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ARTICLE

Multimodal high-intensity interval training increases muscle function and metabolic performance in females

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Abstract: High-intensity interval training (HIIT) is a time-efficient method of improving aerobic and anaerobic power and capacity. In most individuals, however, HIIT using modalities such as cycling, running, and rowing does not typically result in increased muscle strength, power, or endurance. The purpose of this study is to compare the physiological outcomes of traditional HIIT using rowing (Row-HIIT) with a novel multimodal HIIT (MM-HIIT) circuit incorporating multiple modalities, including strength exercises, within an interval. Twenty-eight recreationally active women (age 24.7 ± 5.4 years) completed 6 weeks of either Row-HIIT or MM-HIIT and were tested on multiple fitness parameters. MM-HIIT and Row-HIIT resulted in similar improvements ($p < 0.05$ for post hoc pre- vs. post-training increases for each group) in maximal aerobic power (7% vs. 5%), anaerobic threshold (13% vs. 12%), respiratory compensation threshold (7% vs. 5%), anaerobic power (15% vs. 12%), and anaerobic capacity (18% vs. 14%). The MM-HIIT group had significant ($p < 0.01$ for all) increases in squat (39%), press (27%), and deadlift (18%) strength, broad jump distance (6%), and squat endurance (280%), whereas the Row-HIIT group had no increase in any muscle performance variable (p values 0.33–0.90). Post-training, 1-repetition maximum (1RM) squat (64.2 ± 13.6 vs. 45.8 ± 16.2 kg, $p = 0.02$), 1RM press (33.2 ± 3.8 vs. 26.0 ± 9.6 kg, $p = 0.01$), and squat endurance (23.9 ± 12.3 vs. 10.2 ± 5.6 reps, $p < 0.01$) were greater in the MM-HIIT group than in the Row-HIIT group. MM-HIIT resulted in similar aerobic and anaerobic adaptations but greater muscle performance increases than Row-HIIT in recreationally active women.

Key words: sprint interval training, intermittent training, strength training, aerobic power, HIIT, multimodal, rowing.

Résumé : L'entraînement par intervalle d'intensité élevée (« HIIT ») est une méthode efficace pour gagner du temps afin d'améliorer la puissance et les capacités anaérobie et aérobie. Toutefois, chez la plupart des individus, l'HIIT soit à vélo, à la course et à l'aviron ne suscite pas systématiquement une augmentation de la force musculaire, de la puissance et de l'endurance. Cette étude se propose de comparer les adaptations physiologiques enregistrées à la suite de l'HIIT classique à l'aviron (« Row-HIIT ») à celles d'une nouvelle approche multimodale (« MM-HIIT ») comprenant des exercices de force au sein d'un intervalle. Vingt-huit femmes (24,7 ± 5,4 ans) actives par loisir participent à six semaines de Row-HIIT ou de MM-HIIT et sont évaluées sur plusieurs aspects de la condition physique. MM-HIIT suscite des améliorations semblables à Row-HIIT ($p < 0,05$, pré et post entraînement) dans les deux groupes en ce qui concerne les variables suivantes : puissance maximale aérobie (7 vs 5 %), seuil anaérobie (13 vs 12 %), seuil de compensation ventilatoire (7 vs 5 %), puissance anaérobie (15 vs 12 %) et capacité anaérobie (18 vs 14 %, respectivement). Le groupe MM-HIIT présente des différences significatives ($p < 0,01$ dans tous les cas) en ce qui concerne l'amélioration de la force à l'accroupissement (39 %), au développé (27 %) et au soulevé de terre (18 %), au saut en longueur (6 %) et à l'endurance à l'accroupissement (280 %); le groupe Row-HIIT ne présente aucune amélioration de toutes les variables de performance musculaire (p variant de 0,33 à 0,90). Après la période d'entraînement, MM-HIIT suscite par rapport à Row-HIIT des plus hautes valeurs de 1RM à l'accroupissement (64,2 ± 13,6 vs 45,8 ± 16,2 kg, $p = 0,02$), au développé (33,2 ± 3,8 vs 26,0 ± 9,6 kg, $p = 0,01$) et à l'endurance à l'accroupissement (23,9 ± 12,3 vs 10,2 ± 5,6 répétitions, $p < 0,01$, respectivement). MM-HIIT suscite chez des femmes actives par loisir des adaptations similaires en aérobie et en anaérobie, mais de meilleures performances musculaires par rapport à Row-HIIT. [Traduit par la Rédaction]

Mots-clés : entraînement par intervalle de sprint, entraînement intermittent, entraînement à la force, puissance aérobie, HIIT, multimodal, aviron.

