Title: Comparing the Acute Effect of an Isometric and Heavy Resistance Training Session on Neuromuscular Function

Brief Heading: Isometric vs Heavy Resistance Training

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ABSTRACT

Purpose This study compared the acute effects of a session of isometric (ISO) and heavy resistance (HRT) training on 20-m sprint, countermovement jump (CMJ) and isometric mid-thigh pull (IMTP) performance.

Methods Ten resistance trained athletes (age: 26.7±6.2 years, body mass: 71.5±16.2 kg, height: 1.68±0.10 m) performed baseline measures for 20-m sprint, CMJ and IMTP prior to either an ISO or HRT session. During both training sessions, participants performed back squat, Romanian deadlift and split squat. Post-test performances were measured 5 min and 24 h after each training session. Participants return a week later to perform the other training session.

Results A significant time x condition effect for 20-m sprint time (*P*=0.007) and IMTP peak force (*P*=0.003). Main time effect was observed for 20-m sprint (*P*<0.001), CMJ height (*P*<0.001) and IMTP peak force (*P*<0.001). HRT resulted in greater increase in sprint time at 5 min (0.17±0.12 vs 0.06±0.05 s, *P*=0.013, *g*=1.15) and 24 h (0.01±0.09 vs 0.00±0.05 s, *P*=0.004, *g*=1.32) post-training as compared to ISO. Similarly, HRT resulted in significantly larger reduction in IMTP peak force than ISO at both 5 min (-363.3±248.8 vs -98.9±230.3 N, *P*=0.024, *g*=1.06) and 24 h (-289.2±256.2 vs 37.9±177.8 N, *P*=0.004, *g*=1.42) post training. Total impulse generated during each exercise were greater during ISO than HRT (*P*<0.001-0.006). Rating of perceived recovery post 24 h was higher in ISO than HRT (*P*=0.002).

Conclusion The results above indicated that HRT acutely led to greater reduction in sprinting strength performance and lower perceived recovery post 24 h than ISO.

Keywords: Sprint, countermovement jump, isometric mid-thigh pull, strength, recovery.

Introduction

Isometric strength training (ISO) involves the generation of force by the muscle without external movement [22]. This mode of resistance training has been reported to enhance sports related skills performance such as cycling peak power output [19], endurance running [23], jumping [23,25,26], kayaking [24] and sprinting [25,26]. Furthermore, it was reported that improvement in strength was greater when half the volume of dynamic heavy resistance strength training (HRT) was replaced by ISO when compared to performing HRT alone [24,26]. Based on these lines of evidence, ISO is a viable option to be included into athletic training regimens.

Although the positive effects of ISO on athletic performance have been previously reported, the fatiguing effects of incorporating ISO are unclear, which is an important factor to consider in the planning of athletic training programmes. With regard to energy cost, an isometric contraction is lower than isotonic contraction [30,34]; however, the acute change in neuromuscular function post-isometric contractions compared to post-concentric and -eccentric contraction is unclear. For example, Babault et al. [1] reported greater decrement in maximal doublet twitch amplitude after a concentric contraction task as compared to an isometric contraction task. In other studies that included assessment of voluntary muscle contraction, Grosprêtre et al. [13] reported greater reduction in plantar flexion force after elastic band exercise compared to isometric exercise; while Bisson et al. [3] reported no difference in plantar flexion force decrement after isometric and isokinetic plantar flexion tasks. One possible reason for the discrepancy could be due to the lack of eccentric contraction in Bisson et al. [3]'s study during the dynamic condition which was present in Grosprêtre et al. [13]'s protocol. Eccentric contraction is known to induce greater amount of muscle soreness and reduction in force generation capability acutely [12,33,35].

From a practitioner perspective, the current body of evidence is equivocal and importantly has not used training modes (e.g. heavy resistance back squat) and intensities (e.g. >80% of 1 repetition maximum) that are typically employed in athletic strength training environments. Furthermore, the assessment modality lacks relevance to sports movement and hence the translation to athletic performance (such as jumping and sprinting performance) is not clear. Given that exercise induced reductions in function can affect muscle activation and movement kinetics, it also has the potential to reduce the execution of technique, reduce movement efficiency and hence compromising the potential training quality for athletes [2,10,15,16,17,33,37].

The used of velocity-based training has been gaining popularity in recent years [31,32]. This training method involved tracking the bar velocity while performing HRT, and the cessation of each set is determined by a specific velocity loss threshold [31,32]. This method of performing HRT may allow for a more the prescription of individualised training volume of work to optimise adaptations [31,32]. Similarly, the use of multi-joint ISO in athletes' physical preparation has also increased in recent years as studies have reported that the inclusion of ISO as compared to traditional strength training alone may result in greater strength improvement [24-26]. While the chronic effect of both methods on muscular performance has been relatively well studied, the acute effect on neuromuscular function is relatively unknown.

