8-9-2023

Effects of plyometric- and cycle-based high-intensity interval training on body composition, aerobic capacity, and muscle function in young females: a field-based group fitness assessment

A. J. Holmes
Kennesaw State University

M. T. Stratton
University of South Alabama

A. R. Bailly
Kennesaw State University

J. S. Gottschall
University of Colorado

Y. Feito
Nea Onnim Consultancy

See next page for additional authors

Recommended Citation

Holmes, A. J.; Stratton, M. T.; Bailly, A. R.; Gottschall, J. S.; Feito, Y.; Ha, P. L.; Lavigne, A.; Persaud, K.; Gagnon, H. L.; Krueger, A.; Modjeski, A.; Esmat, T. A.; Harper, L. N.; VanDusseldorp, T. A.; and Hester, Garrett, "Effects of plyometric- and cycle-based high-intensity interval training on body composition, aerobic capacity, and muscle function in young females: a field-based group fitness assessment" (2023). *Faculty and Research Publications*. 6927.
https://digitalcommons.kennesaw.edu/facpubs/6927

Authors

A. J. Holmes, M. T. Stratton, A. R. Bailly, J. S. Gottschall, Y. Feito, P. L. Ha, A. Lavigne, K. Persaud, H. L. Gagnon, A. Krueger, A. Modjeski, T. A. Esmat, L. N. Harper, T. A. VanDusseldorp, and Garrett Hester

Applied Physiology, Nutrition, and Metabolism

OPEN ACCESS | Article

Effects of plyometric- and cycle-based high-intensity interval training on body composition, aerobic capacity, and muscle function in young females: a field-based group fitness assessment

A.J. Holmes[a], M.T. Stratton[b], A.R. Bailly[a], J.S. Gottschall[c], Y. Feito[d], P.L. Ha[a], A. Lavigne[e], K. Persaud[a], H.L. Gagnon[a], A. Krueger[a], A. Modjeski[a], T.A. Esmat[a], L.N. Harper[a], T.A. VanDusseldorp[f,g], and G.M. Hester[a]

[a]Department of Exercise Science and Sport Management, Kennesaw State University, GA, USA; [b]Department of Health, Kinesiology, and Sport, University of South Alabama, AL, USA; [c]Department of Integrative Physiology, University of Colorado, CO, USA; [d]Nea Onnim Consultancy, St. Augustine, FL, USA; [e]Dr. Betty L. Siegel Student Recreation and Activities Center, Kennesaw State University, GA, USA; [f]Bonafide Health, LLC, JDS Therapeutics, NY, USA; [g]Department of Health and Exercise Sciences, Jacksonville University, FL, USA

Corresponding author: **G.M. Hester** (email: ghester4@kennesaw.edu); **T.A. VanDusseldorp** (email: tvandusseldorp@bonafidehealth.com)

Abstract

High-intensity interval training (HIIT) is an effective alternative to moderate intensity continuous training for improvements in body composition and aerobic capacity; however, there is little work comparing different modalities of HIIT. The purpose of this study was to compare the effects of plyometric- (PLYO) and cycle-oriented (CYC) HIIT on body composition, aerobic capacity, and skeletal muscle size, quality, and function in recreationally trained females. Young (21.7 ± 3.1 yrs), recreationally active females were quasi-randomized (1:1 ratio) to 8 weeks of twice weekly PLYO ($n = 15$) or CYC ($n = 15$) HIIT. Body composition (four-compartment model), VO_{2peak}, countermovement jump performance, muscle size, and echo intensity (muscle quality), as well as strength and power of the knee extensors and plantar flexors were measured before and after training. Both groups showed a similar decrease in body fat percentage ($p < 0.001$; $\eta_p^2 = 0.409$) and echo intensity ($p < 0.001$; $\eta_p^2 = 0.558$), and an increase in fat-free mass ($p < 0.001$; $\eta_p^2 = 0.367$) and VO_{2peak} ($p = 0.001$; $\eta_p^2 = 0.318$). Muscle size was unaffected ($p > 0.05$), whereas peak torque was reduced similarly in both groups ($p = 0.017$; $\eta_p^2 = 0.188$) and rapid torque capacity was diminished only for the knee extensors after CYC ($p = 0.022$; $d = -0.67$). These results suggest that PLYO and CYC HIIT are similarly effective for improving body composition, aerobic capacity, and muscle quality, whereas muscle function may express moderate decrements in recreationally active females. ClinicalTrials.gov (NCT05821504)

Key words: high-intensity interval training, muscle quality, maximal oxygen consumption, strength, plantar flexors, knee extensors

Introduction

Participation in high-intensity interval training (HIIT) is appealing due to its time-efficient nature (≤30 min), and similar body composition and aerobic capacity benefits compared to moderate intensity continuous training (Gibala and McGee 2008; Gibala et al. 2012). An abundance of HIIT research has been conducted in overweight and obese individuals, yielding strong evidence of reduced body fat percentage (BF%) and increased aerobic capacity, indicative of improving cardiovascular health (Martins et al. 2016; Racil et al. 2016; Turk et al. 2017). Similarly, positive adaptations for body mass, triglyceride levels, blood pressure, lean body mass, lower-body strength, and aerobic capacity have been shown in healthy, recreationally active (i.e., meeting or exceeding the current American College of Sports Medicine recommended physical activity guidelines) individuals (Gottschall et al. 2014; Petersen et al. 2016). While several studies have compared the benefits of HIIT to moderate intensity continuous training (Wisloff et al. 2009; Bartlett et al. 2011; Jung et al. 2015; Milanovic et al. 2015), little evidence exists comparing different modalities of HIIT, such as plyometrics versus cycling. HIIT can be performed via weight bearing or non-weight bearing activities, though concerns about high-impact exercise may limit options for some individuals, so it is important to identify modality-specific adaptations. Body weight training has been consistently popular over recent years (Thompson 2018, 2022), thus the study of HIIT performed with no equipment is relevant. Nonetheless, despite this trend, the majority of studies on HIIT use highly controlled, laboratory-based protocols that poorly reflect the exercise environment in home or gym settings. Field-based HIIT research is needed to determine if the typically reported benefits of HIIT can be expected from a real-world exercise setting.

Previous HIIT literature has predominantly focused on metabolic and body composition adaptations. Human growth hormone (GH) has a critical role in the regulation of fat metabolism (McMurray and Hackney 2005), and its release is typically greater at higher intensities of exercise (Luger et al. 1992). Training-induced changes in GH levels have been well studied, but little work has specifically examined if adaptations differ between weight bearing and non-weight bearing HIIT. Compared to metabolic and body composition adaptations, there is substantially less known about changes in skeletal muscle morphology and function (Callahan et al. 2021). HIIT is typically not conducive to adaptations in muscle strength or power in young, healthy individuals (Astorino et al. 2012; de Oliveira et al. 2016; Vera-Ibañez et al. 2017; Clark et al. 2019); however, these findings have been primarily derived from studies utilizing cycling exercise. The stimuli from weight-bearing HIIT (e.g., running, jumping) may be sufficient for increasing muscle strength and power. Furthermore, increased strength and power of the lower body may lead to improved functional performance, which has been less frequently reported in the HIIT literature.

There is limited evidence for HIIT-induced skeletal muscle hypertrophy in young individuals (Estes et al. 2017). However, muscle quality as determined by echo intensity (EI), an ultrasound-derived quantitative gray-scale analysis of fat or fibrous tissue infiltration of muscle (Reimers et al. 1993; Pillen et al. 2009), is another increasingly popular skeletal muscle parameter. Evidence for the influence of HIIT on muscle quality is equivocal, but two studies showing no effect involved a short training period (≤4 weeks) (Blue et al. 2018; Moghaddam et al. 2020), while 8 weeks of training improved muscle quality (Hirsch et al. 2021). It is possible that muscle-specific adaptations occur for the knee extensors (KEs) and plantar flexors (PFs) after cycling and weight-bearing HIIT due to their unique roles during these activities. The assessment of skeletal muscle properties and function of the KEs and PFs is necessary to reveal unique adaptations between these muscle groups.

The purpose of this study was to compare the effects of plyometric- (PLYO) and cycle-oriented (CYC) HIIT on body composition, aerobic capacity, and skeletal muscle size, quality, and function in recreationally trained females. We hypothesized that body composition and aerobic capacity adaptations would be similar between interventions, but changes in muscle size and quality would differ and be muscle-specific.