Introduction

High-intensity interval training (HIIT) consists of repeated execution of high-intensity exercise interspersed with recovery periods of low-intensity exercise or complete rest (Laursen 2010). HIIT has been shown to increase aerobic and anaerobic performance within a short time period (Bayati et al. 2011; Hazell et al. 2010; Ziemann et al. 2011). HIIT results in physiological benefits including improvements in aerobic capacity, cardiorespiratory fitness, glucose tolerance, exercise endurance, skeletal muscle oxidative capacity, and glycogen content and reductions in the rate of lactate production and glycogen utilization (Gibala et al. 2012; Nybo et al. 2010; Weston et al. 2014). Nybo et al. (2010) reported that HIIT resulted in a significant reduction in arterial blood pressure and superior improvements in cardiorespiratory fitness, as indicated by increases in maximal aerobic power ($\dot{V}O_{2max}$), compared with traditional prolonged training.

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Despite the evidence supporting metabolic adaptations with HIIT, there is less evidence regarding the muscle strength benefits of HIIT. It is well known that strength training induces muscle hypertrophy and strength increases (Nybo et al. 2010). Skeletal muscle strength has been shown to be an important determinant of functional capacity (Verdijk et al. 2009). Typically, HIIT does not have a significant long-term impact on muscle mass or indicators of skeletal health (Astorino et al. 2012; Nybo et al. 2010). Thus, the addition of a strength training program to a HIIT program would be required to optimize muscle function, but excessive time would be needed to complete both aspects of training (Astorino et al. 2012).

One potential solution that has emerged to reduce the time required for multiple adaptations is multimodal (MM) training. MM training uses a variety of resistance, body-weight, and (or) traditional conditioning modalities (e.g., sprinting, rowing, kettlebell swings, battle ropes) performed in either a continuous circuit (Myers et al. 2015) or an interval (McRae et al. 2012) format. While the continuous circuit methodology uses multiple modalities within a single session, previous work with interval-style MM training has limited individual sessions to a single body-weight modality (McRae et al. 2012) and rotated modalities between sessions. While this format is effective for inducing aerobic, anaerobic, and muscle endurance adaptations (McRae et al. 2012), the lack of a whole-body strength component within each interval may limit the muscle performance adaptations.

In this study, we examined a novel multimodal HIIT (MM-HIIT) protocol that incorporates resistance and conditioning modalities within the work interval to combine multiple training effects while minimizing training time. This form of training is common in many fitness facilities but has not undergone scientific investigation. The purpose of this study was to document the physiological benefits of an MM-HIIT program compared with HIIT using a more traditional aerobic modality (rowing). First, we hypothesized that MM-HIIT and traditional HIIT using rowing (Row-HIIT) would lead to similar improvements in aerobic and anaerobic energy systems. Our second hypothesis was that the MM-HIIT group would improve to a greater degree in strength, muscle power, and muscle endurance compared with the Row-HIIT group.

Materials and methods

Study design

A prospective longitudinal group-randomized trial was conducted. Participants were grouped using convenience assignment based on their availability for training, and each group was then randomly assigned to complete either the Row-HIIT or the MM-HIIT training program. On day 1, all participants underwent screening and initial testing by a physical therapist, which consisted of a medical history, baseline blood pressure, height and weight, and a treadmill $\dot{V}O_{2max}$ test. Following screening, participants engaged in 3 familiarization, practice, and adaptation sessions for the movements to be used during training and testing. Familiarization was followed by 3 field testing sessions conducted during week 2. Participants then underwent 6 weeks of group training 3 times a week. Post-training testing was then performed on the same measures as the pre-training tests. For the full testing, familiarization, and training program schedules, see Tables S1 and S2[1]. Individual participant attendance was recorded and data were accepted if participants achieved greater than 80% attendance. Test evaluators were blinded to the group randomization.