Knowledge of the consequences of different sport specific training modalities can inform practitioners on the magnitude of decline in neuromuscular function and plan the training programme appropriately. Therefore, the aim of this study was to compare the acute effect of ISO and HRT on neuromuscular performance using exercises commonly performed during athletic strength training sessions. It was hypothesised that HRT will result in greater decrement in performance at all time points, as the HRT protocol would include both concentric and eccentric contractions.

Methods

Participants

A convenient sample of eight male and two female resistance trained athletes (age: 26.7 ± 6.2 years, body mass: 69.2 ± 16.2 kg, height: 1.67 ± 0.10 m, squat 1RM: 135.9 ± 41.76 kg) actively participating in various sports including athletics, cycling, squash and powerlifting, were recruited for the study. The athletes participated in the study during the pre-season of their respective sport. Inclusion criteria were: 18-45 years old, at least 2 years of resistance training experience, had prior experience in performing 1RM squat, had a 1RM squat of ≥1.5 times body weight, was free from injury. All participants signed the inform consent and parental consent was sought for participants below the age of 21 years old. Study commenced after obtaining the approval from the institutional review board of the local sport institute.

Experimental Protocol

The study used a counterbalanced, crossover design. Participants were required to attend a familiarisation and four testing sessions including baseline testing, either ISO or HRT, and a follow-up day for post-test. During the familiarisation session, participants' 1 repetition maximum (1RM) squat were determined. Participants were also familiarised with the 20-m sprint, CMJ and isometric mid-thigh pull (IMTP) tests. Participants then returned to the laboratory seven days later to perform the first testing session. During this session, participants performed baseline testing in the following sequence, 20-m sprint, CMJ and IMTP, each separated by 5 min recovery. Participants were then randomly assigned to perform either the

ISO or HRT 10 min after completing the IMTP. Once the ISO or HRT were completed, participants had 5 min of rest before they commenced the post-test measurement ($Post_{5min}$). Participants returned 24 h later to perform the three tests again to examine the level of recovery ($Post_{24h}$). Participants returned for subsequent testing one week later to repeat the same procedure, but performed the other mode of resistance training.

Procedure

Prior to all testing sessions, participants were required to refrain from consuming alcohol and caffeine for non-regular caffeine users, and from participating in strenuous training for 24 h prior to the visit. Participants were asked to avoid the consumption of any food and beverages other than water for 2 h before each testing session. All testing was conducted at similar time between sessions (±1 hour) to avoid diurnal effect. All sessions commenced with 5 minutes of moderate intensity, self-paced jogging on an indoor running track, followed by 10 repetitions of each lower body exercises performed with a 20 kg Olympic barbell including squat, single leg Romanian deadlift, side lunges, calf raise and submaximal CMJ and pogo hops.

1 repetition maximum squat

The squat was performed with participants starting from the upright position with the knees and hips fully extended, and the feet in parallel approximately shoulder-width apart; the barbell resting across the back at the level of the acromion. Participants descend in a continuous motion till the upper thigh was parallel to the ground, then immediately raised back to the upright position. The test was preceded by three warm up sets ranging from 2-10 repetitions and follows the procedure described by Haff & Triplett [14]. The 1RM was determined within 5 attempts to avoid fatiguing effects.

20-m sprint

Participants performed 3 warm-up 20-m sprints at 50%, 70% and 90% of perceived maximum speed followed by a 2 min passive recovery. Participants then performed two trials separated by a 2 min recovery period. Timing gates (Swift Speedlight, Wacol, Australia) were set up at 0- and 20-m. Participants started 0.2 m from the gate to prevent premature triggering of the initial start gate, with a two-point staggered start. The average time obtained for the 2 trials were used for further analysis. If the timing obtained from the second trial was not within 5% of the first, a third trial was performed.

Countermovement jump test

Prior to the test, athletes performed three repetitions of CMJ at 90% of perceived maximal effort. The CMJ was performed on dual force plates (Force Decks, VALD Performance, FD4000, Queensland, Australia) sampling at 1000 Hz. During the CMJ, athletes were asked to keep their arms akimbo to eliminate arm swing and maintain their back upright to reduce angular displacement of the hips. Athletes performed 3 jumps, separated by 30 s rest intervals. Dependent variables included jump height (calculated from velocity of centre of mass at take-off) using the impulse momentum relationship, mean propulsion force (MPF), time to take off (TTO), propulsion phase time (PPT) and countermovement depth. The average value of all three trials will be recorded and analysed.

