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ORIGINAL ARTICLE

Personal mobile tracking of resting and excess post-exercise oxygen consumption with a mobile indirect calorimeter

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ABSTRACT

BACKGROUND: Excess post-exercise oxygen consumption (EPOC) is indicative of the effect of exercise on tissue repair and recovery from exercise. Detection of EPOC has been performed by indirect calorimetry (IC) on the breath of study subjects, and conducted in professional facilities with reference instruments requiring calibration, power, or/and professional expertise. However, no study has investigated EPOC in a mobile IC device before. Given the increasing use of mobile technologies, which is less expensive, portable, battery-operated, light-weight, user-friendly, and most importantly, easily access anywhere/anytime, individuals can now track their physical performances *via* mobile health devices independently and confidently.

METHODS: In this study, we want to apply a mobile IC technology to examine energy expenditure (EE) in parallel with to evaluate accessibility of EPOC on high-intensity interval training (HIIT) for 6 weeks, as well as the effect on muscle change. Twenty-nine subjects (16 males and 13 females), BMI (17.3-31.8), aged (20-42 years) are divided into a control group (CG, N.=11) and a HIIT intervention group (IG, N.=19). The subjects self-monitor their EPOC with a personal mobile IC device (Breezing®). All 29 subjects conducted over 340 measurements for the entire study.

RESULTS: EPOC effect was measured on HIIT days, and significant differences in EPOC from IG HIIT days *vs*. IG non-HIIT days as well *vs*. CG non-HIIT days ($P<0.01$) ($\alpha=0.05$) were detected. The capability to grow muscle mass after 6 weeks of HIIT training emerged in IG *vs*. CG. IG subjects with 6% or greater muscle change also demonstrated higher EPOC effect (average 247 kcal/day) *vs*. IG subjects with less than 1% muscle change (average 47 kcal/day).

CONCLUSIONS: Independent IC tracking of EPOC was feasible with the mobile device and correlated with higher muscle growth in IG. Thus, personal EPOC may inform about exercise recovery and long-term muscle mass change.

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KEY WORDS: Oxygen consumption; Exercise; Indirect calorimetry; Muscles.

Daily total energy expenditure (TEE) is the energy-sustaining life at resting conditions, in physical activities, and during recovery from physical activities.[1, 2] Physical activity energy expenditure can be tracked using state-of-the-art wearable technologies, such as accelerometers and heart rate monitors under free-living conditions.[3, 4] Non-physical activity energy expenditure, on the other hand, can be measured via indirect calorimetry method or heat production from the body. However, indirect calorimetry is a better way to assess non-physical activity energy expenditure due to its decidedly accurate, reproducible, and non-invasive characteristics. This method measures oxygen consumption (VO_2) and carbon dioxide production rates (VCO_2) and relates to energy expenditure concept using the well-known Weir equation.[1] In the past, obtaining indirect calorimetry requires special instrumentation and/or trained professionals.[1] More recently, emerging technologies have brought indirect calorimetry methods via mobile devices,[5, 6] more accessible to track energy expenditure (EE) assessment under free-living conditions. Mobile technologies are the preferable means because they are less expensive, portable, battery-operated, light weight, user-friendly, and most importantly, easily access anywhere/anytime, which allow individuals track their physical performances via mobile health devices independently and confidently.

Among several non-activity conditions, resting energy expenditure (REE) and excess post-exercise oxygen consumption (EPOC) are relevant due to their importance in weight management[7] and exercise.[8] REE represents, at least, between 60-75% of total energy expenditure,[1] and can be increased with muscle growth due to the higher metabolic activity of this tissue compared to other tissues (*e.g.*, fat, bone).[9] On the other hand, EPOC is a post-exercise phenomenon produced as result of the restoration of body homeostasis (replenishing energy stores with glycogen) and repair of exercise-damaged tissues, including muscle repair and growth.[1, 8, 10]

Since no studies have reported the use of mobile indirect calorimetry (IC) devices to track EPOC under free-living conditions, the present work focuses on a recent commercialized mobile IC device, Breezing®. The device measures VO_2 and VCO_2, is lightweight (6 oz.), battery-operated, and has a smartphone application (mobile app) as user interface. Test subjects can use this Breezing device independently anywhere and anytime. The device has been validated[6] and recently used in many case studies.[11-13] In this work, we examine and evaluate the capability of assessing REE and EPOC under free-living conditions using the abovementioned mobile IC.

