83 | 14 | 99.92 | 13.35 | 13 | 99.84 | 13.99 | 14 | 100.01 | 14.08 | 14 |
| | Starting Knee Angle (°) | -72.96 | 16.66 | 23 | -74.36 | 16.40 | 22 | -74.36 | 15.58 | 21 | -74.05 | 13.33 | 18 | -75.06 | 15.45 | 21 |
| | Starting Ankle Angle (°) | 17.43 | 6.82 | 39 | 17.57 | 5.59 | 32 | 17.70 | 5.59 | 32 | 17.42 | 5.48 | 31 | 17.91 | 6.26 | 35 |
| | PvGRF Trunk Angle (°) | -81.07 | 6.01 | 7 | -82.48 | 5.51 | 7 | -80.98 | 6.94 | 9 | -80.30 | 6.95 | 9 | -81.10 | 8.40 | 10 |
| | PvGRF Hip Angle (°) | 92.88 | 14.50 | 16 | 93.73 | 15.22 | 16 | 92.13 | 13.34 | 14 | 91.12 | 14.02 | 15 | 91.54 | 11.72 | 13 |
| | PvGRF Knee Angle (°) | -58.28 | 12.98 | 22 | -56.88 | 12.76 | 22 | -57.27 | 10.78 | 19 | -57.26 | 11.37 | 20 | -57.24 | 10.14 | 18 |
| | PvGRF Ankle Angle (°) | 12.13 | 4.28 | 35 | 11.29 | 4.05 | 36 | 11.66 | 3.29 | 28 | 11.68 | 4.08 | 35 | 11.74 | 4.90 | 42 |
| | PvGRF (BW) | 2.82 | 0.34 | 12 | 2.81 | 0.37 | 13 | 2.81 | 0.36 | 13 | 2.81 | 0.35 | 12 | 2.78 | 0.34 | 12 |
| | RFD (BW/s) | 3.91 | 1.50 | 38 | 3.90 | 1.20 | 31 | 3.91 | 1.32 | 34 | 3.86 | 1.33 | 34 | 3.70 | 1.43 | 39 |
| | RFA (BW/s) | -0.73 | 0.29 | 40 | -0.66 | 0.24 | 36 | -0.62 | 0.27 | 44 | -0.68 | 0.29 | 43 | -0.66 | 0.34 | 52 |
| | Barbell Velocity (m/s) | 0.47 | 0.08 | 17 | 0.47 | 0.08 | 17 | 0.47 | 0.08 | 17 | 0.47 | 0.09 | 19 | 0.45 | 0.09 | 20 |

*Notes – CON: concentric phase; ECC: eccentric phase; PvGRF: peak vertical ground reaction force; RFD: rate of force development; RFA: rate of force attenuation; CV: coefficient of variation (%; SD/mean*100).*