Isometric mid-thigh pull

The IMTP was performed on the same dual force plates fitted onto a customised rack. Participants were asked to adopt a posture that reflects the start of the second pull of the clean Olympic lifting technique resulting in a knee flexion angle of 125-145^{o} and hip flexion angle of 140-150^{o} stance. The IMTP testing procedure was previously described by Comfort et al.

[8]. Participants performed the IMTP twice, with each attempt separated by a 2 min recovery period. The average peak force generated by the two trials was recorded and analysed. In addition, force at 100, 150 and 200 ms ($Force_{100}$, $Force_{150}$ and $Force_{200}$, respectively) from the onset of pull will be determined for each trial. The onset of pull was based on an increase of >5 standard deviation (SD) of participants body mass [11].

Perceived recovery

Participants were asked to rate their perceived recovery prior to all warm up on all testing sessions and 24 h post-training using the perceived recovery status scale (PRS) [20]. Participants were presented with a continuous 100 mm visual analogue scale with descriptors including ‘‘not at all recovered’’ at 0 mm mark, ‘‘moderately recovered’’ at the 50 mm mark, and ‘‘very well recovered’’ at the 100 mm mark [20].

Perceived rate of exertion (RPE)

Participants were asked to rate their perceived exertion based on the CR-10 RPE scale 5 min after completing each training session [4]. A rating of 0 was associated with no effort and a rating of 10 was associated with maximal effort.

Resistance training

Participants performed three exercises during each training session (Table 1). These exercises were selected as they represent all three fundamental movements, squat, hinge and lunge, of the lower limb [6]. All exercises were performed on the same dual force plate to measure the total impulse produced for each condition as an indication of level of exertion. During the ISO condition, participants performed the back squat at four different knee angles, and Romanian deadlift and split squat at three different knee angles. ISO was performed at multiple joint positions as previous study reported greater improvement in dynamic performance after ISO with multiple joint positions as compared to single joint position [27]. They were required to exert maximal force against a stationary bar as fast as they could for 5 repetitions at each position. Each repetition was sustained for 3 s with 3 s rest in between repetitions, and 2 min rest between sets [23-27]. For the HRT condition, the number of repetitions performed during each set was based on a 20% mean velocity loss from the first repetition of each set. For example, if the participant's attained a 0.5 m.s^{-1} during the first repetition of the back squat, the set ended when the lifting velocity dropped to ≤0.4 m.s^{-1}. This threshold of velocity loss was selected because previous studies reported greater adaptations for strength, power and hypertrophy when a 20% velocity loss threshold was used compared to other velocity loss (0%, 10% and 40%) thresholds [31,32]. Similar to ISO, participants were instructed to perform the concentric phase as fast as they could for each repetition. The range of movement for each exercise during HRT is as follows: back squat – lowered till upper thighs were parallel to ground (~60^{o} knee angle), split squat – lowered till knee angle 70^{o}, Romanian deadlift – lowered till bar was just below patella tendon (~90^{o} hip angle). A linear position transducer (GymAware, Kinetic Performance Technology, Canberra, Australia) was be used to monitor the lifting velocity during HRT. The range of repetitions performed during HRT were as follows: back squat – 3-5, Romanian deadlift – 3-5, split squat – 5-7.

Table 1. Training program for ISO and HRT.

Condition	**Exercise**	**Intensity**	**Sets x Repetitions**
ISO	Isometric squat at 60°, 90°, 120° and 150° knee angle	Maximal voluntary contraction	1 x 5 x 3 s per angle
	Isometric split squat at 70°, 100° and 130° knee angle		
	Isometric Romanian deadlift at 90°, 110° and 130° hip angle		
HRT	Back Squat	85% 1RM	4 x 20% velocity loss threshold
	Split Squat	40% 1RM squat	3 x 20% velocity loss threshold
	Romanian deadlift	95% 1RM squat	

Statistical Analysis

All tested variables are expressed as Mean (±1 SD) and 95% of confidence intervals. Within session test-retest reliability was assessed using two-way mixed intraclass correlation coefficients (ICC) and coefficient of variation (%CV). ICC values were deemed as poor, moderate, good, or excellent if lower bound 95%CI of ICC values were <0.50, 0.50-0.74, 0.75-0.90, or >0.90, respectively [21]. Acceptable within-session variability was classified as <10% [8]. A two-way analysis of variance (ANOVA) with repeated measures and Bonferroni *post-hoc* analysis was used to assess the performance change in all measures. One-way ANOVA analysis was used to compare the absolute change in all variables. All variables were tested for normality and homogeneity of variance using the Shapiro-Wilk test and Levene's test of homogeneity of variance as well as Mauchly's test of sphericity before continuing subsequent statistical analysis. Cohen's d was calculated as standardized effect size for mean comparisons, and deemed a: (i) trivial effect size if *d*<0.20; (ii) small effect size *d*=0.20-0.49 and; (iii) moderate effect size if *d*=0.50-0.80; (iv) large effect size if *d*>0.80 [7].