Participants

Thirty-two recreationally active women between the ages of 18 and 35 were recruited and gave consent to participate in the study, which was approved by the local institutional ethics review board. Recreationally active was defined as engaging in periodic physical activity or exercise between 1 and 3 h weekly for 1 month or longer. Participants were not engaging in systematic endurance or weight training. Study participants were instructed to stay consistent with their levels of exercise activity prior to the study and to not progress these activities. Participants were excluded if they reported any acute or chronic cardiovascular, metabolic, respiratory, or other conditions that would have prevented them from participating in heavy exercise. In addition, if adverse findings were recorded during screening that would have been associated with an increased risk of injury during exercise, participants were excluded from the study. Sixteen participants were assigned to each training group at baseline. Three participants (2 from the Row-HIIT group and 1 from the MM-HIIT group) withdrew consent prior to initiation of the training phase. One participant in the MM-HIIT group dropped out of the study owing to an injury obtained outside of the study. There were no other dropouts for any reason. Thus, 14 participants in each group completed the study (Table 1).

Tests and measures

$\dot{V}O_{2max}$ test

$\dot{V}O_{2max}$ was assessed using a customized graded treadmill protocol. Participants completed a 3-min warm-up at 3.5 km × h^{-1} and 1% grade on a treadmill (TrackMaster TMX425C, Full Vision, Newton, Kans., USA), which was followed by incremental 1-min stages. In the initial stages, speed was progressed by 1 km × h^{-1} every minute and the grade was held constant at 1% until participants indicated they had reached a pace slightly greater than their subjectively determined sustainable running speed. At this point, the speed was held constant and the grade was increased by 2% per minute until voluntary exhaustion. Heart rate was measured continuously with a chest strap (Polar Electro Canada, Lachine, Que., Canada). Ventilatory gases were measured and analysed with a commercial metabolic measurement system (TrueOne 2400, ParvoMedics, East Sandy, Utah, USA). Rating of perceived exertion (RPE) was recorded every 2 min and at peak exercise using the 10-point Borg scale (Noble et al. 1983). $\dot{V}O_{2max}$ was considered to be obtained if 2 of the following criteria were met: (1) heart rate ≥ 90% of the predicted maximum (220 − age), (2) respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) ≥ 1.10, and (3) RPE ≥ 9/10. Data were reported in 20-s averages.

In addition to aerobic power, the anaerobic threshold (AT) and respiratory compensation threshold (RCT) were determined by analysis of ventilatory gases. AT was defined as the breakpoint in the ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}O_2$) while $\dot{V}_E/\dot{V}CO_2$ had plateaued and the respiratory exchange ratio was between 0.98 and 1.02. RCT was defined as the subsequent breakpoint in $\dot{V}_E/\dot{V}CO_2$ (Simon et al. 1983).

Wingate Anaerobic Test

Anaerobic power and capacity were determined by a 30-s Wingate Anaerobic Test as per standard protocol (Bar-Or 1987). A Monark 894E cycle ergometer was used and the resistance was set at 0.075 kg × kg^{-1} body mass. The test was preceded by a practice drop for 3 s at 0.03 kg × kg^{-1} body mass and a 1-min rest period. Power was calculated using standard Monark Anaerobic Test software. Anaerobic power was determined to be the highest 5-s mean power. Anaerobic capacity was determined to be the mean power over the entire 30 s.

Muscle strength

On separate days, muscle strength was assessed using 1-repetition maximum (1RM) testing for back squat, press, and deadlift using standardized protocols (Baechle and Earle 2008). The back squat

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/apnm-2015-0238.

Table 1. Participant characteristics.

	Row-HIIT	MM-HIIT
Age (years)	24.3±5.2	25.1±5.6
Gender	Female (n = 14)	Female (n = 14)
Height (cm)	171.6±7.6	166±2.4
Weight (kg)		
Pre	73.2±11.9	66.6±9.8
Post	73.6±11.9	67.6±10.2

Note: Row-HIIT, high-intensity interval training using rowing; MM-HIIT, multimodal high-intensity interval training.

Table 2. Maximal aerobic power ($\dot{V}O_2$max) and Wingate anaerobic test data.