Materials and methods

Participants

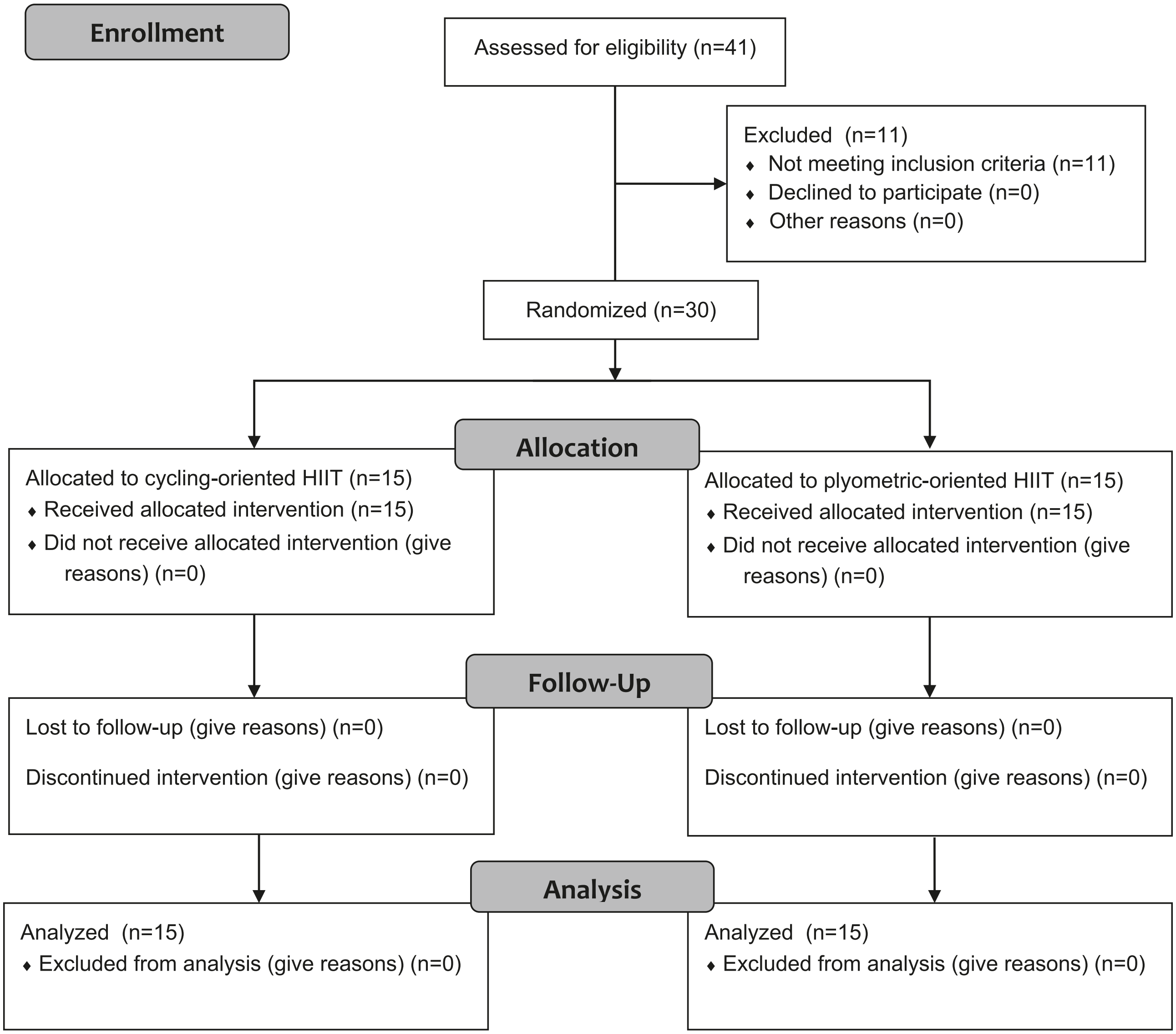
Thirty females between the ages of 18 and 28 years participated in this study (Fig. 1). An a priori analysis using G*Power software (version 3.1.9.4) estimated that a total sample size of 24 would be needed to detect a medium effect size ($f^2 = 0.25$) with a power level of 0.80 and $p < 0.05$ for a three-way repeated measures Analysis of variance (ANOVA). Participants were recreationally active in both resistance and aerobic training (2–4 days·week^{-1} for at least 30–75 min for the past 6 months) but were not engaging in more than 30 min of high-intensity exercise per week. Participants reported no history of cardiovascular, renal, or pulmonary disease, orthopedic limitation, or any other conditions that would contraindicate maximal exercise testing or high-intensity training. All participants reported a regular menstrual cycle except for four and three participants reporting Amenorrhea in CYC and PLYO, respectively. Twelve participants reported using birth control and three indicated no birth control in CYC. Eleven participants reported using birth control and four indicated no birth control in PLYO. This study was approved by the Kennesaw State University Institutional Review Board prior to data collection. Oral and written consent was provided prior to beginning the study.

Experimental design

This field-based study involved participants being quasi-randomized (1:1 ratio) to 8 weeks of PLYO ($n = 15$) or CYC ($n = 15$) HIIT and included three laboratory visits for familiarization and testing (Fig. 2). Testing consisted of 2 separate days prior to the intervention and 1 day following the intervention. The pre-testing days occurred a minimum of 24 h apart but no more than 7 days. The post-testing day occurred within 48–72 h following the intervention. Participants were asked to refrain from strenuous exercise for 48 h and any exercise 24 h before testing. Additionally, participants were instructed to avoid caffeine, alcohol, and food 8 h prior to testing, and to consume similar meals 24 h prior to pre- and post-testing. The first testing visit consisted of body composition analysis, ultrasonography, and familiarization with all performance tests. For the second testing visit, all participants arrived fasted for blood collection and were given the option to have a light snack (i.e., peanut butter crackers) prior to performance testing. Participants adhered to the same dietary routine (i.e., fasted or fed) during post-testing performance testing, which was performed at a similar time of day (±2 h) as pre-testing.

The two exercise protocols consisted of a 30 min high intensity, pre-choreographed group fitness class performed twice per week for 8 weeks. The plyometric-oriented Les Mills BODYATTACK™ program was used for the PLYO group, whereas Les Mills SPRINT™, which exclusively involves stationary cycling, represented the CYC group. Instruction for both classes was given by one of two certified instructors (©Les Mills International) each with over 3 years of experience. Exercise sessions were also supervised by at least one other member of the research team to ensure participants completed all aspects of each workout. All training sessions, separated by at least 24 h, took place at the university's student recreational center. Both protocols involved alternating high-intensity and recovery intervals, and participants were consistently instructed to give maximal effort during

Fig. 1. CONSORT flow diagram.



HIIT = High-intensity interval training

the "work" periods. Both protocols began with a 5 min warm-up and 5 min cooldown. The average and maximal exercise heart rate was recorded for each exercise session and the weekly average was calculated for each of these measures to characterize intensity for both PLYO and CYC. Heart rate was obtained using a chest strap monitor (Polar H10, Polar Electro Inc., Woodbury, NY, USA) that was paired via Bluetooth to Polar A370 fitness trackers. Participants reported their rating of perceived exertion (RPE) using the Borg 6–20 scale at the end of each session prior to cooldown.

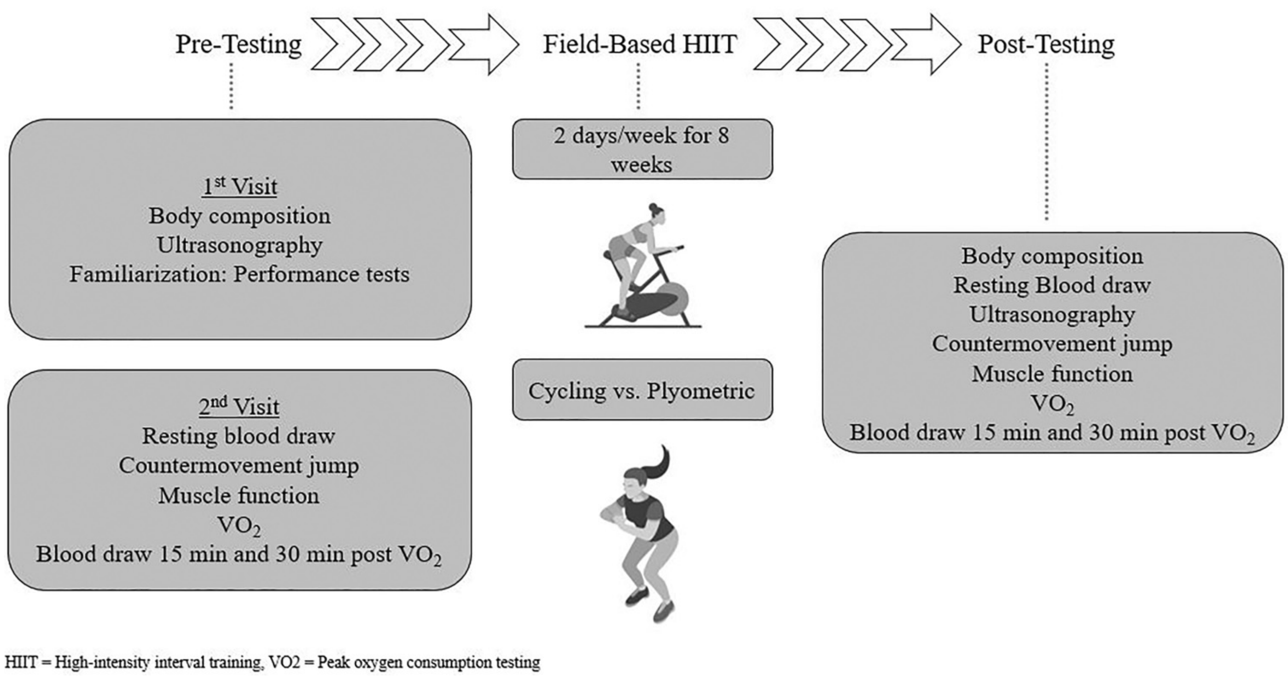
Plyometric (PLYO) exercise

The 30 min PLYO HIIT included four blocks of high-intensity exercise intervals. The "work" portions consisted of the following exercises: high-knee runs, plyometric lunges, jumping jacks, squat jumps, burpees, and speed–agility patterns. The recovery periods consisted of complete rest (transitioning between exercises), a light jog, or a low-impact stepping motion. On average, participants were instructed to give maximal effort for 1–2 min, with recovery intervals of 15–45 s. Four separate routines of plyometric exercises were used throughout the duration of the study with one routine being used per week before alternating to another routine. Participants completed each routine a total of 4 times within a session.

Cycling (CYC) exercise

The 30 min cycling HIIT was performed on upright stationary bikes (Schwinn, AC Performance, Chicago, IL, USA). Protocols involved "work" ranging from 20–80 s with recovery intervals between 10 and 60 s. Recovery intervals consisted of complete rest on bike or particularly slow cycling. Resistance and cycling speed were relatively variable across sessions, with some intervals of higher resistance and lower

Fig. 2. Study design overview.



speed and others involving lower resistance and higher speed (e.g., >120 RPMs). For example, participants were instructed to use a "heavy resistance" during 20 s high-intensity work periods, whereas "moderate resistance" was the prompt for longer work periods (e.g., 60 s). The same four workouts were used throughout the duration of the study alternating each week.

Dietary monitoring

At the start of each testing day, participants completed a 24 h food recall. Over the 8-week training period, participants were instructed to record their dietary intake 3 days for each week (i.e., 2 days during the week and 1 day on the weekend). Dietary logs were analyzed (MyFitnessPal application, Version 20.7.0.29453) for total calories and protein consumption for the first and last week of the training period.

Blood collection

Blood samples from the antecubital space were obtained prior to any performance testing, and at 15 and 30 min after aerobic capacity testing to examine the acute exercise-induced response of GH. The samples were analyzed using an enzyme-linked immunosorbent assay (ELISA) kit in duplicate to determine serum concentrations of GH (ELISA Kit KAQ1081, Invitrogen Corporation). Concentrations were determined using a plate reader (SpectraMax M3 Multi-Mode Microplate Reader, Molecular Devices) according to manufacturer's instructions.