RESULTS

Reliability

The reliability data for all measured variables are displayed in Table 2. Good to excellent reliability was observed for 20-sprint time and CMJ height, MPF, IMTP peak force, force at 100, 150 and 200 ms. Moderate reliability was observed for CMJ TTO, PPT, countermovement depth and IMTP force at 100 ms. All measured variables had <10% variability.

Table 2. Reliability data.

Variables	ICC	95%CI	%CV	95%CI
20-m sprint time (s)	0.97	0.93 – 0.99	1.3	1.0 – 1.6
CMJ Height (cm)	0.97	0.94 – 0.99	4.3	3.5 – 5.6
CMJ MPF (N)	0.97	0.94 – 0.99	6.0	4.9 – 7.9
CMJ TTO (s)	0.87	0.73 – 0.95	5.3	4.3 – 6.9
CMJ PPT (s)	0.79	0.58 – 0.92	3.9	3.2 – 5.1
CMJ Countermovement Depth (cm)	0.95	0.90 – 0.98	4.0	3.2 – 5.1
IMTP Peak Force (N)	0.97	0.94 – 0.99	4.6	3.7 – 5.9
Force$_{100}$ (N)	0.82	0.64 – 0.93	9.2	7.5 – 12.1
Force$_{150}$ (N)	0.91	0.81 – 0.97	8.3	6.7 – 10.8
Force$_{200}$ (N)	0.96	0.90 – 0.98	5.1	4.2 – 6.7

CMJ = countermovement jump, Force$_{100}$ = force at 100 ms, Force$_{150}$ = force at 150 ms, Force$_{200}$ = force at 200 ms, IMTP = isometric mid-thigh pull, MPF = mean propulsive force PPT = propulsive phase time, TTO = time to take off

20-m sprint performance

Significant time x condition and main time effect was observed for 20-m sprint time (Table 3). However, no main condition effect was observed. Time effects showed significant increase in sprint time between baseline and $Post_{5min}$, and baseline and $Post_{24h}$ for HRT. Significant increase in sprint time was observed between baseline and $Post_{5min}$ only for ISO. HRT resulted in greater increase in sprint time at $Post_{5min}$ (0.17±0.12 vs 0.06±0.05 s, P = 0.013, g = 1.15) and $Post_{24h}$ (0.01±0.09 vs 0.00±0.05 s, P = 0.004, g = 1.32) as compared to ISO (Figure 1)

Table 3. Performance measures of all variables.

Variables	ISO			HRT			Time	Time x Condition	Condition
	Pre	Post$_{5min}$	Post$_{24h}$	Pre	Post$_{5min}$	Post$_{24h}$			
20-m sprint time (s)	3.28 (0.25)	3.35 (0.26)*	3.28 (0.26)	3.27 (0.22)	3.45 (0.26)$^{\$\$}$	3.38 (0.25)$^{\$\$}$	P < 0.001	P = 0.007	P = 0.506
CMJ Height (cm)	38.3 (7.0)	35.4 (6.7)*	37.9 (6.4)$^{\#}$	38.5 (7.3)	32.3 (5.5)$^{\$\$}$	36.0 (6.5)$^{\$\$\Psi}$	P < 0.001	P = 0.066	P = 0.581
CMJ MPF (N)	1496.1 (350.3)	1488.3 (354.1)	1487.6 (353.1)	1472.5 (322.7)	1364.9 (305.1)$^{\$\$}$	1411.4 (304.3)$^{\$\$}$	P < 0.001	P = 0.004	P = 0.621
CMJ TTO (s)	0.693 (0.063)	0.680 (0.066)	0.699 (0.058)	0.726 (0.093)	0.753 (0.117)	0.755 (0.091)$^{\$}$	P = 0.170	P = 0.103	P = 0.151
CMJ PPT (s)	0.244 (0.014)	0.241 (0.022)	0.245 (0.015)	0.248 (0.017)	0.256 (0.020)	0.261 (0.015)$^{\$\$}$	P = 0.068	P = 0.103	P = 0.116
CMJ Countermovement Depth (cm)	30.4 (4.7)	28.8 (4.6)	30.9 (3.2)$^{\#\#}$	31.2 (5.5)	30.2 (5.3)	31.6 (5.2)$^{\Psi\Psi}$	P = 0.001	P = 0.795	P = 0.647
IMTP Peak Force (N)	2629.5 (569.5)	2530.6 (518.1)	2667.4 (583.8)$^{\#\#}$	2677.85 (621.4)	2314.6 (527.0)$^{\$\$}$	2388.7 (509.5)$^{\$\$}$	P < 0.001	P = 0.003	P = 0.576
Force$_{100}$ (N)	1259.8 (285.7)	1206.7 (243.2)	1239.0 (286.9)	1272.35 (292.9)	1128.9 (238.7)$^{\$}$	1211.6 (272.0)$^{\$}$	P = 0.011	P = 0.348	P = 0.793
Force$_{150}$ (N)	1761.75 (444.3)	1660.1 (492.3.0)	1720.4 (540.9)	1783.1 (421.4)	1496.8 (386.0)$^{\$\$}$	1567.1 (402.0)$^{\$\$}$	P = 0.002	P = 0.100	P = 0.594
Force$_{200}$ (N)	2111.8 (477.7)	1947.0 (451.1)	2003.8 (505.6)	2104.7 (486.8)	1844.8 (470.1)$^{\$\$}$	1895.3 (416.0)$^{\$\$}$	P < 0.001	P = 0.658	P = 0.774