	Row-HIIT		MM-HIIT	
	Pre	Post	Pre	Post
$\dot{V}O_2$max (mL·kg^{-1}·min^{-1})	36.7±4.7	38.3±4.6*	36.2±5.7	38.5±5.4*
$\dot{V}O_2$ at RCT (mL·kg^{-1}·min^{-1})	33.9±4.7	35.5±4.7	31.1±5.7	33.2±5.6*
$\dot{V}O_2$ at AT (mL·kg^{-1}·min^{-1})	28.7±5.0	31.7±3.8*	27.2±6.7	29.7±5.7*
Anaerobic power (W)	481±135	536±133*	424±93	484±94*
Anaerobic capacity (W)	371±104	417±100*	333±62	389±69*

Note: RCT, respiratory compensation threshold; AT, anaerobic threshold. *p < 0.05 vs. pre-training value. There were no between-group differences.

was performed to below parallel (hip crease below the apex of the patella), the press was initiated with the bar on the clavicles, and the deadlift was performed in the conventional stance.

Muscle endurance and power

Muscle endurance was assessed by repetitive back squats to voluntary exhaustion. The load was set at 70% of the pre-training 1RM back squat for both pre- and post-training tests. Movement standards were the same as those for the 1RM test, and the total number of successful repetitions achieved without a rest was recorded. Muscle power was assessed using a static broad jump. The best horizontal distance achieved out of 3 trials was recorded.

Training program

During the 6-week training program, participants attended group training sessions for 60 min 3 times a week. The 60-min training period was broken down into 20 min of active warm-up, 24 min of training, and 16 min of cooldown. Both the Row-HIIT and MM-HIIT groups were given the same instructions to perform at all-out intensity every interval (i.e., achieve an RPE of 9/10 or 10/10 for each interval).

Rowing (Row-HIIT)

Participants randomized into the Row-HIIT group performed 60 s of all-out intensity rowing followed by 3 min of rest (passive recovery) for a total of 6 rounds. Participants were instructed to engage in all-out intensity during the work period to achieve maximum distance on each interval.

MM-HIIT

Participants randomized into the MM-HIIT group also performed 60 s of all-out intensity work followed by a 3-min rest for 6 rounds. Each MM-HIIT interval was broken down into 3 parts: a strength exercise for 4–6 repetitions, an accessory movement for 8–10 repetitions, and a metabolic component conducted all out for the remainder of the 60 s. For the strength exercise and accessory movement, participants were instructed to load "heavy", with the purpose of fatiguing by the end of the intervals. For example, for the strength exercise, a "heavy" load was defined as the 4–6 repetition maximum; if participants were able to sustain 6 repetitions across all 6 intervals, the load would be progressed in the next session using the same exercise. Participants were instructed to engage in all-out intensity during every interval. Please see Table S2[1] for more information.

Statistical analysis

Statistica V8.0 (StatSoft Inc., Tulsa, Okla., USA) was used to analyse the data. Means and standard deviations were reported for each descriptive variable. A 2-way, repeated-measures factorial ANOVA was used to analyse the main effects for each of the main outcomes ($\dot{V}O_{2max}$ test, Wingate test, and muscle strength/power/endurance tests). Where significant main effects were observed, Tukey's post hoc analysis was performed to determine specific differences. Percent attendance was compared between groups using an unpaired t test. Alpha was set a priori to 0.05.

Results

Attendance

All participants who completed the study performed greater than 80% of the training sessions. There was no difference in attendance between groups (89% ± 5% and 91% ± 6% for MM-HIIT and Row-HIIT, respectively; p = 0.69).

$\dot{V}O_{2max}$ test

All participants achieved the criteria for attaining $\dot{V}O_{2max}$ and reached tolerance at 8:13 ± 0:44 min:sec for the pre-training test and 10:36 ± 1:21 min:sec for the post-training test. There were no interaction effects for the $\dot{V}O_2$ values at maximum, AT, or RCT. There was a significant main effect of time, but not group, for each of $\dot{V}O_{2max}$ (p < 0.01), $\dot{V}O_2$ at AT (p < 0.01), and $\dot{V}O_2$ at RCT (p < 0.01). Table 2 shows the individual group data and indicates that there were increases in $\dot{V}O_{2max}$ and $\dot{V}O_2$ at AT for both groups, whereas $\dot{V}O_2$ at RCT increased only in the MM-HIIT group. There were no significant post-training differences between groups for $\dot{V}O_{2max}$ (p = 0.99), $\dot{V}O_2$ at AT (p = 0.09), or $\dot{V}O_2$ at RCT (p = 0.08).