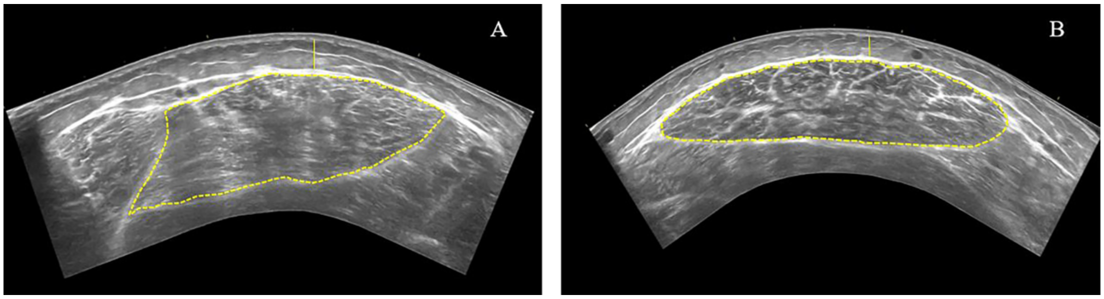
Body composition

Participants wore a sports bra, compression shorts, and swim cap for anthropometric and body composition assessments. Anthropometric assessments consisted of an initial measurement of body mass and height, followed by measurements of body composition. A four-compartment model (Wang et al. 2002) was used to estimate BF% based upon body mass, bone mineral content via dual-energy X-ray absorptiometry (GE Lunar iDXA, Chicago, IL, USA), body volume via air displacement plethysmography (Cosmed Bod-Pod, Chicago, IL, USA), and total body water via bioelectrical impedance (InBody 770, Cerritos, CA, USA). Segmental fat-free mass was determined from the bioelectrical impedance analysis for the arms, trunk, and legs. All equipment underwent daily calibration prior to use per manufacturer guidelines.

Aerobic capacity

Participants underwent an individualized VO_{2peak} (peak rate of oxygen uptake) protocol, following a 10 min warm-up consisting of self-selected cycling and standardized dynamic stretches of the lower body. This method of VO_2 testing is a validated, graded maximal treadmill exercise test (Sperlich et al. 2015). Briefly, participants identified their comfortable running speed and grade was increased by 1% every minute. Oxygen consumption was recorded using a metabolic cart (Parvo Medics TrueOne 2400, Sandy, UT, USA), calibrated according to manufacturer guidelines, and VO_2 was recorded as relative VO_2 in $mL{\cdot}kg^{-1}{\cdot}min^{-1}$. In addition, respiratory exchange ratio and heart rate via chest monitor (Polar Electro Inc., Woodbury, NY, USA) was continuously recorded. VO_{2peak} was defined as the peak VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$), which was determined using 11-breath averaging (Astorino et al. 2000). All subjects fulfilled the following three criteria for VO_{2peak} achievement: (1) respiratory exchange ratio greater than 1.1; (2) peak HR ($_{P}HR_{VO2}$) at least equal to 90% of the age-predicted maximum; and (3) an RPE of 18 or greater. The same stages,

Fig. 3. Panoramic ultrasound images of the lateral (A) and medial (B) gastrocnemius muscles. The discontinuous line surrounds the area for which cross-sectional area and echo-intensity were calculated, while the vertical line represents subcutaneous fat thickness.



including speed, were used during post-testing. If participants were able to surpass their previous grade during the final stage, the incline was increased until participants ended the test.

Ultrasonography

Panoramic images of the medial and lateral gastrocnemius (Fig. 3), and vastus lateralis (VL) were obtained using ultrasound (LOGIQ S7, General Electric Company, Milwaukee, WI, USA). Three transverse images of each muscle group were acquired with a multifrequency linear-array probe (ML6-15 L; 5–MHz; 50 mm field of view; General Electric Company, Milwaukee, WI, USA) using the LogicVIEW function. Participants rested in a supine position for 5–10 min prior to the images being captured. The investigator slowly moved the probe in the transverse plane while applying minimal and consistent pressure. Thick, double-sided tape was placed over each muscle in the transverse plane to ensure the probe was moved perpendicular to the skin. The settings included a frequency of 12 Hz and depth of 4 cm (Rosenberg et al. 2014) and 5 cm (Cadore et al. 2012) for imaging of the gastrocnemii and VL, respectively. All ultrasound settings were kept the same for pre- and post-testing. Images for the gastrocnemii were captured at one-third the distance from the tibial articular cleft between the femur and tibia condyle to the lateral malleolus on the dominant leg (Mota et al. 2018), while images of the VL were taken on the midline between the greater trochanter and lateral epicondyle (Cadore et al. 2012). Images were scaled from pixels to centimeters prior to analysis. The polygon function in ImageJ software (version 1.46r, National Institutes of Health, Bethesda, MD, USA) was used to select as much of each whole muscle as possible without including the surrounding fascia. Subsequently, cross-sectional area (CSA) and muscle quality were calculated for each muscle. Muscle quality was determined from EI, which was assessed via grey-scale analysis using the histogram function. The mean EI was expressed as a value between 0 (black) and 255 (white). Subcutaneous fat thickness for both muscles was measured using the straight line function, and was used to normalize EI as suggested by Young et al. (2015). CSA and EI of the VL were recorded for subsequent analysis. The lateral and medial gastrocnemius CSA values were summed (i.e., PF CSA), and EI was calculated as the average of the lateral and medial gastrocnemius (i.e., PF EI) (Mota et al. 2018). We have shown "excellent" and "good" reliability for CSA ($ICC_{2,1}$: 0.998, SEM: 0.273 cm^2, CV: 1.2%) and EI ($ICC_{2,1}$: 0.748, SEM: 4.650 a.u., CV: 3.2%) (Olmos et al. 2019).

Countermovement vertical jump

Maximum countermovement vertical jumps (CMJs) were performed on a portable force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA). CMJ height and power were calculated using AccuPower 2.0 software (Boston, MA, USA) with sampling at 1 KHz. Prior to CMJ testing, all participants completed a general warm-up consisting of 5 min on a cycle ergometer at a self-selected speed and resistance, and 10 repetitions of the following unloaded exercises: squats, lunges, knee hugs, butt kicks, and toe touches. Participants wore socks and were instructed to stand with their feet shoulder width apart on the force plate, descend to a self-selected depth without pausing, and jump as high as possible while maintaining hands on hips. Three trials were completed with 1 min of rest between trials. The trial producing the great height was used for statistical analysis.

Muscle strength and power testing

Muscle function parameters were recorded for the dominant (van Melick et al. 2017) PFs and KEs using a calibrated Biodex 4 isokinetic dynamometer (Biodex Medical Systems, Inc. Shirley, NY, USA). The order for the muscles was randomized at baseline and kept the same during post-testing. The Biodex torque and velocity signals were sampled at 2 kHz using an eight-channel Bagnoli Desktop System (Delsys, Inc., Natick, MA, USA). Participants were seated with hands across the chest, restraining straps over the trunk, pelvis, and thigh, and the input axis of the dynamometer aligned with the axis of rotation. For PF testing, the knee was extended to 170° (180° = full extension) and hip was maintained at 120°. The foot was secured to the footplate with two straps over the dorsal aspect and a custom ankle wrap technique to anchor the heel to the footplate. Ankle position was set at a neutral angle (90° = neutral) at the beginning of dynamic contractions, which involved a 30° range of motion (0°–30° plantar flexion). For KE testing, an 80° range of motion consisting of knee extension from 90° to 170° (180° = full extension) was used for dynamic contractions. All participants received con-

Table 1. Participant characteristics.

Group	n	Age (yr)	Body mass (kg)	Body fat (%)	Height (cm)
Plyometric	15	20.7 ± 2.4	68.8 ± 10.4	32.9 ± 6.1	162.7 ± 6.9
Cycling	15	22.7 ± 3.5	62.2 ± 11.6	28.4 ± 6.9	159.9 ± 5.4

Table 2. Calorie and protein consumption.

	Plyometric		Cycling	
Variable	Pre	Post	Pre	Post
Calories (kcal·day^{-1})	1966 ± 358	1882 ± 342	2025 ± 338	2020 ± 336
Protein (g·kg^{-1}·day^{-1})	1.50 ± 0.44	1.45 ± 0.35*	1.63 ± 0.63	1.47 ± 0.51*

*Indicates a similar decrease in protein consumption for both groups.

sistent verbal encouragement and visual biofeedback. Testing began with three maximal isometric contractions for determination of isotonic load. Participants performed three concentric isokinetic contractions at 60°·s^{-1}, separated by 1 min of rest, which were used to determine peak torque (PT) and time to PT. Then, concentric isotonic contractions were performed at 30% of maximal isometric strength to determine peak power. During post-testing, 30% of isometric strength at that time point was used for the test. Participants were instructed to push "as hard and fast as possible" for all contractions. During off-line processing, the scaled torque and velocity signals were digitally filtered with a zero-lag low-pass (50 Hz) Butterworth filter using custom-written software (LabVIEW, National Instruments, Austin, TX, USA). PT was determined from isokinetic contractions and defined as the highest 5 ms average and time to PT was calculated as the time from velocity onset (2°·s^{-1}) to PT (Hester et al. 2019). For isotonic contractions, the velocity signal was converted to radian and multiplied by torque to obtain peak power. The isokinetic and isotonic trials producing the highest PT and peak power, respectively, were used for subsequent analysis.

Statistical analyses

Normality was assessed with the Kolmogorov–Smirnov test and outliers were identified as being greater or less than 2.2 multiplied by the interquartile range (Hoaglin and Iglewicz 1987). Independent samples t tests were used to compare groups at baseline. A two-way [study time point (pre-test vs. post-test) × group (PLYO vs. CYC)] repeated measures ANOVA was used for analysis of body composition, CMJ height, and power, $_{P}HR_{VO2}$, average exercise HR, maximal exercise HR, and exercise RPE. Three-way [study time point (pre-test vs. post-test) × muscle (KEs vs. PFs) × group (PLYO vs. CYC)] repeated measures ANOVA was used to analyze peak power, PT, and time to PT, CSA, and EI. Finally, a three-way [study time point (pre-test vs. post-test) × testing time point (resting vs. post 15 min VO_{2peak} vs. post 30 min VO_{2peak}) × group (PLYO vs. CYC)] was used for GH responses. Significant interactions were decomposed with repeated measures ANOVAs and dependent or independent sample t tests on the simple main effects with a Bonferroni correction factor. Due to technical issues during exercise sessions, a sample size of 26 (PLYO = 12; CYC = 14) and 27 (PLYO = 13; CYC = 14) was used for the analysis of average and maximal exercise HR, as well as RPE, respectively. Due to challenges with blood collection, a sample size of 28 (PLYO = 14, CYC = 14) was used for the analysis of GH. Equality of variances was tested using Levene's Test for Equality of Variances. Statistical analyses were performed using PASW software version 27.0 (SPSS Inc., Chicago, IL, USA) and an alpha level of $p \leq 0.05$ was used to determine statistical significance. Effect size was reported using partial eta squared (η_p^2) for ANOVA analyses and <0.06, 0.07–0.14, and >0.14 indicated small, medium, and large effect sizes, whereas Cohen's d was used for pairwise comparisons with 0.20, 0.50, and 0.80 indicating the same effect size classifications (Cohen 1988). Data are provided as mean ± SD in the text and tables, while mean ± SEM is displayed in figures.