*Denotes significant difference from ISO Pre (P < 0.05)

**Denotes significant difference from ISO Pre (P < 0.01)

$^{\#}$Denotes significant difference from ISO Post$_{5min}$ (P < 0.05)

$^{\#\#}$Denotes significant difference from ISO Post$_{5min}$ (P < 0.01)

$^{\$}$Denotes significant difference from HRT Pre (P < 0.05)

$^{\$\$}$Denotes significant difference from HRT Pre (P < 0.01)

$^{\Psi}$Denotes significant difference from HRT Post$_{5min}$ (P < 0.05)

$^{\Psi\Psi}$Denotes significant difference from HRT Post$_{5min}$ (P < 0.01)

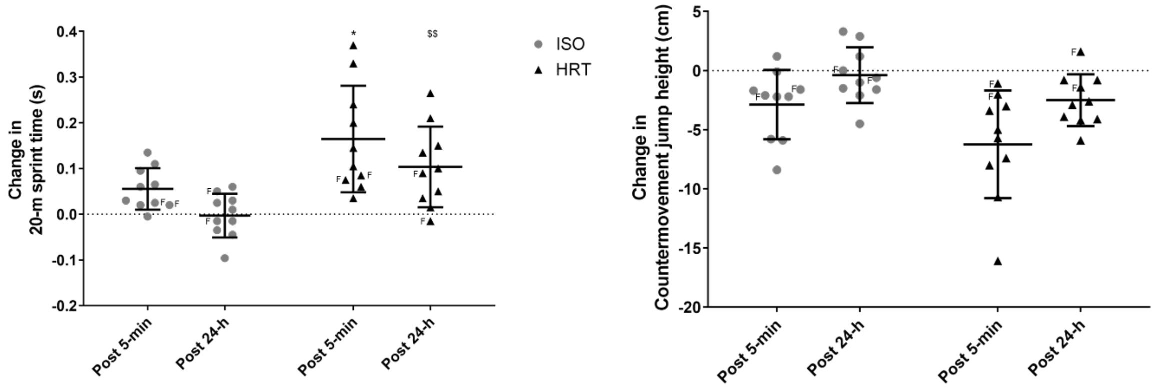

Figure 1. Change in 20m sprint and countermovement jump height.
[*]Denotes significantly different from ISO Post5min (P<0.05).
[$$]Denotes signi ficantly different from ISO Post24h (P<0.01).
[F]Denotes female participant.

Countermovement jump performance

Significant main time effect was observed for CMJ height, MPF, and countermovement depth (Table 3). Significant time x condition effect was observed for MPF only, while no main condition effect was observed for all CMJ measures. For CMJ height, simple time effect showed decrease at $Post_{5min}$ and $Post_{24h}$ from baseline, and increase at $Post_{24h}$ from $Post_{5min}$ for HRT. A decrease in jump height at $Post_{5min}$ from baseline, and increase at $Post_{24h}$ from $Post_{5min}$ was observed for ISO. Baseline measures for MPF was lower at $Post_{5min}$ and $Post_{24h}$ as compared to baseline for HRT but not for ISO. There were increases in TTO at $Post_{24h}$ and PPT at $Post_{24h}$ from baseline for HRT. Countermovement depth was higher at $Post_{24h}$ than at $Post_{5min}$ for both ISO and HRT. When change in jump height was compared, there were large but insignificant difference between HRT and ISO at $Post_{5min}$ (-6.2±4.6 vs -2.9±2.9 cm, P = 0.065, g = 0.83) and $Post_{24h}$ (-2.5±2.2 vs -0.4±2.4 cm, P = 0.053, g = 0.87) (Figure 1).