One of the metrics of exercise intervention efficacy is long-term adoption of sustainable exercise practice. Short and effective exercise is emerging as better method for exercise interventions.[14] Given the increasing prevalence of sedentary lifestyles, short and effective execution can take place, using relatively simple instrumentation in most of contexts.[15] In order to produce an impact from short-period exercise, exercise intensity should be adjusted to induce the desired EPOC phenomena. In this context, the work[16] has historically been followed for its inspirational development of performance enhancing protocols that require short yet efficient exercises. The protocols have been inspiration for the modification and execution of High Intensity Interval Training, HIIT studies.[15, 17, 18]

Sports performance research has explored HIIT-based training for developing optimal stimulation and exercise recovery strategies.[19] This has fueled exploration of HIIT for determining the short-, medium-, and longer-term benefits in several populations. These populations included recreational and scholastic athletes,[20] adults,[21] children,[22, 23] patients under medical supervision,[24, 25] overweight and/or obese populations,[26, 27] and sedentary workers.[28] The subjects of this study were all office workers which are sedentary, mostly sitting at a desk all day long. Sedentary lifestyle is commonly known as a lifestyle with little or no physical activity. The exercise routine of choice was HIIT because of its low time commitment[14] and its use of simple tools (body weight, sand bags, and free weights).[15] Energy expenditures at resting, and at pre- and post- HIIT exercise were assessed for REE and EPOC measurements.

Materials and methods

Study tools

In this study, each subject was assigned a mobile and wireless IC device (Breezing® Metabolism Tracker, Breezing Co., Tempe, AZ, USA), and a heart rate monitor to encourage them to conduct self-assessments of energy expenditure and

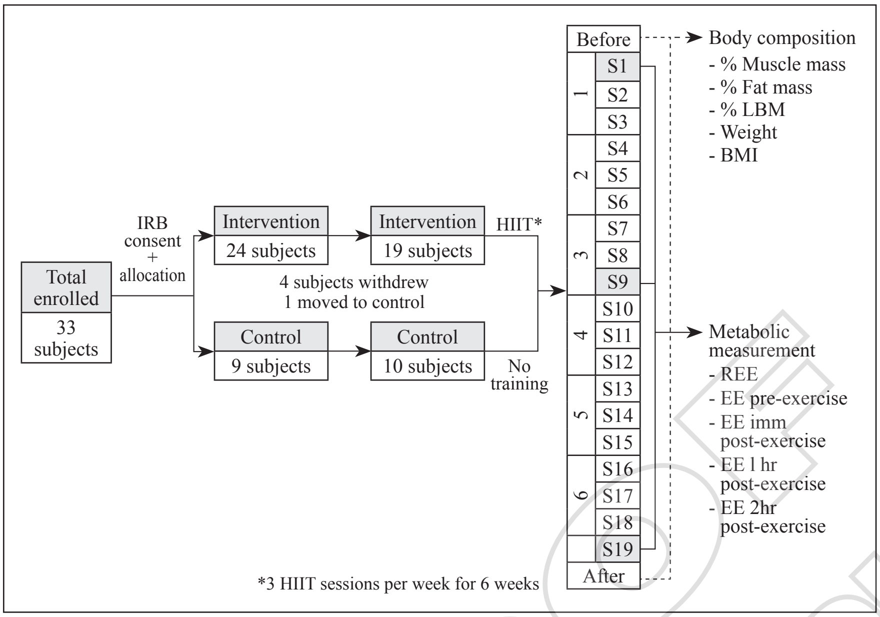

Figure 1.—Schematic representation of study subject recruitment and study design. 1-6 (first column on the right) indicate the number of weeks while 1-19 (second column on the right) indicate the number of sessions in the study.

heart rate during training (HIIT) and non-training (non-HIIT) days. It is important to note that all study subjects were lay-users, and conducted their own energy expenditure and heart rate measurements during the full period of the study.