Results

Baseline comparisons, training compliance, and adherence

Participant characteristics were similar between groups (Table 1). In addition, all dependent variables were similar between groups at baseline ($p = 0.832$–0.065). Compliance with training sessions was 15.33 ± 0.90 (95.8%) and 15.40 ± 0.74 (96.3%) for PLYO and CYC, respectively. No subject missed more than two training sessions. A 100% adherence rate was demonstrated as all subjects enrolled completed the study.

Calorie and protein consumption

There were no interactions for calorie ($p = 0.350$; $\eta_p^2 = 0.031$) or protein ($p = 0.280$; $\eta_p^2 = 0.041$) consumption (Table 2). There was a main effect for time for protein consumption ($p = 0.046$; $\eta_p^2 = 0.135$) as it demonstrated a moderate decrease at post. No main effect was shown for caloric intake ($p = 0.242$; $\eta_p^2 = 0.041$).

Weekly exercise HR and RPE

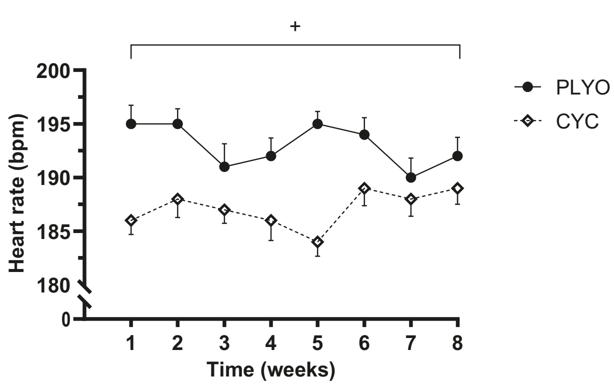
Maximal HR demonstrated an interaction ($p = 0.049$; $\eta_p^2 = 0.076$) and main effect for group ($p = 0.028$; $\eta_p^2 = 0.178$) as it was consistently higher over the course of 8 weeks in the PLYO group (Fig. 4). Similarly, while there was no interaction ($p = 0.149$; $\eta_p^2 = 0.061$) for average HR, a main effect for group ($p = 0.007$; $\eta_p^2 = 0.265$) indicated it was also higher throughout the training period (PLYO = 171.64 ± 2.18 bpm

Table 3. Body composition before and after plyometric (PLYO) and cycling (CYC) high-intensity interval training.

Variable	Pre	Post	Time × group interaction; ES	Main effect for time; ES
Body mass (kg)			$p = 0.288$; 0.040	$p = 0.901$; 0.001
PLYO	68.76 ± 10.38	68.42 ± 10.31		
CYC	62.17 ± 11.58	62.44 ± 11.48		
Body fat (%)			$p = 0.354$; 0.031	$p < 0.001$; 0.409
PLYO	32.92 ± 6.07	31.11 ± 5.87*		
CYC	28.35 ± 6.89	27.19 ± 6.38*		
Fat-free mass (kg)			$p = 0.924$; 0.001	$p < 0.001$; 0.367
PLYO	45.81 ± 5.55	46.83 ± 5.73*		
CYC	43.89 ± 4.61	44.86 ± 4.94*		
Fat mass (kg)			$p = 0.244$; 0.048	$p = 0.001$; 0.333
PLYO	22.95 ± 6.71	21.59 ± 6.34*		
CYC	18.28 ± 8.01	17.57 ± 7.50*		
Arms fat-free mass (kg)			$p = 0.177$; 0.064	$p = 0.738$; 0.004
PLYO	4.68 ± 0.85	4.65 ± 0.83		
CYC	4.32 ± 0.72	4.38 ± 0.71		
Trunk fat-free mass (kg)			$p = 0.122$; 0.083	$p = 0.544$; 0.013
PLYO	20.56 ± 2.71	20.47 ± 2.65		
CYC	19.27 ± 2.27	19.50 ± 2.30		
Legs fat-free mass (kg)			$p = 0.757$; 0.003	$p = 0.342$; 0.032
PLYO	13.58 ± 2.05	13.64 ± 2.12		
CYC	12.67 ± 1.41	12.78 ± 1.48		

*indicates similar change from baseline for both groups
Note: ES, effect size.

Fig. 4. Weekly maximal heart rate for plyometric (PLYO) and cycling (CYC) high-intensity interval training. + indicates greater heart rate for PLYO compared to CYC for all weeks.



vs. CYC = 162.17 ± 3.48 bpm). There was no interaction for RPE ($p = 0.292$; $\eta_p^2 = 0.047$) or difference between groups ($p = 0.205$; $\eta_p^2 = 0.063$) for the 8-week average (PLYO = 16.06 ± 0.29 a.u. vs. CYC = 16.87 ± 0.35 a.u.).

Effect of training on body composition

There were no interactions for any body composition variables (Table 3). A main effect for time indicated a decrease in fat mass and BF%, and an increase in fat-free mass regardless of group. No main effects for time were shown for any segmental fat-free measures.

Effects of training on skeletal muscle CSA and quality

No interactions ($p = 0.757$–0.124; $\eta_p^2 = 0.003$–0.083) or main effect for time ($p = 0.818$; $\eta_p^2 = 0.002$) were demonstrated for CSA, indicating no changes for the VL (PLYO: pre = 23.10 ± 5.25 cm^2 vs. post = 24.11 ± 5.74 cm^2; CYC: pre = 20.12 ± 3.30 cm^2 vs. post = 20.48 ± 5.06 cm^2) or PFs (PLYO: pre = 20.99 ± 4.33 cm^2 vs. post = 21.03 ± 3.85 cm^2; CYC: pre = 19.29 ± 4.77 cm^2 vs. post = 18.21 ± 3.73 cm^2). An outlier was identified for EI of the VL in the CYC group, so that individual was excluded from this analysis. No interactions were found for EI ($p = 0.488$–0.071; $\eta_p^2 = 0.18$–0.152), but a main effect for time ($p < 0.001$; $\eta_p^2 = 0.558$) indicated a decrease in EI (Fig. 5).

Effect of training on peak aerobic capacity

There was no interaction for VO_{2peak} ($p = 0.826$; $\eta_p^2 = 0.001$), but a main effect for time was revealed ($p = 0.001$; $\eta_p^2 = 0.318$) (Fig. 6), as VO_{2peak} increased similarly for both groups. No interaction ($p = 0.863$; $\eta_p^2 = 0.001$) or main effect for time ($p = 0.231$; $\eta_p^2 = 0.051$) was found for $_{P}HR_{VO2}$

Effect of training on growth hormone

GH responses did not differ between groups ($p = 0.772$; $\eta_p^2 = 0.006$), but there was a study time point × testing time point interaction ($p = 0.009$; $\eta_p^2 = 0.204$) (Fig. 7). When groups were collapsed, relative to baseline values, follow-up dependent samples t tests found that GH levels were higher at 15

Fig. 5. Echo intensity of the (A) vastus lateralis and (B) plantar flexors before and after 8 weeks of plyometric (PLYO) and cycling (CYC) high-intensity interval training. + indicates echo intensity decreased similarly for both muscles after PLYO and CYC. Parentheses indicate outlier.

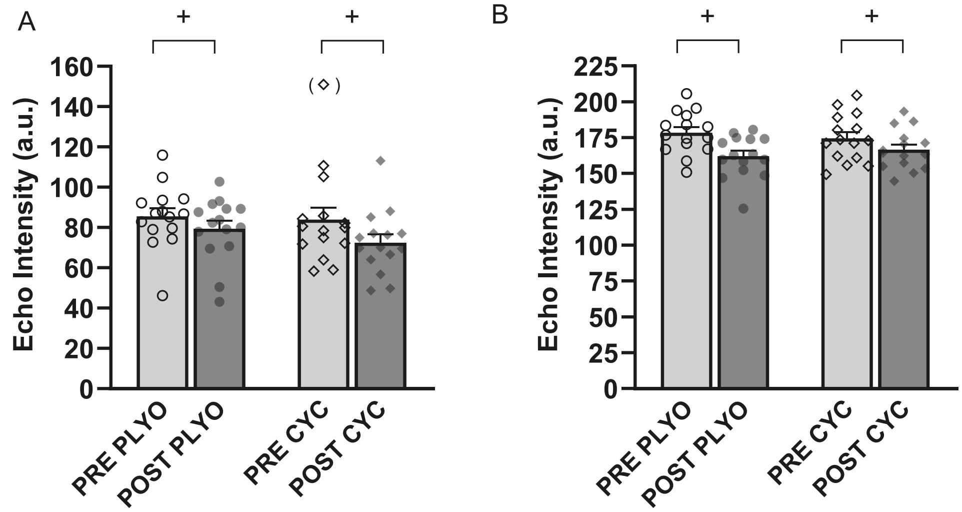
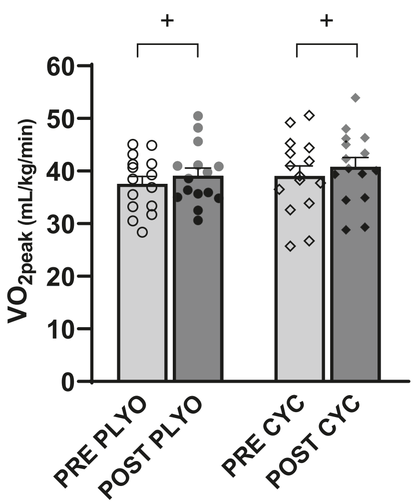


Fig. 6. Aerobic capacity (VO2peak) before and after 8 weeks of plyometric (PLYO) and cycling (CYC) high-intensity interval training. + indicates VO2peak increased similarly for both PLYO and CYC.



(p = 0.001; d = 0.68) and 30 min (p = 0.001; d = 0.73) post VO2max testing compared to resting levels.