Isometric mid-thigh pull performance

Significant time x condition effect was observed for peak force, while significant main time effect was observed for all IMTP measures (Table 3). No main condition effect was observed. Simple time effect for peak force showed decrease at $Post_{5min}$ and $Post_{24h}$ from baseline in HRT. While no decrease in peak force from baseline to $Post_{5min}$ was observed in ISO, there was an increase in peak force at $Post_{24h}$ from $Post_{5min}$. $Force_{100}$ was decreased at $Post_{5min}$ and $Post_{24h}$ from baseline in HRT. $Force_{150}$ was also decreased at $Post_{5min}$ and $Post_{24h}$ from baseline in HRT. Similarly, $Force_{200}$ was decreased at $Post_{5min}$ and $Post_{24h}$ from baseline in HRT. No change in early force development at all time points was observed in ISO. When comparing the change in peak force, HRT resulted in greater reduction than ISO at both $Post_{5min}$ (-363.3±248.8 vs -98.9±230.3 N, P = 0.024, g = 1.06) and 24 h (-289.2±256.2 vs 37.9±177.8 N, P = 0.004, g = 1.42) (Figure 2). There was no significant difference in the change for $Force_{100}$, $Force_{150}$ and $Force_{200}$ between conditions at all time points (P = 0.078 to 0.806, g = 0.11 to 0.80).

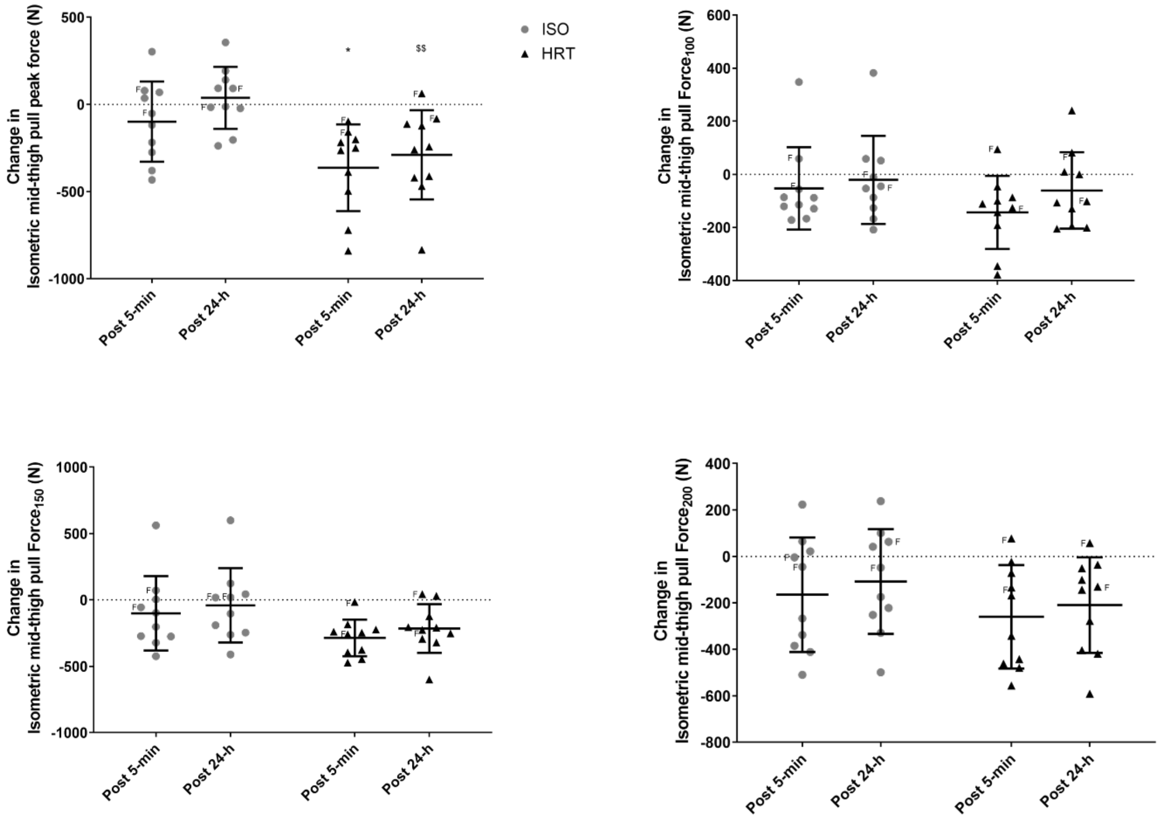

Figure 2. Change in isometric mid-thigh pull measures.
*Denotes significantly different from ISO Post5min (P<0.05).
$$Denotes significantly different from ISO Post24h (P<0.01).
FDenotes female participant.

Impulse

Impulse produced during ISO and HRT are displayed in Table 4. The results showed that impulse produced for all exercises were significantly higher during ISO than HRT.

Table 4. Measures for training effort and perceived recovery.

