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Citation: Brandon, Raphael, Howatson, Glyn, Strachan, Fiona and Hunter, Angus (2015) Neuromuscular response differences to power vs strength back squat exercise in elite athletes. *Scandinavian Journal Of Medicine & Science In Sports*, 25 (5). pp. 630-639. ISSN 1600-0838

Published by: Wiley-Blackwell

URL: <http://onlinelibrary.wiley.com/doi/10.1111/sms.12289>
<<http://onlinelibrary.wiley.com/doi/10.1111/sms.12289/full>>

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1 Neuromuscular response differences to power versus strength back squat exercise in
2 elite athletes

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23 Running head: EMG, power, interpolated twitch force

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1 **Abstract**

2 The study's aim was to establish the neuromuscular responses in elite athletes
3 during and following maximal 'explosive' regular back squat exercise at heavy,
4 moderate and light loads. Ten elite track and field athletes completed 10 sets of 5
5 maximal squat repetitions on three separate days. Knee extension maximal
6 voluntary isometric contraction (MVIC), rate of force development (RFD) and evoked
7 peak twitch force (Pt) assessments were made pre- and post-session. Surface
8 electromyography amplitude (RMS) and mechanical measurements were made
9 continuously during all repetitions. The heavy session resulted in the greatest
10 repetition impulse in comparison to moderate and light sessions ($p < 0.001$), whilst
11 the latter showed highest repetition power ($p < 0.001$). MVIC, RFD and Pt force values
12 were significantly reduced post-session ($p < 0.01$), with greatest reduction observed
13 after the heavy, followed by the moderate and light sessions accordingly. Repetition
14 power significantly reduced during sets of the heavy session only ($p < 0.001$), and
15 greater increases in repetition RMS occurred during heavy session ($p < 0.001$),
16 followed by moderate, with no change during light session. In conclusion, this study
17 has shown in elite athletes that the moderate load is optimal for providing a
18 neuromuscular stimulus but with limited fatigue. This type of intervention could be
19 potentially used in the development of both strength and power in elite athletic
20 populations.

21 **Keywords:**

22 Neuromuscular, Resistance Exercise, Strength Training, Fatigue, Surface
23 Electromyography

24

1 **Introduction**

2

3 Elite athletes perform different types of resistance exercises, to gain specific physical
4 adaptations. For example, training for increasing muscle strength, involves lifting
5 heavier loads i.e. 80 – 95% of 1 repetition maximum (RM) at a slower velocity
6 (Aagaard et al. 2002; Campos et al. 2002). Conversely, to increase muscle power, the
7 correct load selection is required to enable optimal velocity, according to the force-
8 velocity-power relationship (Lynn and Noffal 2013). As such, the load is
9 comparatively lighter (i.e. 50-60% of 1RM) than loads used for strength development
10 training (Cronin et al. 2000, 2003).

11

12 When exploring some of the involved physiological mechanisms during and following
13 differing types of resistance exercise; it is thought that neuromuscular fatigue
14 related to central activation, or reduced neural drive, may be indicative of the
15 necessary stimulus for enhanced muscle activation and ultimately maximum
16 strength development (Häkkinen 1994). Furthermore, acute neuromuscular
17 responses indicated by an increase in surface electromyographic (sEMG) signals
18 during resistance exercise are purported to signify greater motor unit recruitment,
19 and hence provide the neuromuscular stimulus required for adaptation (Pincivero et
20 al. 2006; Ahtiainen and Häkkinen 2009; González-Izal et al. 2010).

21

22 The neuromuscular and fatigue responses to power and strength type sessions, have
23 been studied in recreational athletes (Häkkinen 1994; Ahtiainen and Häkkinen 2009;
24 Smilios et al. 2010) providing an indication of what might occur in elite populations;
25 nevertheless, there is a paucity of information in elite populations. Importantly,

1 these populations elicit relatively greater acute responses to resistance exercise
2 (Ahtiainen and Häkkinen 2009), which maybe due to enhanced tolerance (Fry et al.
3 1994) provided by greater capacity to recruit additional motor units (Häkkinen et al.
4 1998; Aagaard et al. 2002; Aagaard 2003). Elite athletes commonly perform
5 resistance exercise sessions using a variety of speeds and intensities
6 (Schmidtbleicher 1992) to stimulate specific adaptations relevant to their event.
7 Explosive lifting across a range of loads is also performed to optimise rate of force
8 development (RFD) capabilities (Newton et al. 1997), which is important to improve
9 athletic performance. Interestingly, literature relating to neuromuscular fatigue are
10 based on indirect or limited evidence, as central fatigue cannot be assumed solely
11 from changes in sEMG (Søgaard et al. 2006). However, specific measures such as
12 central activation ratio (CAR) and evoked peak twitch force (Pt) can provide valuable
13 information regarding central (e.g. motor neuron firing) and peripheral (e.g.
14 excitation-contraction coupling) neuromuscular components of fatigue (Kent-Braun
15 1999).

16

17 To our knowledge, no studies have examined the within-session responses, or post-
18 session neuromuscular fatigue in response to resistance exercise sets of explosive
19 squat exercises performed with a range of loads. This is of particular interest to elite
20 athletes that commonly perform explosive squat exercises, with a variety of loads to
21 improve both power and maximum strength (Moss et al. 1997). It has also been
22 proposed that the explosive effort required to move a load as fast as possible results
23 in enhanced neuromuscular activation that is critical to develop both power and
24 maximum strength (Behm and Sale 1993). Therefore, explosive lifting execution

1 could influence the neuromuscular responses and hence further our understanding
2 of the load that could optimise neuromuscular adaptation in this special population.
3 As such, repetitive lifting of a heavier load will recruit more motor units at higher
4 firing rates than a lighter load (De Luca 1997) and will result in earlier/greater fatigue
5 due to less availability of non fatigued motor units to recruit (Dias da Silva and
6 Gonçalves; Adam and De Luca 2005). Furthermore, the heavier load will take longer
7 to lift than a lighter one (Perrine and Edgerton 1978; Gregor et al. 1979) resulting in
8 greater time under tension which is likely to recruit a greater range of motor units
9 (Burd et al. 2012) . In addition, possible greater alterations in ionic exchange and
10 metabolite accumulation will result in reduced excitation-contraction (E-C) coupling
11 to lower maximal force capacity (Allen et al. 2008), to contribute to premature
12 fatigue. As such, it is likely that there is a central CNS strategy to alter neural
13 recruitment, but it is also possible that, from the onset of fatigue, peripheral factors
14 will contribute to any force decline. Therefore, there is limited evidence to be able to
15 describe what the relative central peripheral contributions would be when
16 comparing strength to power based training. Consequently, the aim of this study was
17 to establish the neuromuscular responses during an explosive resistance exercise at
18 3 different loads designed to produce different power outputs in an elite athletic
19 population. Specifically, we examine how RFD and maximal isometric voluntary
20 contraction (MIVC) change, along with other neuromuscular measures to assess the
21 nature and magnitude of fatigue. We hypothesised, that explosive, heavy load
22 training will induce the greatest post-session central and relative peripheral fatigue
23 and neuromuscular recruitment, during the exercise, when compared to the lighter
24 loads.