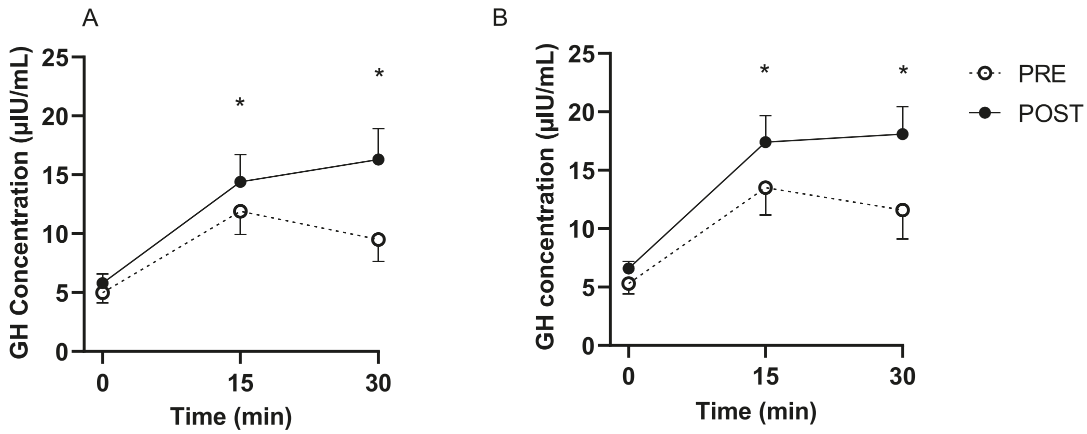
Effects of training on CMJ and muscle performance

There was no interaction (p = 0.478; η_p^2 = 0.018) or main effect for time (p = 0.616; η_p^2 = 0.009) for CMJ height (PLYO: pre = 62.53 ± 17.27 cm vs. post = 59.46 ± 14.85 cm; CYC: pre = 60.78 ± 6.37 cm vs. post = 62.17 ± 7.21 cm). Similarly, no interaction (p = 0.383; η_p^2 = 0.027) or main effect for time (p = 0.812; η_p^2 = 0.002) was revealed for CMJ power (PLYO: pre = 2934.01 ± 688.47 W vs. post = 2867.60 ± 598.37 W; CYC: pre = 2565.93 ± 536.34 W vs. post = 2575.40 ± 513.12 W). No interactions (p = 0.074–0.522; η_p^2 = 0.110–0.015) were found for PT. However, a main effect for time was revealed (p = 0.017; η_p^2 = 0.188), which indicated that PT decreased regardless of group or muscle (Fig. 8A–8B). Time to PT demonstrated a time × muscle × group interaction (p = 0.045; η_p^2 = 0.136) (Fig. 8C–8D). Follow-up repeated measures ANOVAs for both muscles failed to reveal an interaction (p = 0.564; η_p^2 = 0.012) or main effect for time (p = 0.269; η_p^2 = 0.044) for the PFs. However, for the KEs, a time × group interaction (p = 0.025; η_p^2= 0.167) indicated an increase in time to PT for CYC (p = 0.022; d = −0.67), but no change in PLYO (p = 0.267; d = 0.30). Finally, there were no interactions (p = 0.224–0.786) or main effect for time (p = 0.159; η_p^2 = 0.069) for peak power of the KEs (PLYO: pre = 404.12 ± 83.11 W vs. post = 396.64 ± 85.21 W; CYC: pre = 385.08 ± 70.33 W vs. post = 374.37 ± 62.17 W) or PFs (PLYO: pre = 178.81 ± 42.96 W vs. post = 175.57 ± 35.73 W; CYC: pre = 194.77 ± 52.41 W vs. post = 183.68 ± 48.99 W).

Discussion

The purpose of this study was to compare the effects of plyometric- and cycle-oriented HIIT on body composition, aerobic capacity, and skeletal muscle size, quality, and function in recreationally trained females. Previous reports regarding training-induced adaptations of HIIT have been limited to a particular domain of health or fitness; our findings comprehensively capture health- and performance-related outcomes after two differing modalities of HIIT performed in a field setting. Moreover, a unique feature of the present study is the inclusion of whole muscle-specific (i.e., VL vs. PF) outcomes for muscle size, quality (ultrasound-derived EI), strength, and explosiveness. Overall, positive adaptations in body composition, muscle quality, and aerobic capacity, which were similar between groups, were shown after 8 weeks of training. Muscle function and CMJ performance

Fig. 7. Exercise-induced growth hormone (GH) concentrations before and after 8 weeks of (A) plyometric (PLYO) and (B) cycling (CYC) high-intensity interval training. * indicates similar increases for PLY and CYC at 15 and 30 min post-exercise.

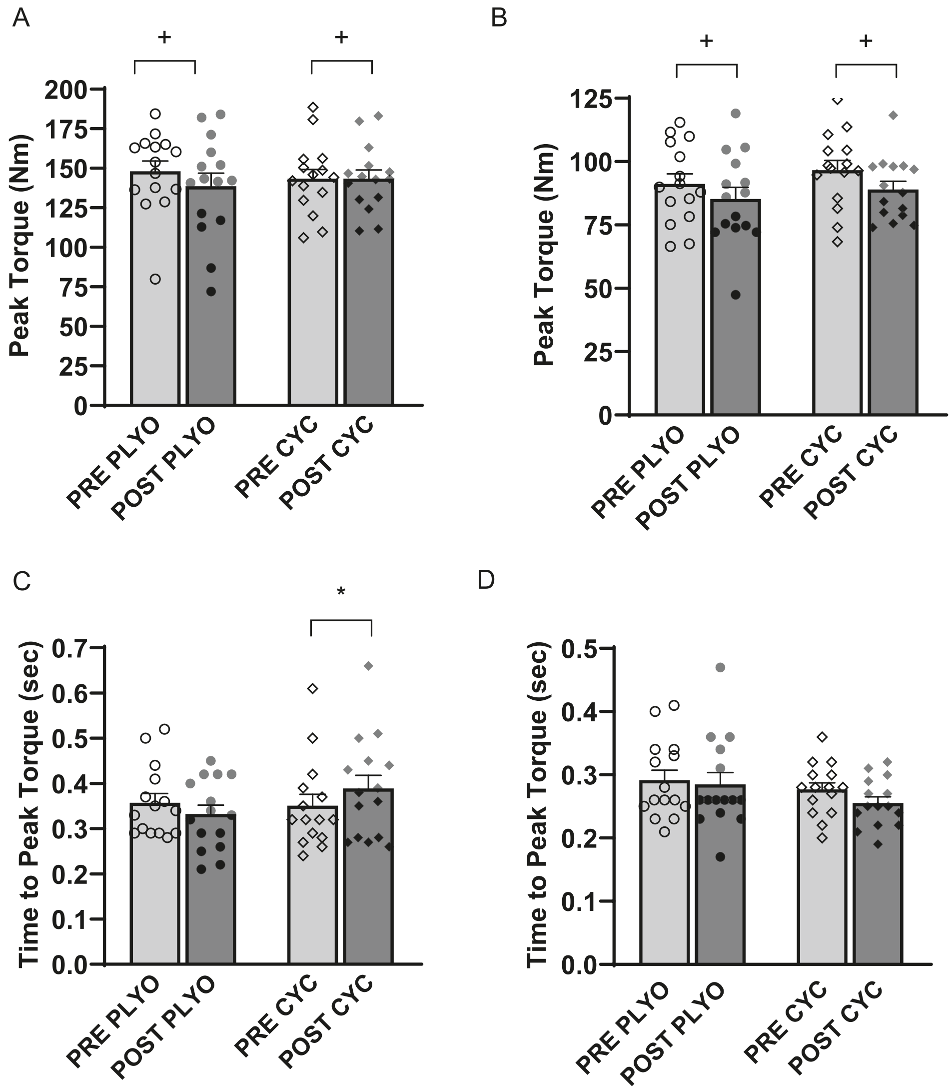


were either unaffected or negatively affected, with some evidence for muscle-specific decrements after cycling-oriented HIIT. These findings indicate that real-world HIIT performed in a group fitness setting effectively promotes body composition and aerobic capacity improvements.

Our findings indicate that, regardless of modality, twice weekly HIIT training promotes positive changes in body composition, including decreases in fat mass, BF%, and increases in fat-free mass with no changes in overall body mass in young, recreationally trained healthy females. Despite differences in muscular engagement between plyometric and cycling exercise, including the potential for greater caloric energy expenditure during the full-body plyometric protocol (Scott et al. 2006), these differences were not sufficient for unique body composition changes between interventions. In the present study, fat-free mass increased similarly in both groups, which is consistent with a few studies examining shorter training durations in a similar population (Macpherson et al. 2011; Gillen et al. 2013). However, as indicated by a comprehensive review (Callahan et al. 2021), several studies report no change in fat-free mass, and typically increases in young adults result from ≥12 weeks of HIIT. Our dietary recall indicated that both groups consumed a diet adequate in protein consumption previously reported to build and maintain muscle mass (1.4–2.0 $g \cdot kg^{-1} \cdot day^{-1}$) (Jager et al. 2017), which may have contributed to the positive fat-free mass changes. Numerous studies have reported decreases in fat mass and BF% in overweight and obese populations following running-based HIIT (Schjerve et al. 2008; Nybo et al. 2010; Sijie et al. 2012; Kemmler et al. 2014; Ahmadizad et al. 2015; Zhang et al. 2015). In contrast, several studies on cycle-based HIIT have demonstrated inconclusive results with some reporting no changes in body composition (Keating et al. 2014; Fisher et al. 2015; Shepherd et al. 2015; Sim et al. 2015; Kong et al. 2016; Martins et al. 2016; Sawyer et al. 2016) and others demonstrating positive changes in body composition (Trapp et al. 2008; Zhang et al. 2017). Zhang et al. (2017) examined females with obesity (38.1 ± 2.3 BF%) and compared a HIIT protocol (4:3 work (90% VO_{2max}) to rest ratio) to continuous exercise at 60% VO_{2max} on a cycle ergometer until 300 kJ was met achieved. The HIIT group significantly decreased fat mass and BF% similar to steady-state exercise. In a 15-week study conducted in young, healthy females, those who participated in the cycling HIIT protocol (8 s sprint with 12 s easy spin intervals for up to 20 min) reduced body fat more compared to steady-state exercise (60% VO_{2peak}) (Trapp et al. 2008). The relative decrease for fat mass (−4.8%) and BF% (−4.7%) in the present study, which were associated with large effect sizes, were similar to the HIIT group in Trapp et al. (2008). Collectively, it appears that meaningful improvements in body composition outcomes can be seen after HIIT, even in young, healthy females who are recreationally active. The aforementioned variability in fat mass and BF% outcomes in reports is likely due to differences in HIIT interventions (e.g., type and volume, work to rest ratios), as well as the use of different body composition assessments. A strength of the current work was the use of the "gold standard" four-compartment model for the measurement of BF% (Wilson et al. 2012).