**Table 3.** Descriptive statistics for all eccentric phase variables across repetitions per set.

| Phase | Variable | Set 1 | | | Set 2 | | | Set 3 | | | Set 4 | | | Set 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV | Mean | SD | CV |
| Con | Joint Work Sum (N·m/kg) | -3.10 | 0.62 | 20 | -3.12 | 0.67 | 21 | -3.09 | 0.67 | 22 | -3.09 | 0.67 | 22 | -3.05 | 0.65 | 21 |
| | Hip Contribution | 0.95 | 0.07 | 7 | 0.96 | 0.06 | 6 | 0.95 | 0.06 | 6 | 0.95 | 0.06 | 6 | 0.96 | 0.05 | 5 |
| | Knee Contribution | < 0.01 | 0.06 | 600 | -0.01 | 0.05 | 500 | -0.01 | 0.06 | 600 | -0.01 | 0.05 | 500 | -0.02 | 0.05 | 250 |
| | Ankle Contribution | 0.05 | 0.04 | 80 | 0.05 | 0.04 | 80 | 0.06 | 0.04 | 67 | 0.06 | 0.04 | 67 | 0.06 | 0.04 | 67 |
| | Starting Trunk Angle (°) | -1.60 | 8.93 | 558 | -0.34 | 9.47 | 2785 | -0.52 | 8.81 | 1694 | -0.39 | 8.16 | 2092 | -0.96 | 9.87 | 1028 |
| | Starting Hip Angle (°) | 10.44 | 10.74 | 103 | 10.58 | 10.90 | 103 | 9.74 | 11.02 | 113 | 9.58 | 10.82 | 113 | 10.80 | 11.62 | 108 |
| | Starting Knee Angle (°) | -11.80 | 8.90 | 75 | -12.50 | 9.09 | 73 | -12.68 | 9.11 | 72 | -12.60 | 9.36 | 74 | -13.73 | 9.54 | 69 |
| | Starting Ankle Angle (°) | 2.80 | 3.58 | 128 | 2.69 | 3.49 | 130 | 2.82 | 3.09 | 110 | 3.17 | 3.54 | 112 | 3.69 | 3.22 | 87 |
| | PvGRF Trunk Angle (°) | -75.97 | 8.97 | 12 | -78.57 | 7.84 | 10 | -77.89 | 10.90 | 14 | -79.73 | 7.11 | 9 | -80.58 | 8.03 | 10 |
| | PvGRF Hip Angle (°) | 85.84 | 17.93 | 21 | 89.98 | 14.55 | 16 | 88.88 | 17.92 | 20 | 89.78 | 13.99 | 16 | 89.49 | 12.81 | 14 |
| | PvGRF Knee Angle (°) | -46.83 | 11.49 | 25 | -49.57 | 9.65 | 19 | -51.02 | 9.95 | 20 | -49.80 | 7.14 | 14 | -48.84 | 6.08 | 12 |
| | PvGRF Ankle Angle (°) | 8.45 | 4.19 | 50 | 8.82 | 3.50 | 40 | 9.82 | 3.40 | 35 | 9.46 | 3.18 | 34 | 9.12 | 3.54 | 39 |
| | PvGRF (BW) | 2.67 | 0.31 | 12 | 2.68 | 0.31 | 12 | 2.67 | 0.29 | 11 | 2.69 | 0.32 | 12 | 2.67 | 0.30 | 11 |
| | RFD (BW/s) | 0.96 | 0.40 | 42 | 0.83 | 0.20 | 24 | 0.90 | 0.38 | 42 | 0.97 | 0.36 | 37 | 1.03 | 0.55 | 53 |
| | RFA (BW/s) | -3.06 | 1.61 | 53 | -3.38 | 1.97 | 58 | -3.74 | 1.55 | 41 | -4.21 | 3.53 | 84 | -3.62 | 1.73 | 48 |
| | Barbell Velocity (m/s) | -0.39 | 0.07 | 18 | -0.38 | 0.04 | 11 | -0.40 | 0.04 | 10 | -0.40 | 0.05 | 13 | -0.40 | 0.08 | 20 |

*Notes – CON: concentric phase; ECC: eccentric phase; PvGRF: peak vertical ground reaction force; RFD: rate of force development; RFA: rate of force attenuation; CV: coefficient of variation (%; SD/mean*100).*

so familiar that many of these resistance-trained individuals had previously accommodated to the stimulus.

It is important to consider the concept of pacing with respect to these results. Based on these findings, it seems a possible explanation for the lack of observed changes within the current study is that there was no control over the rate at which the participants were asked to perform the deadlift exercise and no specific cues were given to maximize or minimize velocity. While the average velocity across repetitions per set was relatively consistent during both the concentric and eccentric phases when averaged across participants, a brief inspection of the individual concentric phase time across the five repetitions indicated the difference between the quickest and slowest concentric phases ranged from 9% to 41% across participants. This suggests within-phase velocity changes were employed by

**Table 4.** Statistical probabilities and effect sizes for the comparisons among sets for all concentric and eccentric phase variables.