1 **Methods**

2

3 **Subjects**

4 Ten male elite strength and power athletes were recruited (Table I); all were
5 international standard competitors in sprint track and field events and had produced
6 typical performances within 3 months of the study of 100 m sprint= ~10.25 s, javelin
7 = ~78.33 m and triple jump = ~17.23 m. To put these performances into context, the
8 International Association of Athletics Federation set qualification times and
9 distances for London 2012 Olympics of 100m sprint 10.18 s(A) and 10.24 s(B); javelin
10 81.8 m(A) and 77.8 m(B) and; triple jump 17.20 m(A) and 16.85m(B). All of the
11 athletes recruited for the study had a minimum of four years experience of regular
12 squat exercise training. Each subject provided written informed consent following
13 institutional research ethics committee approval.

14

15 **Experimental Design**

16 Familiarisation of all test procedures was performed, included 3-5 MIVCs to minimise
17 the possibility of a learning affect on the subsequent test session days. On following
18 days, comparisons of neuromuscular responses to moderate, heavy and then light
19 loads were each performed as separate trials on 3 different days (but within a 2
20 weeks period) with at least one day of rest between sessions. This rest period
21 ensured sufficient recovery to maintain the pre session MIVC on subsequent
22 sessions. The trials were done in this order so the moderate session would act as a
23 controlled dose to provide a protective effective for any damage occurring during
24 the subsequent heavy session. The light session was used finally to minimise any
25 fatigue effects that could influence athletic commitments following completion of all

1 3 trials. The protocol consisted of 10 sets of 5 repetitions “high intensity” (explosive
2 concentric phase) barbell back squat exercise. Participants arrived at the testing
3 centre at 08:00 hours following a 12 hour fast and consumed a standardised
4 breakfast. As the study took place during the summer athletics competition season
5 no resistance exercise took place between trials, only low intensity specific event
6 training with a minimum period of complete rest 24 hours prior to arrival. The warm
7 up consisted of 10 minutes (at 100 W) of cycling on an ergometer (Keiser M3, Keiser
8 Corp, USA). Subjects then performed muscle function measures pre, mid (5 sets) and
9 post exercise back squat session (Figure 1).

10

11

12 **Muscle Function**

13 Subjects were seated and secured in to an isokinetic dynamometer according to the
14 manufacturers recommendations for the assessment of knee extension (Kin Com,
15 Chattanooga, USA); briefly, the hip angle was 90° and the knee was secured at a 70°,
16 where 0° was full extension. The exact position for each participant was recorded
17 and replicated on subsequent testing sessions. Whilst in this set up the subjects
18 performed evoked peak twitch force (Pt), MIVC (including RFD) and CAR.

19

20 *Evoked peak twitch force (Pt)*

21 Whilst positioned in the dynamometer subjects performed evoked peak twitch force
22 (Pt), MVC (including RFD) and CAR. Two 4 x 8 cm electrical stimulation pads
23 (Campbell Medical, UK) were attached to the proximal medial thigh aligned over the
24 femoral nerve and over the greater trochanter (Nybo and Nielsen 2001; Lattier et al.

1 2004). The femoral nerve was located by identifying the femoral artery and placing
2 the electrode approximately 2 cm laterally. Then the electrode was repositioned,
3 until the optimal stimulation site was located by observing twitch response
4 magnitude. Pt was assessed using a stimulator (StimISOC, Biopac Systems Inc, USA)
5 to deliver sub-maximal single triangular pulses of 35 ms with a maximum constant of
6 200 V to the passive quadriceps as described previously (Markovic et al. 2004; Zory
7 et al. 2010). Participants were instructed to relax the leg muscles and not anticipate
8 the shock, so the full effect of the stimulation could be recorded. Pt values were
9 taken as the peak change in force from pre-stimulated values recorded by the
10 dynamometer.

11

12 *Maximal Voluntary Isometric Contraction (MIVC) and Central Activation Ratio (CAR)*

13 Subjects performed three warm up contractions, with increasing intensity followed
14 by 3 X 7 s MIVCs with 60 s rest between efforts. The CAR assessment occurred during
15 one of the MIVC trials, chosen at random and without warning. Subjects were
16 percutaneously stimulated with a 250 ms 100 Hz tetanic pulse train (Nybo and
17 Nielsen 2001), at the voltage pre-determined during the familiarisation session. The
18 stimulation occurred six seconds into the MIVC test, with subjects instructed and
19 coached to maintain consistent force levels during the stimulation (Kent-Braun and
20 Le Blanc 1996). The trial resulting in the best peak force value was taken to
21 represent MIVC force. Peak force was processed as the mean value from a 200 ms
22 window centred on the peak force value. The same 200 ms interval was used to
23 process pre trial MIVC RMS and also used as the reference sEMG value for
24 normalisation.

1

2 The CAR value was obtained from the ratio of peak voluntary force (prior to the
3 stimulation) to the peak stimulated force; where $CAR = (MIVC \text{ force} / \text{superimposed}$
4 $\text{stimulated force}) \times 100$; (Kent-Braun and Le Blanc 1996; Nybo and Nielsen 2001). The
5 RFD was calculated from the MIVC as the average slope of the force profile from 0-
6 50, 0-100, 0-200 and 0-300ms (Aagaard et al. 2002). The onset of muscle contraction
7 was defined as the point at which the force curve exceeded the baseline level by 5%
8 of MIVC (Blackburn, et al 2009). Baseline resting torque was computed by taking the
9 average reading over 0.5s, starting 1s before the onset of muscle contraction for
10 MIVC.