Energy expenditure measurements

Energy expenditure was measured using the mobile IC device, which uses a sensor cartridge and a flow meter for determining rate of consumed oxygen and produced carbon dioxide in a ~2-minute test optimized for a personal breathing feedback (www.breezing.com). The device's sensing technology,[5] as well as the stand-alone device[6] itself have been previously validated against the Gold Standard method (Douglas Bag), demonstrating almost 100% accuracy. Weighing at 6.0 oz (170 g) and measuring 1.8×2.1×4.8 inches (4.7×5.4×12.3 cm), the IC mobile device connects wirelessly to a mobile phone or tablet, which receives IC data from the device sensors, processes the information, and then provides REE or EE measurement values through a graphic user interface. Breezing® uses a QR code to carry calibration of the sensor cartridges, which can be scanned and then recognized by the mobile application (app). The device measures VO_2 and VCO_2 from an individual's breath, and determines energy expenditure according to the Weir equation.[1] The device is used together with a single-use sensor cartridge, nose clip, and a two-way non-rebreathing valve as illustrated in Supplementary Digital Material 1 (Supplementary Figure 1).

For heart rate monitoring, the subjects in this study wore the Polar HR FT4 (Polar Electro, Kempele, Finland) before, during, and after the HIIT sessions. The heart rate monitor comprised a chest strap and a wristwatch connected to the strap via radio frequency transmission. Its functionality was individually checked and compared with a reference heart rate monitor by Zephyr (which in turn was validated with BioPac system (white paper v1c ©Zephyr Technology 2008: "Validity of BioHarness™ Heart Rate *vs*. 3-lead ECG" from BioPac System, Inc. (www.biopac.com, New Zealand). Both heart rate monitors showed no significant performance differences between them.

Subjects

Originally, 33 subjects agreed to participate voluntarily in this study. The subjects answered affirmative to the following personal historical exclusion criteria: history of pulmonary cardiovascular disease or organ failure, planned surgeries,

TABLE I.—*HIIT group summary: baseline values as mean±SD, and range.*

Gender	N.	Age (years)	Height (m)	BM (kg)	BMI (kg/m²)	WHR	Glucose (mg/dL)	Ketones (mM)
Men	12	28±5 (21-38)	1.79±0.61 (1.68-1.89)	74±7 (65-92)	23±3 (20-30)	0.79±0.05 (0.72-0.90)	85±8 (77-100)	0.1±0.04 (0.1-0.2)
Women	7	30±8 (20-42)	1.63±0.68 (1.50-1.70)	53±8 (43-65)	20±3 (17-25)	0.75±0.05 (0.66-0.81)	90±3 (86-95)	0.2±0.1 (0.0-0.4)

BM: body mass; BMI: Body Mass Index; WHR: waist-to-hip ratio.

TABLE II.—*Control group summary: baseline values as mean±SD, and ranges.*

Gender	N.	Age (years)	Height (m)	BM (kg)	BMI (kg/m²)	WHR	Glucose (mg/dL)	Ketones (mM)
Men	4	30±5 (24-35)	1.75±0.53 (1.68-1.80)	74±12 (62-89)	24±5 (20-32)	0.81±0.03 (0.77-0.85)	89±6 (81-94)	0.1±0 (0.1)
Women	6	27±4 (23-33)	1.64±0.61 (1.57-1.71)	56±4 (49-60)	21±3 (17-24)	0.74±0.04 (0.69-0.80)	93±9 (81-108)	0.3±0.2 (0.1-0.6)

BM: body mass; BMI: Body Mass Index; WHR: waist-to-hip ratio.