| Phase | Variable | Set 1v2 *p* | Set 1v2 ES | Set 1v3 *p* | Set 1v3 ES | Set 1v4 *p* | Set 1v4 ES | Set 1v5 *p* | Set 1v5 ES |
|---|---|---|---|---|---|---|---|---|---|
| CON | Joint Work Sum | 1.000 | < 0.01 | 1.000 | 0.030 | 1.000 | 0.070 | 1.000 | 0.020 |
| | Hip Contribution | 0.999 | 0.060 | 0.994 | 0.070 | 0.998 | 0.080 | 1.000 | 0.030 |
| | Knee Contribution | 0.991 | 0.110 | 0.319 | 0.210 | 0.549 | 0.240 | 0.995 | 0.180 |
| | Ankle Contribution | 1.000 | 0.040 | 0.763 | 0.160 | 0.909 | 0.150 | 0.973 | 0.180 |
| | Starting Trunk Angle | 0.402 | 0.190 | 0.885 | 0.110 | 0.970 | 0.110 | 0.935 | 0.130 |
| | Starting Hip Angle | 1.000 | 0.130 | 0.997 | 0.090 | 0.992 | 0.080 | 0.340 | 0.090 |
| | Starting Knee Angle | 0.951 | 0.090 | 0.997 | 0.090 | 1.000 | 0.080 | 0.989 | 0.140 |
| | Starting Ankle Angle | 1.000 | 0.020 | 1.000 | 0.040 | 1.000 | < 0.01 | 1.000 | 0.080 |
| | PvGRF Trunk Angle | 0.611 | 0.260 | 1.000 | 0.010 | 1.000 | 0.130 | 1.000 | < 0.01 |
| | PvGRF Hip Angle | 0.987 | 0.060 | 1.000 | 0.060 | 0.972 | 0.130 | 1.000 | 0.110 |
| | PvGRF Knee Angle | 0.995 | 0.110 | 1.000 | 0.090 | 0.997 | 0.090 | 1.000 | 0.090 |
| | PvGRF Ankle Angle | 0.775 | 0.210 | 0.996 | 0.130 | 0.985 | 0.110 | 1.000 | 0.090 |
| | PvGRF | 1.000 | 0.040 | 0.997 | 0.050 | 0.992 | 0.060 | 0.340 | 0.130 |
| | RFD | 1.000 | 0.010 | 1.000 | 0.000 | 1.000 | 0.040 | 0.999 | 0.150 |
| | RFA | 0.969 | 0.260 | 0.950 | 0.380 | 0.999 | 0.180 | 1.000 | 0.230 |
| | Barbell Velocity | 1.000 | 0.060 | 1.000 | 0.010 | 1.000 | 0.030 | 0.993 | 0.260 |
| ECC | Joint Work Sum | 1.000 | < 0.01 | 1.000 | 0.030 | 1.000 | 0.070 | 1.000 | 0.020 |
| | Hip Contribution | 0.999 | 0.060 | 0.994 | 0.070 | 0.998 | 0.080 | 1.000 | 0.030 |
| | Knee Contribution | 0.991 | 0.110 | 0.319 | 0.210 | 0.549 | 0.240 | 0.995 | 0.180 |
| | Ankle Contribution | 1.000 | 0.010 | 0.490 | 0.180 | 0.915 | 0.120 | 0.937 | 0.140 |
| | Starting Trunk Angle | 0.908 | 0.140 | 0.991 | 0.130 | 0.847 | 0.240 | 1.000 | 0.070 |
| | Starting Hip Angle | 1.000 | 0.010 | 1.000 | 0.070 | 0.992 | 0.080 | 1.000 | 0.030 |
| | Starting Knee Angle | 0.954 | 0.080 | 0.936 | 0.100 | 0.936 | 0.090 | 0.603 | 0.220 |
| | Starting Ankle Angle | 1.000 | 0.030 | 1.000 | < 0.01 | 0.994 | 0.110 | 0.571 | 0.270 |
| | PvGRF Trunk Angle | 0.648 | 0.320 | 0.999 | 0.200 | 0.290 | 0.490 | 0.236 | 0.570 |
| | PvGRF Hip Angle | 0.563 | 0.270 | 0.990 | 0.180 | 0.709 | 0.260 | 0.895 | 0.250 |
| | PvGRF Knee Angle | 0.980 | 0.270 | 0.909 | 0.410 | 0.925 | 0.320 | 0.999 | 0.230 |
| | PvGRF Ankle Angle | 1.000 | 0.100 | 0.720 | 0.380 | 0.506 | 0.280 | 0.989 | 0.180 |
| | PvGRF | 1.000 | 0.020 | 1.000 | 0.010 | 0.984 | 0.060 | 1.000 | < 0.01 |
| | RFD | 0.836 | 0.450 | 1.000 | 0.170 | 1.000 | 0.030 | 1.000 | 0.140 |
| | RFA | 0.962 | 0.180 | 0.062 | 0.450 | 0.745 | 0.440 | 0.665 | 0.340 |
| | Barbell Velocity | 1 .000 | 0.090 | 1.000 | 0.140 | 0.999 | 0.190 | 1.000 | 0.160 |

*Notes – CON: concentric phase; ECC; eccentric phase; PvGRF: peak vertical ground reaction force; RFD: rate of force development; RFA: rate of force attenuation.*

participants and a strict control of pacing might have been required. We speculate that placing tempo/time-under-tension controls on the participants during the concentric, eccentric, or isometric phases could have created an environment in which increased effort would be required to control velocity at every instant in time during each repetition, which could therefore lead to changes in mechanical output across sets. Still, controlled pacing should be a purposeful methodological decision and not employed to simply achieve altered mechanics.