11

12 *Counter movement jump (CMJ)*

13 Three maximal counter movement jumps (CMJ) were performed with a 30 s pause
14 between each. Subjects held a wooden pole upon their shoulders during the jump
15 to remove any extraneous movements from the arms (Markovic et al. 2004) and to
16 attach a linear position transducer device (Celesco PT5A, USA) for measurement of
17 jump height displacement.

18

19 **Back Squat**

20 The barbell load during the heavy session was determined during the familiarisation
21 session. Full squats were defined by the hips descending below the level of the knee
22 at the bottom of the movement (Newton 2006). Subjects performed a series of
23 incrementally loaded sets of five repetitions and rated the intensity of the load
24 against the active muscle RPE, with descriptive anchors provided at RPE = 11 and 20

1 (Gearhart et al. 2001). This scale has been shown to be a consistent method of
2 assessing strength exercise intensity (Gearhart et al. 2001), giving exercise loads
3 relative to maximum capabilities (Gearhart et al. 2002; Lagally and Amorose 2007).
4 The exercise load used in the heavy intensity squat trials corresponded to an active
5 muscle RPE = 16 or 17 (very hard). This method resulted in a mean \pm SD barbell load
6 of 129 ± 22 kg in the heavy session. Based upon the subjects' current repetition
7 maximum squat load, this was equivalent to 6 ± 1 repetition maximum load, or $\sim 85\%$
8 of maximum (Shimano et al. 2006). During the moderate and light sessions, subjects
9 lifted 75% and 50% of heavy session load, respectively, of the system mass terms.
10 System mass was defined as the total barbell and 88% body mass which was
11 assumed to be involved in the squat, as the remaining 12%, comprising the shank
12 and foot segments, do not move vertically during this action (Zatsiorsky et al. 1990).
13
14 Using a standard squatting procedure (Brandon et al. 2011); during heavy and
15 moderate sessions, subjects squatted down at a controlled speed in time to a
16 metronome, emitting audio pulses at 1 Hz followed by an upward explosive maximal
17 effort. During the light session, subjects performed the eccentric and concentric
18 repetition cycle as fast as possible; however, subjects were instructed not to jump,
19 so that repetition speed was optimised. This protocol is the type typically used for
20 training of elite athletes whereupon to ensure maximum intensity of effort during
21 the light load it is important to execute fast up and down phases of the squat.
22 Whereas, to do the same during the heavier loads would be considered
23 contraindicated due to the higher probability of incurring an injury during the

1 eccentric phase, hence why it is important to control the eccentric phase. Blood
2 lactate was assessed from earlobe capillary puncture using a portable device
3 (LactatePro LT-1710, ArkRay Inc., Kyoto, Japan) at rest and after the 5th and 10th set.
4 On completion of each training session, subjects provided an overall Rating of
5 Perceived Exertion (RPE) (Borg 1973).

6

7 **Squat Kinematics**

8

9 Knee angle was captured during the squat using a flexible electrogoniometer (TDA-
10 100, Biopac Systems Inc., USA) attached to the lateral aspect of leg. The knee angle
11 measurements were used to determine the beginning and end of the concentric
12 phase of the squat ensuring consistency of the period from which mean power and
13 RMS values were processed between subjects and across sessions as described
14 previously (Brandon et al. 2011). Barbell displacement data was also measured using
15 the aforementioned linear position transducer and subsequently power was
16 calculated using the system's software (AcqKnowledge[®] 3.8.1, Biopac Systems Inc.,
17 USA): where, Force (load) = System mass x (Acceleration + 9.812), then, Power =
18 Force (load) x Velocity. Power was processed as the mean power value from the time
19 interval defined by maximum to minimum knee angle values as the barbell was
20 being lifted upwards.

21

22

23 **sEMG**

24 sEMG was recorded during the MIVC and continuously throughout the back squat
25 sessions. Following shaving, abrading and cleaning with alcohol swabs a pair 10 mm

1 diameter electrodes (PNS Dual Element Electrode; Vermed, Vermont, USA), with 10
2 mm inter-electrode distance, was secured to the right vastus lateralis and biceps
3 femoris (BF) muscle in accordance with the Surface ElectroMyoGraphy for the Non-
4 Inva- sive Assessment of Muscles (SENIAM) guidelines (Hermens et al. 2000).

5 Raw sEMG was selected from the beginning to the end of the concentric phase of
6 the squat as defined by maximum and minimum knee angles. From this sEMG
7 amplitude was determined by transferring the raw signal to root mean square
8 (RMS), which was obtained via bespoke sEMG amplifiers (Biopac Systems Inc., Santa
9 Barbara, USA). The sEMG data was sampled at 2000 Hz and automatically anti-
10 aliased and filtered using a 1 Hz - 500 Hz band pass filters. RMS was processed from
11 the sEMG amplitude, using a 100 ms moving window and averaged at 10 Hz. RMS
12 values during barbell squat repetitions and MVC and RFD were normalised to a
13 reference RMS value captured during pre trial MVC; specifically from the average of
14 the concentric phase of each movement (Brandon et al. 2011).

15 Within-set RMS was normalised to the first repetition of each set. To determine the
16 influence of antagonistic activity under fatigue, RMS was also measured during the
17 knee extension MIVC and squat exercise from the BF muscle (De Luca 1997; Weir et
18 al. 1998; Hassani et al. 2006; Zory et al. 2010).

19

20 **Statistical methods and analysis**

21 Statistics were performed using Minitab 15 software (USA), which reports statistics
22 to nearest three decimal places; all data were expressed as mean \pm SD and statistical
23 significance was accepted at $p < 0.05$.. To compare differences between sessions and

1 time a two factor repeated measures ANOVA test (session x time) was processed for
2 MIVC, RFD, RFD: MIVC ratio, VL and BF RMS during MVC, VL RMS during RFD, CAR,
3 Pt, CMJ height, and lactate. To compare session characteristics, a two factor ANOVA
4 test (session x set) was processed for power, impulse, and repetition duration. To
5 compare session differences in repetitions within sets and between exercises a
6 three-factor ANOVA test (session x set x rep) was processed for RMS amplitude and
7 power. For brevity these variables were used from sets 1, 5 and 10 only. Where
8 necessary, effects were followed by *post-hoc* Tukey's tests. Due to methodological
9 issues, not all measurements of evoked twitch and CAR assessments were recorded.
10 Therefore, two factor ANOVA was performed with eight subjects for Pt and CAR.