reluctance to participate, or participation in prior similar studies. Subjects were allocated to either an intervention group (IG, N.=24) or a control group (CG, N.=9) based on availability and an agreement to participate in 19 HIIT sessions over 6 weeks. Four subjects in the IG dropped out of the study and one switched to the CG after two HIIT sessions. Thus, 19 subjects completed HIIT intervention and 10 controls participated in regular evaluations, leaving 29 subjects for the study (Figure 1). Subjects were recruited and assigned randomly to intervention group or control group. Control group maintained their routine sedentary work, and was not involved in HIIT training. One subject was switched from IG to CG after just the 1st session since he/she could no longer commit to HIIT training.

The protocol of the study was approved by the Institutional Review Board of the Arizona State University (IRB protocol number: 1012005855). All subjects provided written informed consent prior to participation. The entire study, including formal introduction, body composition assessments, and intervention exercises, was carried out at Arizona State University for 9 weeks in total. Relevant bio-chemical and physiological parameters of each subject were measured before, during, and after the 6 weeks of the HITT study and assessed to reveal the characteristics of the group subjects, as summarized in Table I and II.

Dietary intervention

Total daily caloric intake was not restricted for any subject and no attempt was made to manage a subject's body mass. The major exception occurred on each measurement day, wherein explicit calorie intake of all 29 subjects served to limit variations in energy expenditure (data based on individual Breezing's measurements of energy expenditure) due to dietary intake and thus food-induced thermogenesis. A breakfast after REE measurement (between 8 and 9 a.m.), and a snack of 500 kcal after immediate post-exercise EE measurement ($EE_{imm\ post}$) (between 2 and 3 p.m.) were made available to each subject. The breakfast consisted of milk, cereal, eggs, fruits, a little amount of jelly, and/or cheese sandwiches, and/or yogurt. The snack consisted of fruits, carrots, and omega-3-rich trail mix purchased from a worldwide grocery store chain. The same dietary intervention was provided to the control group during measurement days to ensure both groups received the same quantity and type of foods.

HIIT intervention

Exercise protocol

The exercise protocol of HIIT consisted of 8 sets of 20-second kettle bell thrusters or sandbag front squats, with 10 seconds of seated resting between sets, totaling 4 minutes per session.

The HIIT was repeated 3 sessions per week for 6 weeks with 19 sessions (S1-S19). A certified professional from the National Academy of Sports Medicine (NASM), and a performance enhancement specialist with related training and certification, led the design of the exercise protocol, as well as the intervention. The above-described exercise protocol was to stimulate stretching and overload of muscle tissue while placing aerobic demand on the subjects.[29] Progressive overload throughout the HIIT session was selected to stimulate neuromuscular growth. In addition, full deep front squats were chosen as the longest term, broadest view exercise for strength gain[29] and from the safety standpoint. Furthermore, to encourage safety[30] yet effective overload of muscle tissue, 20-minute light stretching and warm up routines prepared the subjects for each bout of maximum work performance.

During the HIIT sessions, the performance specialist provided ongoing feedback and ensured good technique, relative comfort, and full free range of motion. For instance, feet were shoulder-width apart and back flat during full front squat, and sandbags were held toward the chest thereby compressing the chest and engaging upper back postural muscles. Fifteen of the IG subjects utilized the sandbag form while the other four used the "thruster" movement protocol, which, by replacing sandbag with kettle bells, included overhead press movements, and thus additional distances to overcome.

Study subjects from the IG met with the performance specialist from 12 noon to 1 p.m. Heart rates of the subjects were monitored throughout the training to evaluate for intensity, and for reaching the goal of near HR_{max}. In fact, all subjects reached at least 95% of maximum heart rate (calculated as HR_{max} = 220 – age) during the HIIT session. Subjects belonging to the CG did not participate in HIIT, and they were neither informed about the intervention, nor encouraged to change their lifestyles during the 6 weeks.