Hip, knee, and ankle joint angles and joint work contributions were calculated to provide possible explanation for any changes observed in RFD and barbell velocity. If the joint angle and work variables had changed while RFD and barbell velocity remained the same, it could have been concluded that the same stimulus was being achieved even though the movement strategy was altered. Differences could have indicated that the participants selected new or refined movement strategies to accommodate for tiredness or neuromuscular fatigue in a limiting muscle group (15). However, the results suggest that consistent movement strategies can be employed by resistance trained males in a deadlift session using the current loading scheme. The lack of observed differences could be considered as a beneficial finding for strength training professionals prescribing the current loading scheme in trained populations. The results of the current study provide new evidence that a resistance-trained athlete should be able to perform deadlift training with a five-sets-of-five-repetitions loading scheme without overt concerns for technical or mechanical output changes during later sets. In other words, similar movement and force application strategies appear to be employed by athletes from set to set, and coaches can be confident that training quantity is not likely performed at the expense of targeted mechanical output. Still, the lifting intensity associated with the five-sets-of-five loading scheme might not be high enough to challenge the neuromuscular system in a way that leads to sub-optimal movement strategies or mechanical output. This working hypothesis will require more detailed investigation.

A limitation of the current study was that guidelines were not given to participants regarding their preparatory movements prior to beginning a repetition [i.e., hitch versus no hitch]. While our approach was selected to increase the ecological validity of the results by not restricting the participants' preferred strategies, it made our method of determining phase onsets for each repetition more difficult. For participants who used a hitch action to begin the repetitions, a small local maximum was present in the total lower limb joint power curve prior to the true onset of the concentric phase [i.e., start of the repetition]. We accommodated for this by selecting the onset as the time point when the net sum of joint power became positive and increased continuously until the greatest local maximum was achieved. Another potential limitation was the lack of maximum strength testing. While percentages of maximum could not be reported here, when cross-referencing the observed barbell velocity of ~0.47 m/s across sets to a recent regression analysis (3), our participants were likely in the appropriate loading range. Still, it is important to mention that there is a possibility that the participants incorrectly prescribed their own intensity due to the subjective nature of RPE (14).

Furthermore, another limitation of this present study was the load prescription. Since RPE was used there was a high likelihood of participants being under prescribed load that did not match the intensity as their percentage counterpart. For example, an RPE 8 would be approximately 81% (14), which is not in line with the aforementioned guidelines on load prescription (8). While there were no statistically significant differences detected within this present study, it is important to note that an RPE 8 load can be performed at a moderate volume with high training quality where velocity and technique were consistent (20). This information could be utilized by strength coaches or practitioners attempting to maximize movement quality and workload in their athletes of choice.

A final consideration relates to the conventional statistical methodology used, While ANOVA-based repeated measures designs are appropriate the type of research question posed (7), they might not be ideal for the handling the between-repetition or between-set variability that appears to be associated with deadlift exercise. As shown in Table 2, the group variability across repetitions for each set may have been too great to reveal any significant changes for most, if not all, variables. Upon post-project consultations and inquiries, collapsing the repetitions to a single value representing each set should be avoided in subsequent studies of this kind. Instead, more complex statistical modeling techniques [e.g., autoregressive integrated moving average] should be considered when aiming to detect repetition-to-repetition changes at the group average level. Similarly, single-subject designs could be employed to reveal potentially meaningful changes across repetitions per participant and generalizations could be made after considering each participant's results (2).

## CONCLUSIONS

In summary, the results of this preliminary study suggest the deadlift exercise can be performed using preferred techniques at a constant, moderate-to-high intensity for five sets of five repetitions without altered kinematics or mechanical output. However, follow-up experiments employing complex statistical modeling or single-subject designs may be required to reveal changes across repetitions as opposed to across sets.

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## CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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