11 **Results**

12 **Power and work during back squats**

13 As expected, repetition power (Table II) significantly ($F=1361.6$, $p<0.001$) increased
14 across loads from heavy, to moderate and then light. Within each of the 3 sessions
15 only the heavy load significantly ($F=8.9$, $p<0.001$) declined by sets 5 and 10 (Table II
16 and Figure 2B). As such repetition duration ($F=1694.5$, $p<0.001$) and impulse
17 ($F=2387.3$, $p<0.001$) were also significantly greater with increased session load
18 (Table II).

19

20 **sEMG during back squats**

21 VL sEMG increased ($p<0.01$) within the sets as the repetitions progressed for all 3
22 loads. However, it was only during sets 5 and 10, significant increases were only
23 shown with the heavy ($p<0.01$) and moderate ($p<0.05$) loads; the light load showed

1 no significant increases (Figure 2A). No differences were shown for BF sEMG
2 between loads and across reps and sets.

3

4

5 **Muscle function tests**

6 MIVC significantly ($p < 0.001$) declined across pre, mid and post sessions for the heavy
7 (13%) and moderate (9%) but not light loads (Table III and Figure 3B). However, RFD
8 significantly, ($p < 0.001$) declined across pre, mid and post sessions for all 3 loads with
9 the heavy session declining by 28% in comparison to 13 and 15% for the respective
10 moderate and light sessions (Figure 3A).

11

12 Pt significantly declined across pre- to post- heavy ($p < 0.01$) and moderate ($p < 0.05$)
13 but not the light session (Table III). No significant differences were found for CAR and
14 CMJ height within or between sessions. There was a significant reduction across all
15 sessions combined for VL RMS during MIVC ($F = 7.9$, $p = 0.001$) and VL RMS during RFD
16 ($F = 3.7$, $p = 0.034$) (Table III).

17

18 **Lactate and RPE**

19 Lactate was significantly greater ($F = 57.0$, $p < 0.001$) than the baseline (0.9 ± 0.3
20 mmol.L^{-1}) for post heavy and moderate (4.9 ± 2.5 and 2.6 ± 1.7 mmol.L^{-1}
21 respectively), but not for the light session (1.8 ± 0.9 mmol.L^{-1}). Post session RPE
22 scores significantly ($F = 50.8$, $p < 0.001$) increased along with load showing 11.3 ± 2.4 ,
23 13.3 ± 1.8 and 16.5 ± 0.9 , for light, moderate and heavy loads respectively.

24

1 **Discussion**

2 This study is the first to characterise the neuromuscular response during and
3 following resistance exercise that elite athletic populations typically engaged in. This
4 work provides novel information on resistance training prescription for elite,
5 strength and power-trained populations. As hypothesised the heavy load produced
6 the least power whereas the light load produced the most power during the back
7 squat. Back squat repetition power, within the sets, declined for the heavy load but
8 was maintained in the moderate and light loads. This caused a greater decline in
9 MIVC post session when compared to the moderate and light loads.

10

11 *sEMG during squats*

12 VL sEMG recorded during the squats increased for the heavy and moderate loads
13 across all 3 sets, whereas although the light load increased in the 1st set, it only
14 showed negligible increases in the 5th and 10th sets. Therefore, it is possible that
15 these increases observed during the heavy and moderate loads (sets 5 and 10) were
16 caused from the recruitment of larger (type II) non-fatigued motor units to
17 compensate for the smaller (type I) fatigued units (Dias da Silva and Gonçalves;
18 Adam and De Luca 2005), which is indicative of submaximal fatigue (Moritani et al.
19 1986). In addition, the greater time under tension for the heavier loads (Table II) will
20 result in recruitment of a greater range of available motor units (Burd et al. 2012),
21 which will also contribute to the increased sEMG observed. However, it is evident
22 that a possible neural compensation strategy was only effective in maintaining
23 power in the moderate and not the heavy session. The residual impact of this fatigue
24 was shown by a greater reduction in MVC and RFD following the heavy session. Also,

1 the higher post-heavy session lactate suggests that metabolic factors, particularly
2 the glycolytic pathway, could have contributed to the fatigue.

3

4 *Muscle function tests*

5 Firstly, there was evidence of peripheral fatigue following the heavy and moderate
6 load sessions as Pt declined, whereas it was maintained following the light load.

7 These reductions would likely have been derived from post-synaptic events such as
8 an inhibition of the excitation-contraction coupling process (Hill et al. 2001).

9 However, evoked twitch force values were small, relative to MVC, which limit

10 conclusions based upon these findings but may be indicative of the highly trained

11 status of the subjects (Garland et al. 2003). Secondly, no differences in CAR were

12 shown across loads, therefore minimal central activation failure was responsible for

13 the fatigue following the heavy load (Kent-Braun 1999). Thirdly, despite a greater

14 reduction in MIVC following the heavy load, there was no difference for sEMG

15 (recorded during MVC) across the loads. This is somewhat contradictory given the

16 findings during the back squat, however MIVC is representative of a maximal force

17 task as opposed to functional back squat, which is a submaximal position task. These

18 differences are likely to produce very diverse excitatory and inhibitory input into the

19 motor neurons of the spinal cord, which can result in altered neuromuscular

20 recruitment strategies (Hunter et al 2004). Nevertheless, the increased decline in

21 MIVC following the heavy load was caused by more peripheral post-synaptic factors,

22 rather than reduced neural input. This might be an important consideration for

23 “concurrent training” plans shortly after a heavy load strength session such as this.

24 One other factor that could explain these observations is that this population was a

1 highly trained, elite athletic population and conceivably the physiological responses
2 and recovery could be faster than other populations described in the literature.

3

4 *Summary*

5 This study has shown that during the heavy back squat load the subjects' were
6 unable to maintain the initial barbell velocity, as the repetitions and sets progressed.

7 Whereas, during the light and moderate loads, the participants managed to
8 successfully maintain velocity throughout all the sets. We therefore propose that

9 during the moderate and light loads, the participants were able to employ a pacing
10 strategy (Foster et al. 1994; St Clair Gibson and Noakes 2004), whereas during the

11 heavy load they were not. Nevertheless, it has been well established that weight-
12 training interventions are highly specific (Stone and Stone 2013), i.e. to achieve

13 strength gains, to improve power, and so on. However, many elite athletic
14 programmes require adaptations of both factors to achieve performance gains.