Numerous mechanisms likely played a role in the observed reductions in fat mass, and given the difference in weight-bearing between protocols, adaptations for the exercise-induced GH response were of interest. Previous research has demonstrated that high-intensity exercise increases adipose tissue lipolysis via lipolytic hormones, such as GH and catecholamines (McMurray and Hackney 2005). While catecholamine levels were not assessed, we examined the response of acute, exercise-induced (i.e., VO_2max) GH fluctuations following training. As expected, GH concentrations demonstrated an exercise-induced increase at 15 and 30 min after the VO_2max at baseline. This acute GH response was increased at both time points following training, with no differences between groups. GH is released in a substantial manner when exercising above lactate threshold compared to below this threshold (Luger et al. 1992; Weltman et al. 1992). One of the crucial roles of GH, during periods of enhanced secretion, is to activate the mobilization of free fatty acids to elevate the amount accessible for oxidation (Cersosimo et al. 1996). Therefore, the increased GH secretion after 8 weeks

Fig. 8. Peak torque for the (A) knee extensors and (B) plantar flexors, and time-to-peak torque of the (C) knee extensors and (D) plantar flexors before and after 8 weeks of plyometric (PLYO) and cycling (CYC) high-intensity interval training. + indicates PT decreased similarly for both muscles after PLYO and CYC. * indicates an increase in time to PT after only CYC for the knee extensors.



of training is likely at least partially responsible for the positive body fat outcomes. Although we were unable to track lactate threshold during training sessions, we did assess intensity via continuous heart rate monitoring. Average exercise heart rate, which included rest intervals, across the 8 week training sessions was ∼172 bpm and ∼162 bpm (≥80% $_{p}HR_{VO2}$) for PLYO and CYC, respectively, and maximal exercise heart rate was above 90% $_{p}HR_{VO2}$. Though not verified, it is reasonable to believe that large portions of exercise sessions were performed above lactate threshold (Demello et al. 1987). However, it appears there were not sufficient differences in intensity or muscle-mass involvement between protocols for unique adaptations in acute, exercise-induced GH fluctuations in response to a maximal exercise test.

As expected, due to the aerobic nature of both the plyometric and cycle-based protocols, aerobic capacity improved similarly for both the PLYO (4.1%) and CYC (4.2%) groups, with no differences between protocols. The improvements in aerobic capacity are consistent with previous reports examining training interventions involving high-intensity aerobic training in the forms of running (Helgerud et al. 2007) and cycling (Gottschall et al. 2014). When studying healthy, recreationally active individuals, twice weekly low-impact HIIT (i.e., cycle ergometer) for 6 weeks at 85%–95% HR_{max} improved VO_{2max} by 9.7% (Petersen et al. 2016). In female soccer players, 5 weeks of running HIIT (maximal sprint efforts of 30 s and 4.5 min of active recovery, twice weekly) caused a mean VO_{2max} improvement of 2.36 mL·kg^{-1}·min^{-1} (4.73%). The rapid improvement in VO_{2max} or VO_{2peak} after 2–8 weeks of HIIT training may result from enhanced central function such as an increment in stroke volume (Helgerud et al. 2007), or peripheral adaptations, for example, up-regulated mitochondrial enzyme activity (e.g., content and efficiency) (Perry et al. 2008). The PLYO modality was unique relative to previous literature, which is predominantly based on cycling and running interventions. Despite the PLYO modality requiring greater intensity, as indicated by average and maximal exercise heart rate, neither aerobic capacity nor body composition changes differed between protocols. However, it is important to note that exercise energy expenditure was not measured, so it is unclear if it differed between interventions.

This study afforded a comprehensive examination of skeletal muscle size and quality to complement typically reported body composition outcomes in HIIT literature. In contrast to previous studies in young adults (Estes et al. 2017), hypertrophy did not occur for either the VL or PFs as a result of HIIT. The rationale for this finding is unclear, but training status and study duration were likely influential since our participants were currently involved in resistance training, while Estes et al. (2017) examined untrained individuals. In addition, the inconsistent mechanical loading for the KEs and PFs due to movement and resistance variability in PLYO and CYC, respectively, was not optimal for a hypertrophic response. More specifically, the wide variety of movements implemented in PLYO likely did not enable an adequate stimulus for the VL or PFs, while the minimal loading of these muscles in CYC was not conducive to muscle hypertrophy. Interestingly, EI decreased (indicative of improved muscle quality) for both, the VL and PFs, which expands on similar findings following resistance training (Radaelli et al. 2013; Cadore et al. 2014). In contrast to this finding, a previous study found no effect of HIIT on EI (Blue et al. 2018). The discrepancy between studies is likely due to the longer training period for the present study (6 weeks vs. 3 weeks) or differences between populations (healthy vs. overweight/obese). It is possible that decreases in inter- and intramuscular adipose tissue, corresponding to the total body composition improvement, were influential for this finding, but this is not clear. Ultrasound-derived EI is an indirect measure of tissue composition, which may be affected by other factors. For example, it has been suggested that muscle glycogen levels affect EI, but there are mixed findings (Hill and Millan 2014; Nieman et al. 2015; Routledge et al. 2019). It is unclear if an altered muscle glycogen status after HIIT would affect EI. A recent study elegantly demonstrated the influence of skeletal muscle pennation angle on EI, whereby an increase in the former is associated with decreased EI (Pinto et al. 2022). The sensitivity of pennation angle to exercise training is well established (Timmins et al. 2016), so the influence of exercise-induced changes in muscle architecture cannot be ruled out. Regardless, it is not suspected that muscle swelling contributed to the changes in EI given the post-testing timeline and the unaltered CSA values (Radaelli et al. 2012). Additional research using more precise imaging technology (e.g., computed tomography) is warranted to substantiate the influence of HIIT on whole-muscle quality.

We comprehensively examined performance adaptations via CMJ as well as muscle strength and explosiveness for the KEs and PFs. CMJ performance nor peak power of the KEs or PFs was influenced by either training protocol. Our findings are in line with several reports indicating no benefit of HIIT on muscle power (Astorino et al. 2012) or strength (Astorino et al. 2012; de Oliveira et al. 2016; Vera-Ibañez et al. 2017; Clark et al. 2019) in healthy, untrained adults, although some evidence exist for an increase in strength (Martinez-Valdes et al. 2017). Strength decreased for both muscle groups in the current study, which may be due to the training history of participants. Perhaps interference resulting from the HIIT stimuli (Hickson 1980; Fyfe et al. 2016), or the possibility that participants reduced the amount of resistance training performed on a weekly basis was influential for this finding. A unique feature of the present study was our assessment of rapid torque production (i.e., time to PT) and power via isokinetic and isotonic contractions, respectively. While no changes occurred for PLYO, CYC showed a moderate increase in time to PT for the KEs, meaning KE torque production was slower. The finding that strength was reduced exacerbates this finding since it illustrates that a greater amount of time was needed to achieve a lower torque capacity. The emphasis on the quadriceps in the cycle-based protocol may have preferentially induced endurance adaptations that are typically inversely related with explosive torque production in this musculature (Häkkinen et al. 2003). The finding for time to PT after CYC only demonstrated a moderate effect size, which should explain the lack of translation to decreased explosiveness during more practical movement patterns, including isotonic power and CMJ performance after training. The positive effect of plyometric training on CMJ performance is well-established (Gehri et al. 1998; Markovic 2007; Makaruk et al. 2014), thus it could have been postulated that the PLYO group would demonstrate increased CMJ performance. While it was not surprising that the cycle-based group did not improve CMJ performance due to the lack of training specificity, the PLYO failed to demonstrate improved performance as well. Unlike standard plyometric training, the plyometric-oriented exercise consisted of longer duration work bouts (1–2 min) and very short rest intervals (15–45 s). Thus, while participants were verbally encouraged to perform plyometric movements with maximal effort, it is likely that fatigue presented relatively early in each session and attenuated performance. Therefore, despite PLYO being weight-bearing in nature and possessing some degree of movement specificity, the implementation of plyometrics in a more endurance-based manner was not effective at improving muscle function or CMJ performance.

There were several limitations within this study. Participants were asked to record and maintain their normal diet throughout the study, but we did not strictly measure their dietary intake over the 8 weeks. The duration for each session was equal between groups, but the specific work to rest intervals, as well as the total volume, were not directly measured or compared. For example, the stationary bikes utilized a resistance controller that allowed arbitrary adjustments in resistance. Despite limited control of exercise variables (e.g., repetitions and cycling resistance), we believe our training protocols reflect good external validity as the exercise routines are typical in fitness settings (i.e., university and community gyms). Although participants were asked to maintain their current physical activity upon enrollment in the study, we could not confirm their adherence. Therefore, it is possible that participation in usual exercise habits (i.e., resistance training) may have diminished, especially given the higher intensity nature of the training protocols. Finally, although protein consumption and overall caloric intake were monitored, data for carbohydrate or fat consumption were not recorded.

Conclusions

The results of this study indicate that 8 weeks of HIIT is effective for improving overall body composition and aerobic capacity, regardless of whether it is plyometric- or cycle-oriented, when performed twice per week for 30 min. Thus, similar changes for body composition and aerobic capacity can be expected for plyometric- and cycle-oriented HIIT in young females. This finding is important since these are common modalities offered in group fitness settings at university and community gyms. Individuals who do not have access to a stationary bike can opt for body weight HIIT that does not require equipment to improve health and fitness outcomes. These implications are timely as body weight training is increasingly popular (Thompson 2018; Thompson 2022), so evidence for its efficacy is critical. HIIT protocols completed in this study improved an index of muscle quality (i.e., echo-intensity), but this finding should be interpreted with caution as the underlying whole-muscle tissue alterations were not directly identified. Otherwise, size and function of the KEs and PFs were mostly unaffected with some decrements in rapid torque capacity after cycle-oriented HIIT. The 100% adherence rate was also noteworthy, indicating that high-intensity exercise, especially in a group exercise setting, is a conducive option for consistent engagement for 8 weeks.

Acknowledgements

The authors would like to thank the participants for dedicating their time to this study.

Article information

History dates

Received: 28 December 2022
Accepted: 13 July 2023
Accepted manuscript online: 9 August 2023
Version of record online: 18 September 2023

Copyright

Data availability

Data generated or analyzed during this study will be made available by request.

Author information

Author ORCIDs

Y. Feito https://orcid.org/0000-0001-6790-6294
G.M. Hester https://orcid.org/0000-0002-9790-7586

Author contributions

Conceptualization: AJH, JSG, YF, TAE, TAV, GMH
Data curation: AJH, MTS, ARB, LH, TAV, GMH
Formal analysis: GMH
Funding acquisition: TAV
Investigation: AJH, MTS, ARB, PLH, AL, KP, HLG, AK, AM
Methodology: AJH, GMH
Project administration: AJH, TAV
Resources: TAV
Software: GMH
Supervision: TAV, GMH
Visualization: LH
Writing – original draft: AJH, TAV, GMH
Writing – review & editing: AJH, MTS, ARB, JSG, YF, PLH, AL, KP, HLG, AK, AM, TAE, LH, TAV, GMH

Competing interests

The authors declare there are no competing interests.

Funding information

No funding was received for this study.

Clinical trial information

Clinical Trials.gov registration number NCT05821504 (registered on 19 April 2023).