Variables	**ISO**	**HRT**	***P***	***g***
Squat Impulse (N.s)	125365.0 (42560.3)	76959.4 (24734.3)**	0.006	1.33
Romanian Deadlift Impulse (N.s)	102179.4 (12384.7)	60519.2 (22109.0)**	< 0.001	2.23
Split Squat Impulse (N.s)	108925.5 (19013.1)	62475.6 (19767.6)**	< 0.001	2.29
Rating of Perceived Exertion	6.9 (1.5)	7.6 (1.1)	0.206	0.51
Rating of Perceived Recovery (Pre) (mm)	75 (14)	80 (12)	0.402	0.37
Rating of Perceived Recovery (Post) (mm)	62 (12)	41 (13)**	0.002	1.61

**Denotes significant difference from ISO(P < 0.01)

Rating of perceived exertion and recovery

There was no significant difference in RPE between conditions (Table 4). Similarly, there was no difference in $PRS_{baseline}$ between conditions. However, PRS_{post24} was significantly higher in ISO than HRT.

Discussion

The purpose of the study was to compare the acute effect of ISO and HRT on neuromuscular performance using exercises commonly performed during athletic strength training sessions. The current findings showed that HRT resulted in greater decrease in performance for 20-m sprint and IMTP at both $Post_{5min}$ and $Post_{24h}$ than ISO. In addition, while no difference in the level of perceived exertion was observed between conditions, HRT resulted in a lower rating for perceived recovery despite exerting lower impulse during the training session. Based on these findings, our hypothesis was supported.

To overcome the limitations of previous studies, the current study used ISO and HRT methods that have been shown to induce adaptations that would benefit strength and sports performance [23-27,31,32]. Specifically, the ISO protocol used in this study was reported to benefit both strength and dynamic performance [23-27]. Furthermore, the inclusion of ISO resulted in greater improvement in both strength and dynamic performance than traditional strength training alone over a 24-week period [26]. The current results showed that ISO did not lead to changes in all IMTP measures at both $Post_{5min}$ and $Post_{24h}$. However, HRT resulted in significant decrease in IMTP peak force and all early force development measures at both time points. Furthermore, the decrease in peak force at both time points was significantly larger after HRT than ISO, indicating a greater fatigue effect after HRT. This was despite a greater amount of total impulse produced by ISO. One possible reason for the greater impairment in strength performance after HRT could be due to the heavy eccentric loading, which is known to induce greater levels of muscle soreness than other modes of muscle contraction [12,33,35]. For example, Raeder et al. [33] reported that the eccentric overload training protocol resulted in the greatest decrease in maximal voluntary isometric contraction $Post_{5min}$ and $Post_{24h}$ compared to other resistance training protocol. The higher level of soreness after HRT, as reflected by the lower PRS, possibly resulted in lower force generation capability [35]. Results of previous studies that used similar HRT protocol also showed impaired strength performance 24 h after training, which was attributed to both central and peripheral fatigue [15,18,36]. It was also indicated that HRT might require up to 72 h for neuromuscular function to recover fully [36]. It is, however, not possible to comment on the mechanism for the decrease in strength performance after HRT in this study as no specific assessment was performed to investigate this factor. In contrast to HRT, and to the best of knowledge, no study was conducted to investigate the acute neuromuscular effect of ISO using a protocol similar to the current one. Notwithstanding, Grospretre et al. [13] reported that the decrease in maximal force of the plantar flexor after 120 s of intermittent maximal intensity isometric plantar flexion, was due to central fatigue. Given that no decrease in peak force was observed in ISO, it seems that the recovery period was sufficient for the participants to recover near to baseline from the fatigue induced by the ISO protocol.

While peak force is a common measure used to indicate levels of fatigue, it has been suggested that rate at which force is developed is more sensitive to fatigue [5,38]. In the current study, significant decrease in early force development at 100, 150 and 200 ms were observed in HRT only. However, unlike peak force, change in early force development showed no significant difference between conditions. In addition, while peak force was increased by ~2.4% at $Post_{24h}$ from baseline for ISO, early force development remained negative (-1.1 to -5.7%). Although this decrease in early force development in ISO was not statistically different from baseline, it does provide some support to the claim that rate of force development is a more sensitive measure to indicate neuromuscular fatigue. The current results for ISO also differed from Buckthorpe et al. [5] which showed a decrease in early force development after performing ISO of a similar intensity and volume. One possible reason for this discrepancy could be because the current ISO protocol involved several compound exercises which allowed for distribution of load to different muscles, while the protocol by Buckthorpe et al. [5] involved only one single joint exercise concentrating on a single muscle. With the same intensity and volume of contraction performed by a single muscle, the protocol by Buckthorpe et al. [5] would conceptually result in greater levels of fatigue compared to the current protocol. Nevertheless, the current findings indicate that HRT as compared to ISO, resulted in greater decrease in strength performance for 24 h. Hence, athletes and coaches should be aware that activity that requires high force or rate of force development can be impaired for at least 24 h post HRT, while minimal change occur following ISO.