15 Therefore, the medium load would be the optimal intervention as it produced
16 increased neuromuscular recruitment, which is necessary for both strength and

17 power adaptations (Takarada et al. 2000), but without the onset of appreciable
18 fatigue.

19 **Conclusions**

20 This study has shown in a group of elite track and field athletes that heavy load
21 explosive squat exercise increases neuromuscular recruitment, but fails to maintain

22 power, thereby resulting in residual, peripheral fatigue. Conversely, the medium
23 load also increased neuromuscular recruitment but was successful in maintaining

1 power to produce less residual fatigue. The light load did not increase
2 neuromuscular recruitment and maintained power, but completely avoided any
3 residual fatigue. Therefore, athletes, coaches and practitioners seeking to bring
4 about an adaptive response in both strength and power, the medium load (75% of
5 heavy system mass load) is recommended to provide the necessary neuromuscular
6 stimulus with less residual fatigue. Further investigations, that also measure
7 contributions from hip muscles, are required to directly link the within-session
8 neuromuscular responses to chronic strength or power adaptations.

9

10 **Perspective**

11 Back squat exercise is a routinely used resistance exercise to develop both strength
12 and power in elite athletes, however there are no data that describe the
13 physiological consequences of this activity. This is the first study in an elite group of
14 athletes to characterise these acute neuromuscular responses of explosive back
15 squat exercise performed with 3 different loads, to specifically produce 3 different
16 power outputs. The range of measures, conducted in well controlled conditions
17 substantially further our understanding of the physiological consequences for this
18 exercise mode in this elite athletic population (Campos et al. 2002; Burd et al. 2012).
19 The study provides critical information for athletes, coaches and practitioners
20 seeking to use back squat interventions on elite athletes to obtain stimulation of the
21 neuromuscular system; furthermore, it also provides critical information for exercise
22 prescription and in particular consideration for implications of on concurrent
23 training.

24

1 **Acknowledgements**

2 UK Sport's Graduate Innovations Programme for funding the research programme.

3 Professor Christian Cook (UK Sport, Research & Innovation Consultant).

4

5

1 **References**

2

3 Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate
4 of force development and neural drive of human skeletal muscle following
5 resistance training. *J. Appl. Physiol.* 2002 Oct;93(4):1318–26.

6 Adam A, De Luca CJ. Firing rates of motor units in human vastus lateralis muscle
7 during fatiguing isometric contractions. *J. Appl. Physiol.* 2005 Jul;99(1):268–80.

8 Ahtiainen JP, Häkkinen K. Strength athletes are capable to produce greater muscle
9 activation and neural fatigue during high-intensity resistance exercise than
10 nonathletes. *J. Strength Cond. Res.* 2009 Jul;23(4):1129–34.

11 Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms.
12 *Physiol. Rev.* 2008 Jan;88(1):287–332.

13 Behm DG, Sale DG. Intended rather than actual movement velocity determines
14 velocity-specific training response. *J. Appl. Physiol.* 1993 Jan;74(1):359–68.

15 Blackburn JT, Bell DR, Norcross MF, Hudson JD, Engstrom LA. Comparison of
16 hamstring neuromechanical properties between healthy males and females and
17 the influence of musculotendinous stiffness. *J. Electromyogr. Kinesiol.* 2009
18 Oct;19(5):e362–9.

19 Borg GA. Perceived exertion: a note on “history” and methods. *Med. Sci. Sports.*
20 1973 Jan;5(2):90–3.

21 Brandon R, Howatson G, Hunter A. Reliability of a combined biomechanical and
22 surface electromyographical analysis system during dynamic barbell squat
23 exercise. *J. Sports Sci.* 2011 Oct;29(13):1389–97.

24 Burd NA, Andrews RJ, West DWD, Little JP, Cochran AJR, Hector AJ, et al. Muscle
25 time under tension during resistance exercise stimulates differential muscle
26 protein sub-fractional synthetic responses in men. *J. Physiol.* 2012 Jan 15;590(Pt
27 2):351–62.

28 Campos GER, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al.
29 Muscular adaptations in response to three different resistance-training
30 regimens: specificity of repetition maximum training zones. *Eur. J. Appl. Physiol.*
31 2002 Nov;88(1-2):50–60.

32 Cronin JB, McNair PJ, Marshall RN. The role of maximal strength and load on initial
33 power production. *Med. Sci. Sports Exerc.* 2000 Oct;32(10):1763–9.

34 Cronin JB, McNair PJ, Marshall RN. Force-velocity analysis of strength-training
35 techniques and load: implications for training strategy and research. *J. Strength
36 Cond. Res.* 2003 Feb;17(1):148–55.

- 1 De Luca CJ. The use of Surface Electromyography in Biomechanics. *J. Appl. Biomech.*
2 1997;13(2):135–63.
- 3 Dias da Silva SR, Gonçalves M. Dynamic and isometric protocols of knee extension:
4 effect of fatigue on the EMG signal. *Electromyogr. Clin. Neurophysiol.* 46(1):35–
5 42.
- 6 Garland SJ, Walton D, Ivanova TD. Effect of force level and training status on
7 contractile properties following fatigue. *Can. J. Appl. Physiol.* 2003
8 Feb;28(1):93–101.
- 9 Gearhart RE, Goss FL, Lagally KM, Jakicic JM, Gallagher J, Robertson RJ. Standardized
10 scaling procedures for rating perceived exertion during resistance exercise. *J.*
11 *Strength Cond. Res.* 2001 Aug;15(3):320–5.
- 12 González-Izal M, Malanda A, Navarro-Amézqueta I, Gorostiaga EM, Mallor F, Ibañez
13 J, et al. EMG spectral indices and muscle power fatigue during dynamic
14 contractions. *J. Electromyogr. Kinesiol.* 2010 Apr;20(2):233–40.
- 15 Häkkinen K. Neuromuscular fatigue in males and females during strenuous heavy
16 resistance loading. *Electromyogr. Clin. Neurophysiol.* 1994 Jun;34(4):205–14.
- 17 Hassani A, Patikas D, Bassa E, Hatzikotoulas K, Kellis E, Kotzamanidis C. Agonist and
18 antagonist muscle activation during maximal and submaximal isokinetic fatigue
19 tests of the knee extensors. *J. Electromyogr. Kinesiol.* 2006 Dec;16(6):661–8.
- 20 Hill CA, Thompson MW, Ruell PA, Thom JM, White MJ. Sarcoplasmic reticulum
21 function and muscle contractile character following fatiguing exercise in
22 humans. *J. Physiol.* 2001 Mar 15;531(Pt 3):871–8.
- 23 Kent-Braun JA. Central and peripheral contributions to muscle fatigue in humans
24 during sustained maximal effort. *Eur. J. Appl. Physiol. Occup. Physiol.* 1999
25 Jun;80(1):57–63.
- 26 Kent-Braun JA, Le Blanc R. Quantitation of central activation failure during maximal
27 voluntary contractions in humans. *Muscle Nerve.* 1996 Jul;19(7):861–9.
- 28 Lattier G, Millet GY, Martin A, Martin V. Fatigue and recovery after high-intensity
29 exercise part I: neuromuscular fatigue. *Int. J. Sports Med.* 2004 Aug;25(6):450–
30 6.
- 31 Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and factorial validity of squat
32 and countermovement jump tests. *J. Strength Cond. Res.* 2004 Aug;18(3):551–
33 5.
- 34 Moritani T, Muro M, Nagata A. Intramuscular and surface electromyogram changes
35 during muscle fatigue. *J. Appl. Physiol.* 1986 Apr;60(4):1179–85.