Work and power calculation

All work- and power-generation calculations were conducted as "relative" to body mass as follows: Force (mass by gravitational acceleration) was multiplied by distance traveled in the positive direction (negatives were not accounted for). Then, force value was multiplied by the number of repetitions (reps) completed during the 4-minute training. For example: a 75-kg body front squatting a 36 kg sandbag 0.5 meters took roughly: 111 kg × 9.8 m/s^2 × 0.5 meters × 70 reps = 38,073 kg m^2/s^2 ~ 38 kJ total. For the 75-kg person, 38 kJ was normalized by body mass to 507 J/kg. In another example, the total work of a 75 kg body (front loaded) with (2) × 10 kg kettle bells, thrusting the first 0.5 meters, and additional 0.5 meters overhead took roughly: (95 kg × 9.8 m/s^2 × 0.5 meters × 70 reps) + (20 kg × 9.8 m/s^2 × 0.5 meters × 70 reps) = 39,445 kg m^2/s^2 = ~39 kJ or 526 J/kg.

To summarize, the total weight lifted by the study subjects included body mass and the sandbag or kettle bells (range: 55-135 kg). The distance traveled was measured as the difference between center of gravity standing from sitting (range: 0.4-0.6 meters/rep), while additional distance from thrusters was measured as the difference between position of kettle bell at fully extended *versus* standing position (range: 0.48-0.58 m). The totaled reps were added from 8 sets (range: 50-80 reps) and gravity was counted as 9.8 m/s^2. Power was determined by simply dividing work by the duration of the HIIT, 160 seconds (20 seconds × 8).

Anthropometric measurements

All subjects were measured as described by the American College of Sports Medicine's Guidelines for exercise testing.[31] Anthropometric measurement pre- and post-intervention were conducted by a trained professional from Arizona State University's School of Nutrition and Health Promotion, Phoenix, AZ, USA. Body height and 6 circumferences (bicep, forearm, waist, buttock/hip, thigh, and calf) were measured in triplicate. Skinfolds (biceps, triceps, scapular, iliac crest, supra-spinal, abdominal, thigh, and calf) were measured with a (Harpenden Skinfold Caliper (HSK-BI, Baty International, West Sussex, UK) at least twice, and the mean value was calculated. If two measurements had 25% or greater difference (International Society for the Advancement of Kinanthropometry), a third measurement was performed.

From all these measurements, several calculations were performed: BMI was calculated as body mass/height^2 (kg/m^2). Seven-site skin fold data was used to calculate Jackson & Pollock body density. The Siri equation converted body density into body fat percentage. Finally, the muscle mass of each subject was estimated using Lee's equation.[32] In addition, in order to validate and enhance the assessment of body composition via skin fold analysis, a body composition analyzer SC-240 from Tanita Co. was used to corroborate percentage of fat assessed from skin fold analysis.

Breath analysis

The energy expenditure measurements with Breezing® mobile IC device were performed by all 29 subjects from the CG and the IG at the beginning (S1), middle (S9), and end of the study (S19), and each measurement day included REE and four EE values (Figure 1). IG measurements were conducted throughout HIIT days at pre- and post-exercise (enabling quantification of EPOC), as well as on non-HIIT days at HIIT-day equivalent time periods. CG measurements were assessed similarly to non-HIIT day conditions.

Measurement protocol at S1, S9, and S19

A typical measurement day consisted of a total of five measurements as follows:

Resting energy expenditure (REE) was measured according to standard resting conditions: 1) be seated in a comfortable position in a quiet environment under comfortable temperatures; 2) be fasted, overnight and first thing upon arriving at work; 3) no strenuous exercise for 12 hours nor moderate exercise for 4 hours; and 4) double-check the "resting" state by measuring a low and steady heart rate. Once complete, subjects were permitted to consume any portion of an immediate, complimentary breakfast.

Pre-exercise energy expenditure (EE_{pre}) is energy expenditure recorded at resting state right before the HIIT section. It measures at mid-day for: 1) all CG subjects; 2) all IG subjects in a non-HIIT day; 3) all IG subjects in a HIIT day, immediately prior to warming up for the HIIT session. EE_{pre} measurement were followed up with post-exercise energy expenditure measurements.