Wingate test

There were no interaction effects for anaerobic power or capacity. There were significant main effects for time, but not group, for both anaerobic power (p < 0.01) and capacity (p < 0.01). As shown in Table 2, there were significant increases in anaerobic power and capacity for both groups, but there were no post-training differences between the Row-HIIT and MM-HIIT groups for anaerobic power (p = 0.643) or capacity (p = 0.825).

Strength

There were significant interaction effects for 1RM squat (p < 0.01) and 1RM press (p < 0.01). There were also significant main effects for time in squat, press, and deadlift (p < 0.01) and for group in squat and press (p < 0.01). Post hoc analysis revealed that the MM-HIIT group increased strength in the squat (p < 0.01), press (p < 0.01), and deadlift (p < 0.01), whereas the Row-HIIT group did not (Fig. 1; p = 0.69, 0.82, and 0.33, respectively). There were significant post-training differences between groups for the 1RM squat (p = 0.02) and the 1RM press (p = 0.01) but not the 1RM deadlift (p = 0.99).

Muscle power and endurance

There was a significant interaction for squat endurance (p < 0.01). There were significant main effects for time for both the broad jump test (p < 0.01) and the squat endurance test (p < 0.01). Figure 2 shows that the MM-HIIT group increased distance achieved in the broad jump (Fig. 2A; p < 0.01) and the number of reps completed on the squat endurance test (Fig. 2B; p < 0.01), whereas the Row-HIIT group did not (p = 0.90 and 0.88, respectively). Post hoc testing revealed there was a significant difference in post-training values between groups for the squat endurance test (p < 0.01) but not the broad jump (p = 0.99).

Fig. 1. Muscle strength test data for (A) 1-repetition maximum (1RM) squat, (B) 1RM press, and (c) 1RM deadlift for the multimodal high-intensity interval training (MM-HIIT) and traditional HIIT with rowing (Row-HIIT) groups. *Significantly different than the corresponding pre-training value, $p < 0.05$; †significantly different than post-training for Row-HIIT, $p < 0.05$.