- 1 Moss BM, Refsnes PE, Abildgaard A, Nicolaysen K, Jensen J. Effects of maximal effort
2 strength training with different loads on dynamic strength, cross-sectional area,
3 load-power and load-velocity relationships. *Eur. J. Appl. Physiol. Occup. Physiol.*
4 1997 Jan;75(3):193–9.
- 5 Newton RU, Murphy AJ, Humphries BJ, Wilson GJ, Kraemer WJ, Häkkinen K.
6 Influence of load and stretch shortening cycle on the kinematics, kinetics and
7 muscle activation that occurs during explosive upper-body movements. *Eur. J.*
8 *Appl. Physiol. Occup. Physiol.* 1997 Jan;75(4):333–42.
- 9 Nocella M, Colombini B, Benelli G, Cecchi G, Bagni MA, Bruton J. Force decline during
10 fatigue is due to both a decrease in the force per individual cross-bridge and the
11 number of cross-bridges. *J. Physiol.* 2011 Jul 1;589(Pt 13):3371–81.
- 12 Nybo L, Nielsen B. Hyperthermia and central fatigue during prolonged exercise in
13 humans. *J. Appl. Physiol.* 2001 Sep;91(3):1055–60.
- 14 Pincivero DM, Gandhi V, Timmons MK, Coelho AJ. Quadriceps femoris
15 electromyogram during concentric, isometric and eccentric phases of fatiguing
16 dynamic knee extensions. *J. Biomech.* 2006 Jan;39(2):246–54.
- 17 Schmidtbleicher D. Training for power events. London: Blackwell; 1992.
- 18 Scott KL & Guillermo JM. Biomechanics of Human Movement. In: Jeff CT, E BL,
19 editors. *Cond. Strength Hum. Perform.* 2nd ed. Philadelphia: Lippincott Williams
20 & Williams; 2013. p. 82–108.
- 21 Shimano T, Kraemer WJ, Spiering BA, Volek JS, Hatfield DL, Silvestre R, et al.
22 Relationship between the number of repetitions and selected percentages of
23 one repetition maximum in free weight exercises in trained and untrained men.
24 *J. Strength Cond. Res.* 2006 Nov;20(4):819–23.
- 25 Smilios I, Häkkinen K, Tokmakidis SP. Power output and electromyographic activity
26 during and after a moderate load muscular endurance session. *J. Strength Cond.*
27 *Res.* 2010 Aug;24(8):2122–31.
- 28 Sjøgaard K, Gandevia SC, Todd G, Petersen NT, Taylor JL. The effect of sustained low-
29 intensity contractions on supraspinal fatigue in human elbow flexor muscles. *J.*
30 *Physiol.* 2006 Jun 1;573(Pt 2):511–23.
- 31 Stone MH & Stone ME. Strength and Conditioning for Sport. In: TJ C, LE B, editors.
32 *Cond. Strength Hum. Perform.* Second. Philadelphia: Lippincott Williams &
33 Williams; 2013. p. 346–63.
- 34 Takarada Y, Takazawa H, Sato Y, Takebayashi S, Tanaka Y, Ishii N. Effects of resistance
35 exercise combined with moderate vascular occlusion on muscular function in
36 humans. *J. Appl. Physiol.* 2000 Jun;88(6):2097–106.

1 Weir JP, Keefe DA, Eaton JF, Augustine RT, Tobin DM. Effect of fatigue on hamstring
2 coactivation during isokinetic knee extensions. *Eur. J. Appl. Physiol. Occup.*
3 *Physiol.* 1998 Nov;78(6):555–9.

4 Zatsiorsky, V. M., Seluyanov, V. N., & Chugunova L. In-vivo body segment inertial
5 parameter determination using a gamma-scanner method. *Biomechancis Hum.*
6 *Mov. Appl. Rehabil. Sport. Ergon.* ed. N Berme A Cappuzo. Worthington OH:
7 Bertec Corp; 1990. p. 186–202.

8 Zory R, Weist R, Malakieh J, Grenier S. Thigh muscles' responses caused by a single
9 combined aerobic and resistance training session in healthy young men. *Int. J.*
10 *Sports Med.* 2010 May;31(5):311–8.