References

Ahmadizad, S., Avansar, A.S., Ebrahim, K., Avandi, M., and Ghasemikaram, M. 2015. The effects of short-term high-intensityinterval training vs. moderate-intensity continuous training onplasma levels of nesfatin-1 and inflammatory markers. Horm. Mol. Biol. Clin. Investig. **21**: 165–173. doi:10.1515/hmbci-2014-0038.

Astorino, T.A., Allen, R.P., Roberson, D.W., and Jurancich, M. 2012. Effect of high-intensity interval training on cardiovascular function, VO2max, and muscular force. J. Strength Cond. Res. **26**: 138–145.

Astorino, T.A., Robergs, R.A., Ghiasvand, F., Marks, D., and Burns, S. 2000. Incidence of the oxygen plateu at VO2max during exercise testing to volitional fatigue. J. Exerc. Physiol. Online, **3**: 1–12.

Bartlett, J.D., Close, G.L., Maclaren, D.P., Gregson, W., Drust, B., and Morton, J.P. 2011. High-intensity interval running is perceived to be more enjoyable than moderate-intensity continuous exercise: implications for exercise adherence. J. Sports Sci. **29**: 547–553. doi:10.1080/02640414.2010.545427.

Blue, M.N., Smith-Ryan, A.E., Trexler, E.T., and Hirsch, K.R. 2018. The effects of high intensity interval training on muscle size and quality in overweight and obese adults. J. Sci. Med. Sport, **21**: 207–212. doi:10.1016/j.jsams.2017.06.001.

Cadore, E., González-Izal, M., Pallarés, J., Rodriguez-Falces, J., Häkkinen, K., Kraemer, W., et al. 2014. Muscle conduction velocity, strength, neural activity, and morphological changes after eccentric and concentric training. Scand. J. Med. Sci. Sports, **24**: e343–e352.

Cadore, E.L., Izquierdo, M., Conceição, M., Radaelli, R., Pinto, R.S., Baroni, B.M., et al. 2012. Echo intensity is associated with skeletal muscle power and cardiovascular performance in elderly men. Exp. Gerontol. **47**: 473–478. doi:10.1016/j.exger.2012.04.002.

Callahan, M.J., Parr, E.B., Hawley, J.A., and Camera, D.M. 2021. Can high-intensity interval training promote skeletal muscle anabolism? Sports Med. **51**: 405–421. doi:10.1007/s40279-020-01397-3.

Cersosimo, E., Danou, F., Persson, M., and Miles, J.M. 1996. Effects of pulsatile delivery of basal growth hormone on lipolysis in humans. Am. J. Physiol, **271**: E123–E126.

Clark, A., Annie, B., Derevere, J.L., and Astorino, T.A. 2019. Effects of various interval training regimes on changes in maximal oxygen uptake, body composition, and muscular strength in sedentary women with obesity. Eur. J. Appl. Physiol. **119**: 879–888. doi:10.1007/s00421-019-04077-x.

Cohen, J. 1988. Statistical power analysis for the social sciences.

De Oliveira, M.F.M.D., Caputo, F., Corvino, R.B., and Denadai, B.S. 2016. Short-term low-intensity blood flow restricted interval training improves both aerobic fitness and muscle strength. Scand. J. Med. Sci. Sports, **26**: 1017–1025.

Demello, J.J., Cureton, K.J., Boineau, R.E., and Singh, M.M. 1987. Ratings of perceived exertion at the lactate threshold in trained and untrained men and women. Med. Sci. Sports Exerc. **19**: 354–362. doi:10.1249/00005768-198708000-00006.

Estes, R.R., Malinowski, A., Piacentini, M., Thrush, D., Salley, E., Losey, C., and Hayes, E. 2017. The effect of high intensity interval run training on cross-sectional area of the vastus lateralis in untrained college students. Int. J. Exerc. Sci. **10**: 137.

Fisher, G., Brown, A.W., Bohan Brown, M.M., Alcorn, A., Noles, C., Winwood, L., et al. 2015. High intensity interval—vs moderate intensity—training for improving cardiometabolic health in overweight or obese males: a randomized controlled trial. PLoS ONE, **10**: e0138853. doi:10.1371/journal.pone.0138853.

Fyfe, J.J., Bartlett, J.D., Hanson, E.D., Stepto, N.K., and Bishop, D.J. 2016. Endurance training intensity does not mediate interference to maximal lower-body strength gain during short-term concurrent training. Front. Physiol. **7**: 487. doi:10.3389/fphys.2016.00487.

Gehri, D.J., Ricard, M.D., Kleiner, D.M., and Kirkendall, D.T. 1998. A comparison of plyometric training techniques for improving vertical jump ability and energy production. J. Strength Cond. Res. **12**: 85–89.

Gibala, M.J., and Mcgee, S.L. 2008. Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain? Exerc. Sport Sci. Rev. **36**: 58–63. doi:10.1097/JES.0b013e318168ec1f.

Gibala, M.J., Little, J.P., Macdonald, M.J., and Hawley, J.A. 2012. Physiological adaptations to low-volume, high-intensity interval training in health and disease. J. Physiol. **590**: 1077–1084. doi:10.1113/jphysiol.2011.224725.

Gillen, J.B., Percival, M.E., Ludzki, A., Tarnopolsky, M.A., and Gibala, M.J. 2013. Interval training in the fed or fasted state improves body composition and muscle oxidative capacity in overweight women. Obesity, **21**: 2249–2255. doi:10.1002/oby.20379.

Gottschall, J.S., Bopp, C.M., and Hastings, B. 2014. The addition of high intensity interval training reduces cardiovascular disease risk factors and enhances strength in active, healthy adults. Open J. Prev. Med. **4**. doi:10.4236/ojpm.2014.45034.

Häkkinen, K., Allén., M., Kraemer, W.J, Gorostiaga, E., Izquierdo, M., Rusko, H., and Valkeinen, H., 2003. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. Eur J Appl Physiol, **89**: 42–52. doi:10.1007/s00421-002-0751-9.

Helgerud, J., Hoydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., et al. 2007. Aerobic high-intensity intervals improve VO2max more than moderate training. Med. Sci. Sports Exerc. **39**: 665–671. doi:10.1249/mss.0b013e3180304570.

Hester, G.M., Magrini, M.A., Colquhoun, R.J., Barrera-Curiel, A., Estrada, C.A., Olmos, A.A., et al. 2019. Cross-education: effects of age on rapid and maximal voluntary contractile characteristics in males. Eur. J. Appl. Physiol. **119**: 1313–1322. doi:10.1007/s00421-019-04123-8.

Hickson, R.C. 1980. Interference of strength development by simultaneously training for strength and endurance. Eur. J. Appl. Physiol. Occup. Physiol. **45**: 255–263. doi:10.1007/BF00421333.

Hill, J.C., and Millan, I.S. 2014. Validation of musculoskeletal ultrasound to assess and quantify muscle glycogen content. A novel approach. Phys. Sports Med. **42**: 45–52. doi:10.3810/psm.2014.09.2075.

Hirsch, K.R., Greenwalt, C.E., Saylor, H.E., Gould, L.M., Harrison, C.H., Brewer, G.J., et al. 2021. High-intensity interval training and essential amino acid supplementation: effects on muscle characteristics and whole-body protein turnover. Physiol. Rep. **9**: e14655. doi:10.14814/phy2.14655.

Hoaglin, D.C., and Iglewicz, B. 1987. Fine-tuning some resistant rules for outlier labeling. J. Am. Stat. Assoc. **82**: 1147–1149. doi:10.1080/01621459.1987.10478551.

Jager, R., Kerksick, C.M., Campbell, B.I., Cribb, P.J., Wells, S.D., Skwiat, T.M., et al. 2017. International society of sports nutrition position stand: protein and exercise. J. Int. Soc. Sports Nutr. **14**: 20. doi:10.1186/s12970-017-0177-8.

Jung, M.E., Bourne, J.E., Beauchamp, M.R., Robinson, E., and Little, J.P. 2015. High-intensity interval training as an efficacious alternative to moderate-intensity continuous training for adults with prediabetes. J. Diabetes Res. **2015**: 191595. doi:10.1155/2015/191595.

Keating, S.E., Machan, E.A., O'connor, H.T., Gerofi, J.A., Sainsbury, A., Caterson, I.D., and Johnson, N.A. 2014. Continuous exercise but not high intensity interval training improves fat distribution in overweight adults. J. Obes. **2014**: 834865. doi:10.1155/2014/834865.

Kemmler, W., Scharf, M., Lell, M., Petrasek, C., and Von Stengel, S. 2014. High versus moderate intensity running exercise to impact cardiometabolic risk factors: the randomized controlled RUSH-study. Biomed. Res. Int. **2014**: 843095.

Kong, Z., Fan, X., Sun, S., Song, L., Shi, Q., and Nie, J. 2016. Comparison of high-intensity interval training and moderate-to-vigorous continuous training for cardiometabolic health and exercise enjoyment in obese young women: a randomized controlled trial. PLoS ONE, **11**: e0158589. doi:10.1371/journal.pone.0158589.

Luger, A., Watschinger, B., Deuster, P., Svoboda, T., Clodi, M., and Chrousos, G.P. 1992. Plasma growth hormone and prolactin responses to graded levels of acute exercise and to a lactate infusion. Neuroendocrinology, **56**: 112–117. doi:10.1159/000126912.

Macpherson, R., Hazell, T.J., Olver, T.D., Paterson, D.H., and Lemon, P. 2011. Run sprint interval training improves aerobic performance but not maximal cardiac output. Med. Sci. Sports Exerc. **43**: 115–122. doi:10.1249/MSS.0b013e3181e5eacd.

Makaruk, H., Czaplicki, A., Sacewicz, T., and Sadowski, J. 2014. The effects of single versus repeated plyometrics on landing biomechanics and jumping performance in men. Biol. Sport. **31**: 9–14. doi:10.5604/20831862.1083273.

Markovic, G. 2007. Does plyometric training improve vertical jump height? A meta-analytical review. British J. Sports Med. **41**: 349–355. doi:10.1136/bjsm.2007.035113.

Martinez-Valdes, E., Falla, D., Negro, F., Mayer, F., and Farina, D. 2017. Differential motor unit changes after endurance or high-intensity interval training. Med. Sci. Sports Exerc. **49**: 1126–1136. doi:10.1249/MSS.0000000000001209.

Martins, C., Kazakova, I., Ludviksen, M., Mehus, I., Wisloff, U., Kulseng, B., et al. 2016. High-intensity interval training and isocaloric moderate-intensity continuous training result in similar improvements in body composition and fitness in obese individuals. Int. J. Sport Nutr. Exerc. Metab. **26**: 197–204. doi:10.1123/ijsnem.2015-0078.

Mcmurray, R.G., and Hackney, A.C. 2005. Interactions of metabolic hormones, adipose tissue and exercise. Sports Med. **35**: 393–412. doi:10.2165/00007256-200535050-00003.