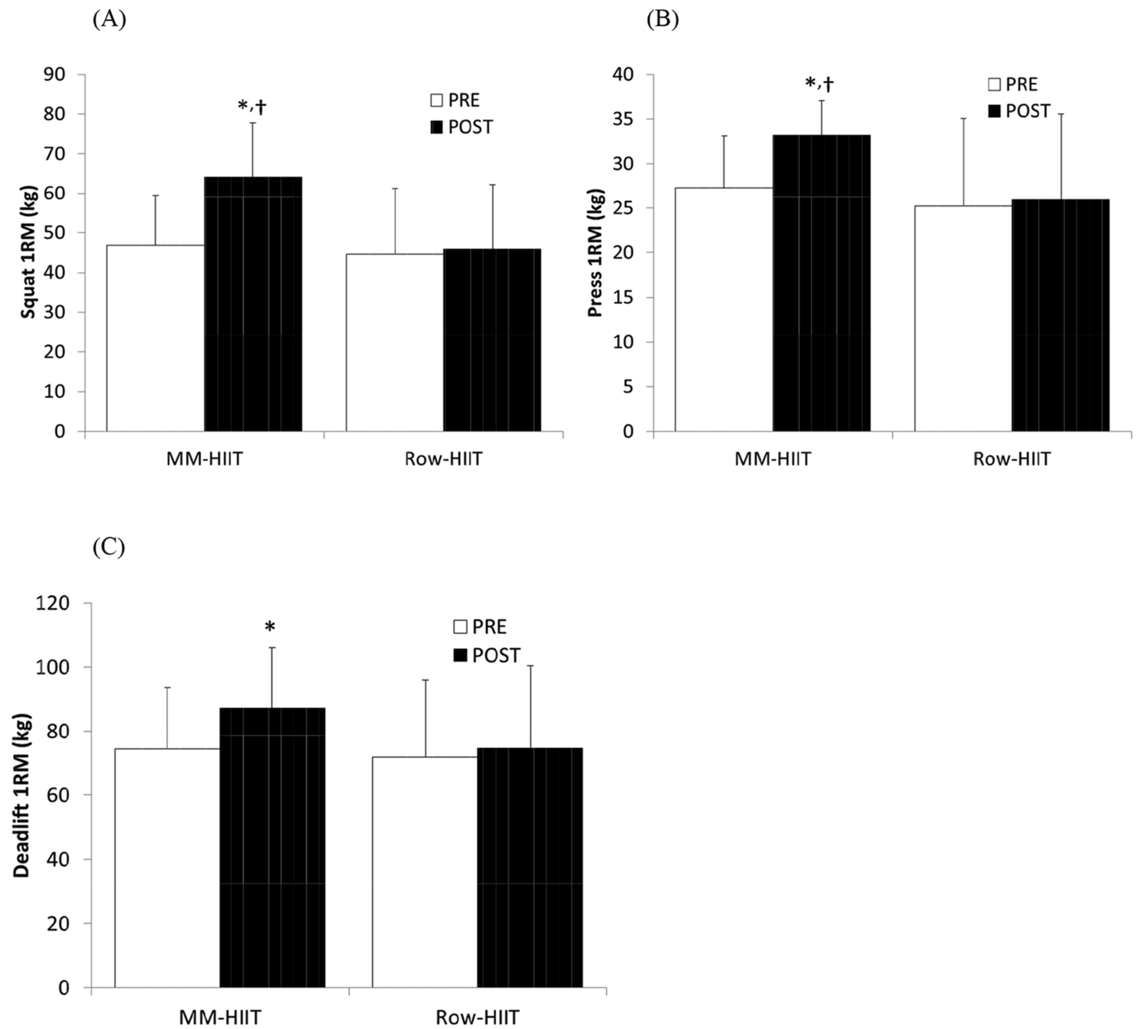
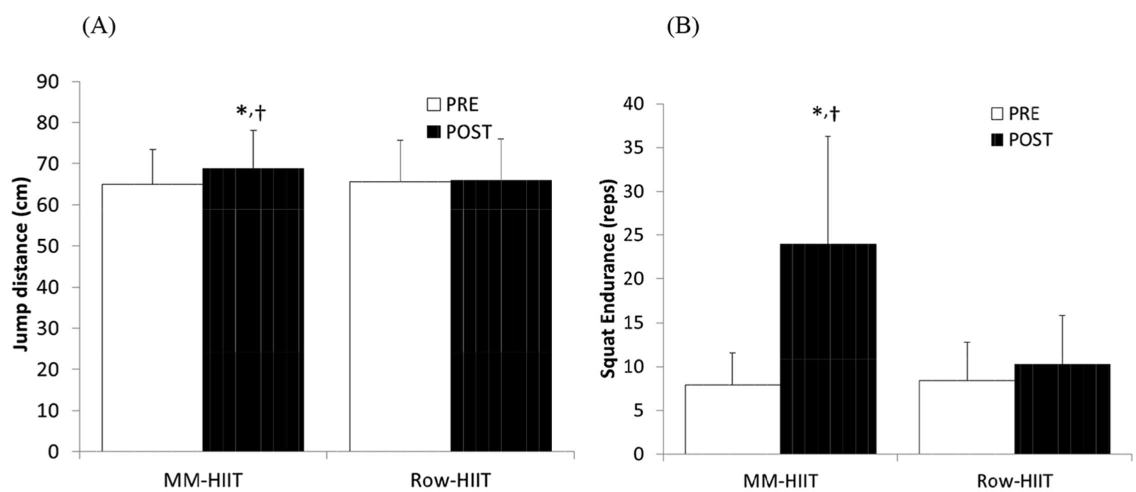


Fig. 2. Muscle power (A: broad jump) and muscle endurance (B: squat endurance at 70% 1RM pre-training squat) for the MM-HIIT and Row-HIIT groups. *Significantly different than the corresponding pre-training value, $p < 0.05$; †significantly different than post-training for Row-HIIT, $p < 0.05$.



Discussion

We examined the effects of a novel MM-HIIT protocol compared with Row-HIIT on aerobic and anaerobic performance and muscle strength, power, and endurance. During the 6-week training period, both MM-HIIT and Row-HIIT increased anaerobic threshold (13% vs. 12%), $\dot{V}O_{2max}$ (7% vs. 5%), and anaerobic power (15% vs. 12%) and capacity (18% vs. 14%). Only the MM-HIIT group had significant increases in RCT (7%). These findings support our first hypothesis that Row-HIIT and MM-HIIT would produce similar adaptations in aerobic and anaerobic energy systems.