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1 **Tables**

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4 **Table I. Descriptive data of the subjects' physical characteristics.**

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Age (years)	Body mass (kg)	Vertical Jump Performance (cm)	Squat 1 Repetition Maximum Load (kg)	Isometric MVC knee extension force (N)
26 ± 3	86.0 ± 13	51 ± 5	152 ± 26	1175 ± 200

6 Values are given as mean ± SD, n = 10.

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1 **Table II. Power, impulse and repetition duration for set 1, 5 & 10 and total work for**
 2 **all sets during heavy, moderate and light sessions**
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		Heavy	Moderate	Light
Power (W)**	Set 1	1194 ± 203	1890 ± 344	2385 ± 299
	Set 5	1025 ± 215*	1964 ± 340	2509 ± 369
	Set 10	945 ± 218*	1932 ± 301	2475 ± 348
Impulse (N.s)**	Set 1	5349 ± 755	3327 ± 756	1064 ± 125
	Set 5	5601 ± 687	3194 ± 451	1107 ± 157
	Set 10	5723 ± 796	3277 ± 433	1102 ± 122
Repetition duration (s)**	Set 1	2.6 ± 0.2	2.1 ± 0.3	0.6 ± 0.1
	Set 5	2.8 ± 0.2	2.0 ± 0.1	0.7 ± 0.1
	Set 10	2.9 ± 0.2*	2.1 ± 0.2	0.7 ± 0.1

4 Values given as repetition mean ± SD, n = 10. * Significantly different Power and
 5 Repetition duration, p<0.05, compared to set 1 within Heavy session. ** Significant
 6 differences in Power, Impulse and Repetition duration between sessions, p<0.001.

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1 **Table III. Pre, mid and post session assessment values from heavy, moderate and**
 2 **light squat sessions.**
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		Heavy	Moderate	Light
MVC (N) \$#	pre	1174 ± 200	1209 ± 234	1181 ± 182
	mid	1112 ± 163	1158 ± 233	1163 ± 173
	post	1030 ± 194**	1124 ± 251**	1155 ± 215
RMS during MVC (%) \$	pre	100	100	100
	mid	96.9 ± 12.1	100.9 ± 11.0	98.9 ± 8.8
	post	92.3 ± 14.3	93.8 ± 11.0	90.8 ± 11.8
RFD (N.s ⁻¹) \$#	pre	6700 ± 912	6454 ± 822	6623 ± 1229
	mid	5162 ± 869**	5778 ± 807**	5840 ± 758**
	post	4872 ± 863**	5626 ± 1099**	5626 ± 1099**
RMS during RFD (%) \$	pre	115.1 ± 18.1	123.4 ± 38.3	112.3 ± 29.3
	mid	90.9 ± 21.5	114.1 ± 37.9	107.9 ± 17.8
	post	100.6 ± 18.0	105.8 ± 26.6	97.4 ± 22.6
RFD: MVC (s ⁻¹) \$#	pre	5.78 ± 0.80	5.44 ± 0.83	5.63 ± 0.67
	mid	4.76 ± 1.19**	5.10 ± 0.88**	5.03 ± 0.51**
	post	4.85 ± 1.08**	5.08 ± 0.71**	5.08 ± 0.91**
Pt (N) \$#	pre	33.5 ± 21.2	37.2 ± 12.9	36.0 ± 12.8
	mid	30.1 ± 16.6	29.2 ± 15.6	31.3 ± 12.5
	post	24.1 ± 13.8*	27.1 ± 14.8*	30.4 ± 12.8
CAR (%)	pre	94.8 ± 2.4	94.3 ± 3.1	95.6 ± 1.8
	mid	95.3 ± 2.3	94.5 ± 2.9	96.8 ± 1.6
	post	94.8 ± 4.2	95.4 ± 2.9	96.3 ± 1.7
CMJ Height (cm)	pre	51.2 ± 4.9	50.3 ± 5.3	51.4 ± 5.8
	mid	51.3 ± 5.3	51.1 ± 4.5	50.2 ± 5.8
	post	50.4 ± 4.5	50.4 ± 5.4	50.4 ± 6.5

4 Values given as mean ± SD pre, mid and post session, where n = 10 except for Pt and
 5 CAR where n = 8. Normalised RMS values are for the *vastus lateralis* relative to pre
 6 session RMS amplitude during MVC. \$ Significant time effect from pre to post,
 7 p<0.01. # Significant interaction between load and pre to post session, p<0.01 Within
 8 session *post hoc* significant difference compared to pre-session values, * p<0.01 and
 9 ** p<0.001.

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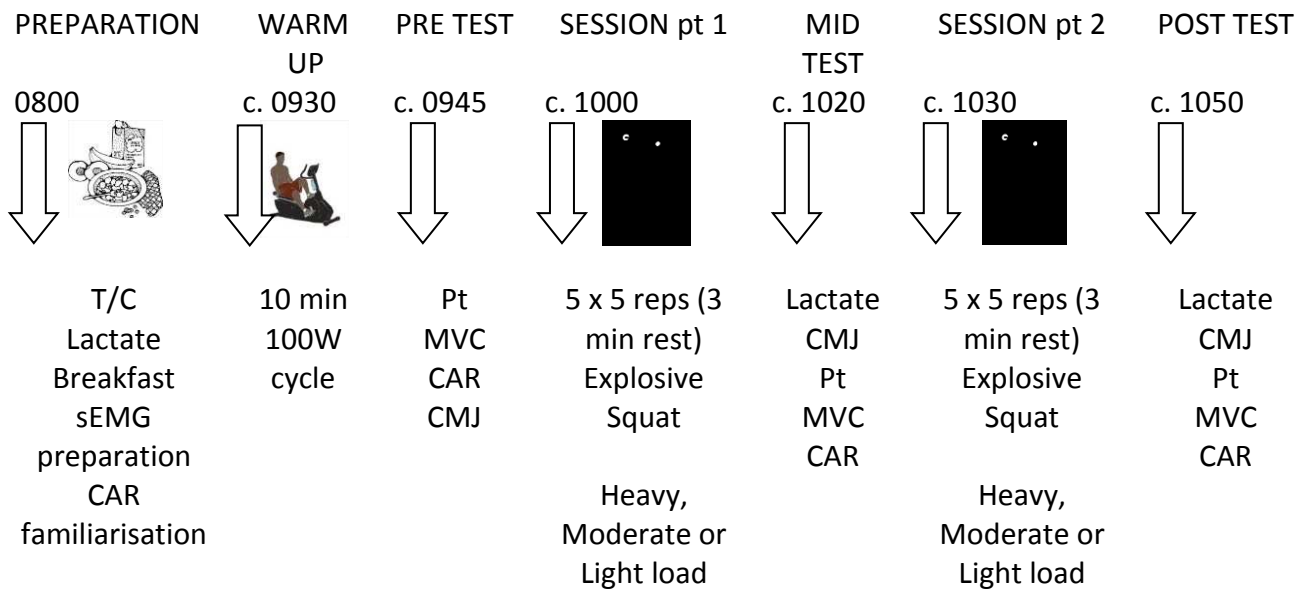
Figures