Findings from previous studies that investigated the acute effect of HRT on CMJ performance have shown conflicting results, with some showing no change [17,37], while others showing a decrease in CMJ height and other performance measures [15,16,33]. This discrepancy is likely due to the difference in training protocol adopted by the different studies. Based on the findings of Helland et al. [15] and Raeder et al. [33], CMJ height decreased by 4.5-8.2 cm at $Post_{5min}$ and 3.2-3.7 cm at $Post_{24h}$. These results were comparable to the current findings for HRT. In addition to the decrease in jump height, Helland et al. [15] also reported significant decrease in rate of force development, concentric and eccentric force during CMJ. The decrease in ability to generate force rapidly over the propulsion phase was considered the cause for the decrease in jump height [15]. Similarly, the current results showed decreases in MPF and greater TTO and PPT. These findings also indicate that the reason for the decrease in jump height in the current study was similar to others [15]. In addition, the decrease in CMJ MPF was in concurrent with the decrease in IMTP measures. This reflects the importance of the ability to generate high force and rapid force in jump performance. While CMJ height was decreased $Post_{5min}$ and $Post_{24h}$ in HRT, it was only decreased at $Post_{5min}$ in ISO. In contrast to HRT whereby jump height was likely due to the inability to generate sufficient propulsive force, there was no other change in CMJ variables that accompanied the drop in jump height for ISO. Hence, the change in jump height was likely due to the accumulated effect of the insignificant changes to MPF and PPT which resulted in decreased propulsive impulse that was sufficient to cause a change in jump height.

Sprint ability is an important physical attribute for the performance of many sports. The ability to perform well during the acceleration phase of sprinting involves being able to produce propulsive force rapidly within a short (<150 ms) amount of time [28]. Therefore, similar to CMJ, reduction in force generation capability would likely result in a decrease in performance [29]. Indeed, Morin et al. [29] reported a reduction in horizontal and total force, and technical ability to apply force when performing 6 s sprints in a fatigued state. To the knowledge of the authors, only Helland et al. [15] had investigated the effects of a HRT session on sprint acceleration performance. The authors reported an increase in sprint time $Post_{5min}$ and $Post_{24h}$ [15]. Although the study did not measure sprint specific performance variables, the concurrent decrease in jump height and squat peak power indicated that the reduced force generation capability was likely the reason for the increased sprint time. Similarly, the current findings showed an increase in sprint time $Post_{5min}$ and $Post_{24h}$ in the HRT condition. This was also associated with decreased CMJ height and IMTP peak force and early force development. In the ISO condition, sprint time was only increased $Post_{5min}$, which was similar to the finding for CMJ height. In addition, the change in sprint time also showed greater performance decrement after HRT than ISO at both $Post_{5min}$ and $Post_{24h}$. This further indicates that participants had greater neuromuscular fatigue after HRT than ISO and were able to recover faster from ISO than HRT. In view of this, coaches should avoid planning activities that include high intensity ballistic movement into the training program within 24 h of HRT as performance will likely be compromised. Instead, where high intensity ballistic movements might be required in the following day, ISO provides a viable alternative to reduce the possibility of a compromised performance.

Several limitations should be taken note while interpreting the current findings. Firstly, the results of the study may not be generalised to elite high-performance athletes due to the participants recruited in the study. Secondly, it has been previously reported that females may have greater resistance to fatigue as compared to males [18]. The current study was not able to perform such analysis due to the low number of female participants. Finally, it was not possible to match the volume and intensity of HRT and ISO due to the different modes of muscle contraction. Hence, the study adopted a well-established protocol for each mode of contraction for the purpose of optimising strength adaptations to increase the ecological validity of the study.

Conclusion

The current results showed that decreased in sprint, jump and strength performance persists after 24 h post cessation of training in HRT but not ISO. This was despite the greater amounts of total impulse generated during ISO. In view of this, it is recommended that sports coaches should plan for a low to moderate intensity sport training session that does not require athletes to exert high and rapid force within 24 h post-HRT. However, if coaches have to include a strength training session within a 24 h period prior to a high intensity sports training, they have the option of selecting ISO. In addition, coaches may plan to substitute a session of HRT with ISO in the weekly program or replace part of the HRT exercises with ISO exercises within a session, to reduce athletes' level of fatigue. Furthermore, ISO may also be planned into the program in the later phase of the training cycle to minimise fatigue, injury risk while still maintaining maximum strength.

Conflict of Interest

The authors declare that there is no conflict of interest.

Availability of data and material

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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