Only MM-HIIT resulted in significant improvements in squat, deadlift, and overhead press strength. Similarly, significant increases in muscle power (broad jump) and endurance (70% 1RM back squat) were observed only in the MM-HIIT group. These findings support our second hypothesis that the MM-HIIT group would improve muscle performance to a greater degree than the Row-HIIT group.

Traditional HIIT has consistently been shown to increase aerobic and anaerobic performance compared with continuous endurance exercise (Gist et al. 2013; Hazell et al. 2010; Tabata et al. 1996). Although our study did not directly compare HIIT with continuous exercise, our findings are similar in regard to aerobic and anaerobic performance adaptations for both methods of HIIT training. Increases due to HIIT of 4%–13% for $\dot{V}O_{2max}$ and 4%–12% for anaerobic performance have been observed previously (Cook et al. 2010; Driller et al. 2009; Gist et al. 2013; Hazell et al. 2010; Rønnestad et al. 2015; Sloth et al. 2013). These changes are similar to the degree of adaptation we observed with both protocols, indicating that our novel MM-HIIT and the rowing HIIT are similarly effective for inducing metabolic system changes. In contrast, traditional HIIT does not typically increase muscle strength (Astorino et al. 2012; Nybo et al. 2010), and this is supported by the present findings. However, we observed increases in muscle strength, power, and endurance with our MM-HIIT protocol that are not typically observed with traditional HIIT.

There are a limited number of studies reporting the effects of multimodal training on multiple aspects of performance. McRae et al. (2012) studied the effects of HIIT using whole-body movements (burpees, jumping jacks, mountain climbers, or squat thrusts) rotated across a 4-week training period but did not incorporate higher resistance activities or different movements within each interval. They demonstrated similar improvements in aerobic capacity but greater benefits to muscular endurance (40%–200% increase) with their HIIT protocol compared with continuous treadmill endurance training. Myers et al. (2015) studied the effects of 5 weeks of training using a continuous MM circuit protocol, which rotated exercises and modalities within and between sessions, compared with a combined strength and aerobic training protocol. They demonstrated superior aerobic changes with their circuit protocol (11% in $\dot{V}O_{2max}$) but similar changes in anaerobic power and capacity (5% and 3%, respectively) compared with the combined program. In terms of muscle strength, while the combined group increased all measures, the MM circuit group increased only vertical chest press (21%) and hamstring curl (8%) strength and not lat pull down or knee extension strength. In addition, the circuit group was inferior in measures of muscle endurance; however, Myers et al. compared the number of repetitions completed at 60% of 1RM on each strength exercise at the corresponding time point rather than using the pre-training 1RM for both tests. In comparison, MM-HIIT in our study resulted in increases in strength of 39% for the 1RM back squat, 27% for the 1RM overhead press, and 18% for the 1RM deadlift, an increase in power of 6% for the broad jump distance, and an increase in muscle endurance of 280% for the squat, demonstrating a large improvement in multiple measures of muscle performance with our protocol, in addition to the aerobic and anaerobic adaptations. While direct comparison between our protocol and that of Myers and colleagues (2015) and McRae and colleagues (2012) cannot be conclusive owing to methodological differences between studies, our protocol appears to result in at least similar, or in some cases greater, adaptations across multiple measures of fitness. Future work should examine the adaptations achieved with differing MM protocols.

Combining HIIT with strength training is typically achieved by participants performing 2 simultaneous training protocols (concurrent training) and requires increased time to complete. Wong et al. (2010) demonstrated that professional soccer players concurrently performing HIIT and muscular strength training had significantly greater improvements in 10-m and 30-m sprint times, vertical jump height, and maximal muscle strength (back half squat and bench press) compared with soccer training alone, but they required increased training time. Concurrent training involving sprint interval and strength training has been shown to result in similar upper and lower body strength gains compared with strength training alone, with the addition of greater increases in $\dot{V}O_{2max}$. The findings of Wong et al. (2010) and others (Cantrell et al. 2014; de Souza et al. 2013; McNamara and Stearne 2013) suggest that concurrent training with HIIT does not attenuate the strength response. In comparison with traditional concurrent training, our MM-HIIT protocol resulted in improvements in aerobic and anaerobic performance, along with improvements in muscle strength, power, and endurance, without the addition of excess training time. Based on these findings, MM-HIIT is a time-efficient training method to achieve metabolic and muscular adaptations; however, further study is required to determine whether an MM-HIIT protocol can maintain the same degree of strength adaptations as more traditional concurrent protocols or strength training alone. In addition, because the generalizability of our study is limited to young, healthy, active females without specific training experience, future studies should examine the effects of MM-HIIT in sedentary individuals, males, and older adults or those with chronic conditions.