Figure 1 Timed summary of the Heavy, Moderate and Light High Intensity Squat Trials (T/C = testosterone and cortisol saliva samples, Lactate = blood lactate samples, Pt = evoked quadriceps twitch force, MVC = knee extension isometric maximal voluntary force, CAR = central activation ratio, CMJ = vertical jump height)

Figure 2 A) VL RMS amplitude and B) power, relative to repetition one (%) within sets 1, 5 and 10 of heavy, moderate and light sessions. Values given are the mean \pm SD relative to repetition one of each set, n = 11. A) VL RMS amplitude * *post hoc* significant difference p<0.01 between repetitions 1 and 5 during heavy and moderate sessions. B) Repetition Power ** *post hoc* significant difference p<0.001 between repetitions 1 and 5 during set 5 and between repetitions 1 and 4 & 5 of set 10 of the heavy session

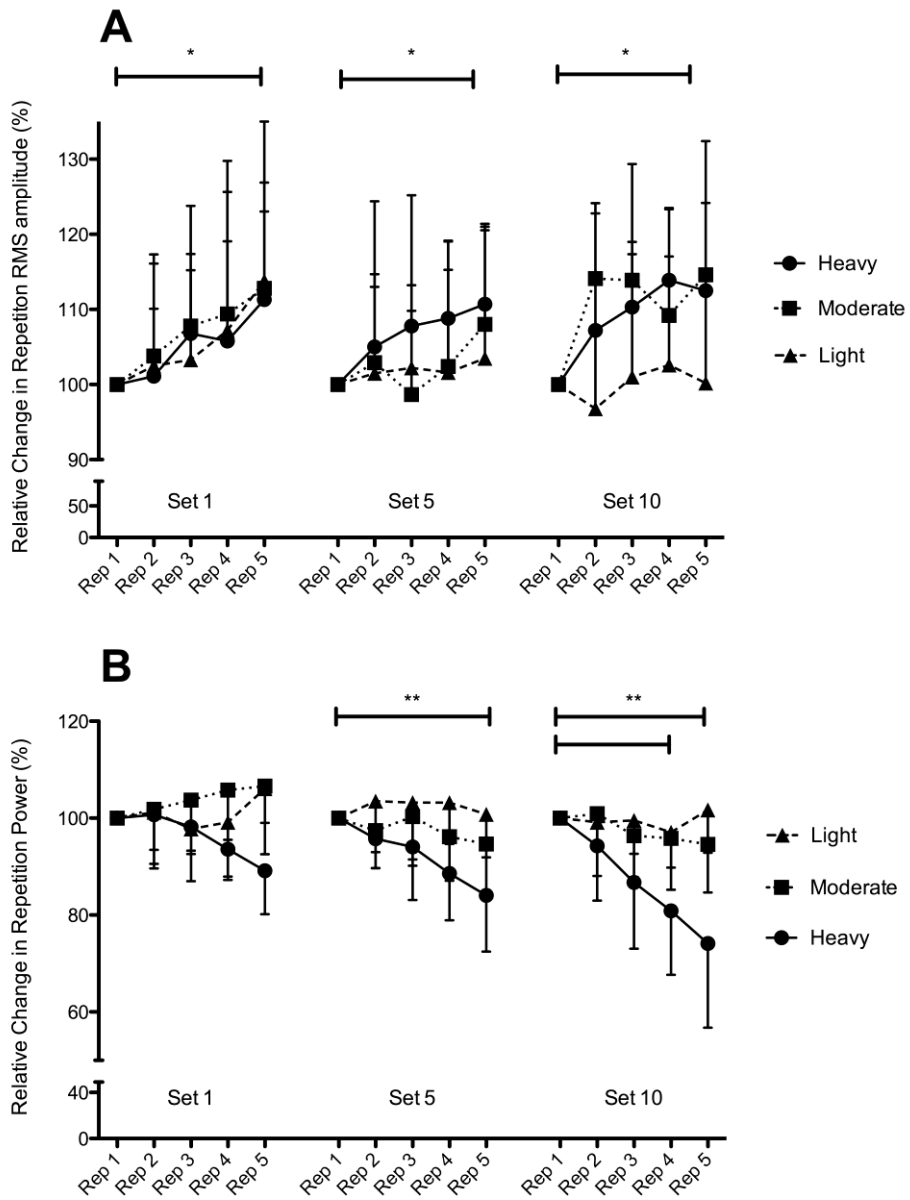
Figure 3 Relative change in A) RFD and B) MVC, expressed relative to pre-session values across heavy, moderate and light sessions, values given as mean \pm SD, n = 10. * Significant difference between post-session values (p<0.01)

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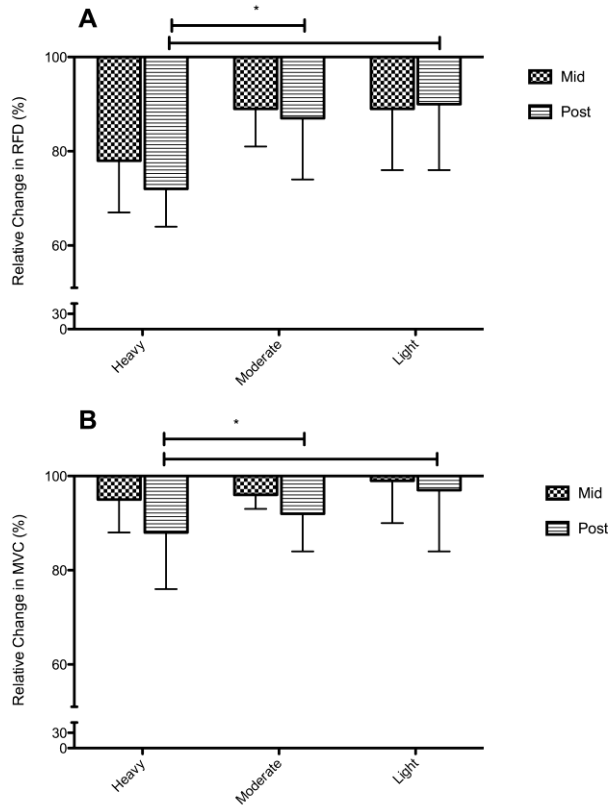


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3 **Figure 1**



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2 **Figure 2**
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3 **Figure 3**