Milanovic, Z., Sporis, G., and Weston, M. 2015. Effectiveness of high-intensity interval training (HIT) and continuous endurance training for VO2max improvements: a systematic review and meta-analysis of controlled trials. Sports Med. **45**: 1469–1481. doi:10.1007/s40279-015-0365-0.

Moghaddam, M., Estrada, C.A., Baghurst, T., and Jacobson, B.H. 2020. Muscular morphological adaptations of two whole-body high intensity interval training configurations. J. Sports Med. Phys. Fitness, **60**: 985–991. doi:10.23736/S0022-4707.20.10526-7.

Mota, J.A., Giuliani, H.K., Gerstner, G.R., and Ryan, E.D. 2018. The rate of velocity development associates with muscle echo intensity, but not muscle cross-sectional area in older men. Aging Clin Exp Res. **30**: 861–865. doi:10.1007/s40520-017-0829-1.

Nieman, D.C., Shanely, R.A., Zwetsloot, K.A., Meaney, M.P., and Farris, G.E. 2015. Ultrasonic assessment of exercise-induced change in skeletal muscle glycogen content. BMC Sports Sci. Med. Rehabil. **7**: 1–7. doi:10.1186/s13102-015-0003-z.

Nybo, L., Sundstrup, E., Jakobsen, M.D., Mohr, M., Hornstrup, T., Simonsen, L., et al. 2010. High-intensity training versus traditional exercise interventions for promoting health. Med. Sci. Sports Exerc, **42**: 1951–1958. doi:10.1249/MSS.0b013e3181d99203.

Olmos, A.A., Stratton, M.T., Ha, P.L., Vandusseldorp, T.A., Bailly, A.R., Feito, Y., et al. 2019. Neuromuscular function of the plantar flexors and predictors of peak power in middle-aged and older males. Exp. Gerontol. **125**: 110677. doi:10.1016/j.exger.2019.110677.

Perry, C.G., Heigenhauser, G.J., Bonen, A., and Spriet, L.L. 2008. High-intensity aerobic interval training increases fat and carbohydrate metabolic capacities in human skeletal muscle. Appl. Physiol. Nutr. Metab. **33**: 1112–1123. doi:10.1139/H08-097.

Petersen, B.A., Hastings, B., and Gottschall, J.S. 2016. High intensity interval cycling improves physical fitness in trained adults. J. Fit. Res. **5**: 39–47.

Pillen, S., Tak, R.O., Zwarts, M.J., Lammens, M.M., Verrijp, K.N., Arts, I.M., et al. 2009. Skeletal muscle ultrasound: correlation between fibrous tissue and echo intensity. Ultrasound Med. Biol. **35**: 443–446.

Pinto, M.D., Pinto, R.S., Nosaka, K., and Blazevich, A.J. 2022. Do intramuscular temperature and fascicle angle affect ultrasound echo intensity values? Med. Sci. Sports Exerc. **55**: 740–750. doi:10.1249/MSS.0000000000003082.

Racil, G., Coquart, J.B., Elmontassar, W., Haddad, M., Goebel, R., Chaouachi, A., et al. 2016. Greater effects of high- compared with moderate-intensity interval training on cardio-metabolic variables, blood leptin concentration and ratings of perceived exertion in obese adolescent females. Biol. Sport, **33**: 145–152. doi:10.5604/20831862.1198633.

Radaelli, R., Bottaro, M., Wilhelm, E.N., Wagner, D.R., and Pinto, R.S. 2012. Time course of strength and echo intensity recovery after resistance exercise in women. J. Strength Cond. Res. **26**: 2577–2584.

Radaelli, R., Wilhelm, E., Botton, C., Bottaro, M., Cadore, E., Brown, L., and Pinto, R. 2013. Effect of two different strength training volumes on muscle hypertrophy and quality in elderly women. J. Sports Med. Phys. Fitness **53**: 6.

Reimers, K., Reimers, C.D., Wagner, S., Paetzke, I., and Pongratz, D. 1993. Skeletal muscle sonography: a correlative study of echogenicity and morphology. J. Ultrasound Med. **12**: 73–77. doi:10.7863/jum.1993.12.2.73.

Rosenberg, J.G., Ryan, E.D., Sobolewski, E.J., Scharville, M.J., Thompson, B.J., and King, G.E. 2014. Reliability of panoramic ultrasound imaging to simultaneously examine muscle size and quality of the medial gastrocnemius. Muscle Nerve, **49**: 736–740.

Routledge, H.E., Bradley, W.J., Shepherd, S.O., Cocks, M., Erskine, R.M., Close, G.L., and Morton, J.P. 2019. Ultrasound does not detect acute changes in glycogen in Vastus Lateralis of Man. Med. Sci. Sports Exerc. **51**: 2286–2293. doi:10.1249/MSS.0000000000002052.

Sawyer, B.J., Tucker, W.J., Bhammar, D.M., Ryder, J.R., Sweazea, K.L., and Gaesser, G.A. 2016. Effects of high-intensity interval training and moderate-intensity continuous training on endothelial function and cardiometabolic risk markers in obese adults. J. Appl. Physiol. (1985), **121**: 279–288. doi:10.1152/japplphysiol.00024.2016.

Schjerve, I.E., Tyldum, G.A., Tjonna, A.E., Stolen, T., Loennechen, J.P., Hansen, H.E., et al. 2008. Both aerobic endurance and strength training programmes improve cardiovascular health in obese adults. Clin. Sci. (Lond.) **115**: 283–293. doi:10.1042/CS20070332.

Scott, C.B., Littlefield, N.D., Chason, J.D., Bunker, M.P., and Asselin, E.M. 2006. Differences in oxygen uptake but equivalent energy expenditure between a brief bout of cycling and running. Nutr. Metab. (Lond.) **3**: 1. doi:10.1186/1743-7075-3-1.

Shepherd, S.O., Wilson, O.J., Taylor, A.S., Thogersen-Ntoumani, C., Adlan, A.M., Wagenmakers, A.J., and Shaw, C.S. 2015. Low-volume high-intensity interval training in a gym setting improves cardiometabolic and psychological health. PLoS ONE, **10**: e0139056. doi:10.1371/journal.pone.0139056.

Sijie, T., Hainai, Y., Fengying, Y., and Jianxiong, W. 2012. High intensity interval exercise training in overweight young women. J. Sports Med. Phys. Fitness, **52**: 255–262.

Sim, A.Y., Wallman, K.E., Fairchild, T.J., and Guelfi, K.J. 2015. Effects of high-intensity intermittent exercise Training on appetite regulation. Med. Sci. Sports Exerc. **47**: 2441–2449. doi:10.1249/MSS.0000000000000687.

Sperlich, P.F., Holmberg, H.C., Reed, J.L., Zinner, C., Mester, J., and Sperlich, B. 2015. Individual versus Standardized Running Protocols in the Determination of VO2max. J Sports Sci Med, **14**: 386–393.

Thompson, W.R. 2018. Worldwide survey of fitness trends For 2019. ACSM's Health Fit. J. **22**: 10–17.

Thompson, W.R. 2022. Worldwide survey of fitness trends for 2022. ACSM's Health Fit. J. **26**: 11–20.

Timmins, R.G., Shield, A.J., Williams, M.D., Lorenzen, C., and Opar, D.A. 2016. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. Br. J. Sports Med., **50**: 1467–1472. doi:10.1136/bjsports-2015-094881.

Trapp, E.G., Chisholm, D.J., Freund, J., and Boutcher, S.H. 2008. The effects of high-intensity intermittent exercise training on fat loss and fasting insulin levels of young women. Int. J. Obes. (Lond.) **32**: 684–691. doi:10.1038/sj.ijo.0803781.

Turk, Y., Theel, W., Kasteleyn, M.J., Franssen, F.M.E., Hiemstra, P.S., Rudolphus, A., et al. 2017. High intensity training in obesity: a Meta-analysis. Obes. Sci. Pract. **3**: 258–271. doi:10.1002/osp4.109.

Van Melick, N., Meddeler, B.M., Hoogeboom, T.J., Nijhuis-Van Der Sanden, M.W., and Van Cingel, R.E. 2017. How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. PLoS ONE, **12**: e0189876. doi:10.1371/journal.pone.0189876.

Vera-Ibañez, A., Colomer-Poveda, D., Romero-Arenas, S., Viñuela-García, M., and Márquez, G. 2017. Neural adaptations after short-term wingate-based high-intensity interval training. J. Musculoskeletal Neuronal. Interact. **17**: 275.

Wang, Z., Pi-Sunyer, F.X., Kotler, D.P., Wielopolski, L., Withers, R.T., Pierson, R.N., Jr., and Heymsfield, S.B. 2002. Multicomponent methods: evaluation of new and traditional soft tissue mineral models by in vivo neutron activation analysis. Am. J. Clin. Nutr. **76**: 968–974. doi:10.1093/ajcn/76.5.968.

Weltman, A., Weltman, J.Y., Schurrer, R., Evans, W.S., Veldhuis, J.D., and Rogol, A.D. 1992. Endurance training amplifies the pulsatile release of growth hormone: effects of training intensity. J. Appl. Physiol. (1985), **72**: 2188–2196. doi:10.1152/jappl.1992.72.6.2188.

Wilson, J.P., Mulligan, K., Fan, B., Sherman, J.L., Murphy, E.J., Tai, V.W., et al. 2012. Dual-energy X-ray absorptiometry–based body volume measurement for 4-compartment body composition. Am. J. Clin. Nutr. **95**: 25–31. doi:10.3945/ajcn.111.019273.

Wisloff, U., Ellingsen, O., and Kemi, O.J. 2009. High-intensity interval training to maximize cardiac benefits of exercise training? Exerc. Sport Sci. Rev. **37**: 139–146. doi:10.1097/JES.0b013e3181aa65fc.

Young, H.J., Jenkins, N.T., Zhao, Q., and Mccully, K.K. 2015. Measurement of intramuscular fat by muscle echo intensity. Muscle Nerve, **52**: 963–971. doi:10.1002/mus.24656.

Zhang, H., T., T., Qiu, W., Wang, J., Nie, J., and He, Y. 2015. Effect of high-intensity interval training protocol on abdominal fat reduction in overweight Chinese women: a randomized controlled trial. Kinesiology, **47**: 57–66.

Zhang, H., Tong, T.K., Qiu, W., Zhang, X., Zhou, S., Liu, Y., and He, Y. 2017. Comparable effects of high-intensity interval training and prolonged continuous exercise training on abdominal visceral fat reduction in obese young women. J. Diabetes. Res. **2017**: 5071740. doi:10.1155/2017/5071740.