Exercise protocols that result in the greatest level of physiological and health adaptations in a limited time frame are of interest to rehabilitation, health, and exercise professionals. Traditional HIIT methods are time-efficient protocols resulting in multiple health and aerobic/anaerobic performance benefits (Gibala et al. 2012), but they usually fail to produce adaptations in muscle strength, power, and (or) endurance. Our novel MM-HIIT protocol results in aerobic and anaerobic performance adaptations similar to those resulting from traditional HIIT protocols but has the additional benefit of improving muscle strength, power, and endurance in recreationally active females.

Conflict of interest statement

Mr. Benko is co-owner of, and Dr. Butcher is an unpaid consultant with, Synergy Strength and Conditioning, where the research was conducted.

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Table S1. Outline of testing and training

Baseline	**Screening Assessment (completed 2-14 days prior to Week 1)** History, blood pressure, anthopometry, VO_2max assessment
Week 1	**Skill Acquisition Week** Monday – Warm-up, squats, back squats, front squats, press Wednesday – Deadlift, rowing Friday – Ring rows, push-ups
Week 2	**Testing** Monday – 1RM back squat and 70% 1RM back squat for max effort reps unbroken Wednesday – 1RM overhead press and Wingate testing Friday – 1RM deadlift and max broad jump
Weeks 3-8	**Training** See Table A2
Week 9	**Testing** Monday – 1RM back squat and 70% 1RM back squat for max effort reps unbroken Wednesday – 1RM overhead press and Wingate testing Friday – 1RM deadlift and max broad jump
Follow-up	**Post-training Assessment (completed 4-7 days following Week 9)** Anthopometry, VO_2max assessment

Table S2. Multi-modal HIIT Training.

	Monday	Wednesday	Friday
Week 1	A. In 60sec complete; 4-6 Back squats 8-10 ring rows Box jumps for the remainder of 60sec Q4min x 6 rounds*	A. In 60sec complete; 4-6 Fat bar bench press 8-10 DB walking lunges D-ball slams for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Trap bar deadlift 8-10 DB push press Double rope undulations for the remainder of 60sec Q4min x 6 rounds
Week 2	A. In 60sec complete; 4-6 Press 8-10 DB bent over rows Top end burpees for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Front squat 8-10 push-ups Lateral hurdle hops for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Incline bench press 8-10 ring rows KBS for the remainder of 60sec Q4min x 6 rounds
Week 3	A. In 60sec complete; 4-6 Clean grip RDL 8-10 DB bench press D-ball slams for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Push press 8-10 DB RDL Box jumps for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Back squat 8-10 DB Push press Alternating rope undulations for the remainder of 60sec Q4min x 6 rounds
Week 4	A. In 60sec complete; 4-6 Front squat 8-10 push-ups Lateral hurdle hops for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Fat bar bench press 8-12 DB walking lunges D-ball slams for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Back squats 8-12 ring rows Box jumps for the remainder of 60sec Q4min x 6 rounds
Week 5	A. In 60sec complete; 4-6 Press 8-12 DB bent over rows Top end burpees for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Back squats 8-12 ring rows Box jumps for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Trap bar deadlift 8-12 DB push press Double rope undulations for the remainder of 60sec Q4min x 6 rounds
Week 6	A. In 60sec complete; 4-6 Clean grip RDL 8-12 DB bench press Alternating rope undulations for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Push press 8-12 DB bent over rows Box jumps for the remainder of 60sec Q4min x 6 rounds	A. In 60sec complete; 4-6 Back squat 8-12 push-ups D-ball slams for the remainder of 60sec Q4min x 6 rounds

*60sec Q4min x 6 rounds – indicates each work interval is 60 seconds every 4 minutes (ie. 3 minutes rest interval) for 6 rounds or sets per session. DB – dumbbell; KBS – kettlebell swings; RDL – Romanian deadlift.