Post-exercise energy expenditure is energy expenditure recorded at resting state right after the HIIT section. These measurements included immediate post-exercise energy expenditure ($EE_{imm\text{-}post}$), 1-hour post-exercise energy expenditure ($EE_{1hr\text{-}post}$), and 2-hour post-exercise energy expenditure ($EE_{2hr\text{-}post}$). $EE_{imm\text{-}post}$ were collected as follows: For the IG subjects on a HIIT day, they conducted the HIIT session, and then recovered to normal breathing and heart rate below 50% of calculated HR_{max} to perform the $EE_{imm\text{-}post}$ measurements. For the IG subjects during a non-HIIT day, or CG subjects, they waited 30 minutes after EE_{pre} measurement to simulate the time that would have been spent in a HIIT exercise protocol. After this measurement, all 29 subjects (IG during a HIIT day, IG during a non-HIIT day, and CG) were then offered a 500 kcal-or-less snack to stave off hunger until the last measurement since this would have been the only food intake since breakfast. As described before, caloric control was intended to reduce the number of factors potentially causing variation in energy expenditure measurements. One- and two-hour post-snack measurements of $EE_{1hr\text{-}post}$ and $EE_{2hr\text{-}post}$, respectively, were recorded.

Mathematical differences between measurements were calculated. For example, the ΔEE immediately following HIIT ($\Delta EE_{imm\text{-}post}$) was calculated by subtracting the pre-HIIT EE (EE_{pre}) from that of immediate-post $EE_{imm\text{-}post}$. This measurement, $\Delta EE_{imm\text{-}post}$, was hypothesized to reveal the biggest change, due to closest proximity in time to HIIT. In addition, a post-HIIT, time-weighted energy expenditure was calculated as an indicator of overall HIIT-induced EPOC. The calculation was performed as the sum of ΔEE over roughly 2.5 hours following HIIT, as follows: HIIT-induced EPOC index = (0.5 h/2.5 h) $\Delta EE_{imm\text{-}post}$ + (1.0 h/2.5 h) $\Delta EE_{1hr\text{-}post}$ + (1.0 h/2.5 h) $\Delta EE_{2hr\text{-}post}$, where $\Delta EE_{imm\text{-}post}$, $\Delta EE_{1hr\text{-}post}$, $\Delta EE_{2hr\text{-}post}$ were calculated by subtracting EE_{pre} from that of immediate-post $EE_{imm\text{-}post}$, $EE_{1hr\text{-}post}$, $\Delta EE_{2hr\text{-}post}$, respectively.

Statistical analysis

Anthropometric measurements

Changes in body mass, anthropometric composition (fat, lean body and muscle mass percentage), and perimeters (thigh, arm, upper arm, calf, waist,

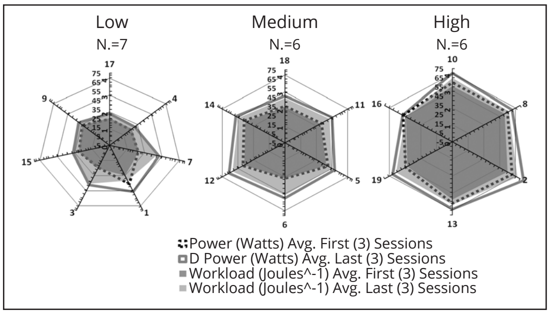

Figure 2.—Work (J^{-1}) and power (W) for IG subjects with "low", "medium", and "high" capacity. Dark grey dotted lines and filled areas connect the 6 (or 7 low) subjects, indicating average work and power during first 3 sessions (week 1 of intervention, S1, S2, and S3). Light grey solid lines and filled areas connect the subjects and indicate average work and power during last 3 sessions (final week of intervention, S17, S18, and S19). Increases in both work and power were observed for each individual in the 3 subgroups, excepting one subject (see #16, high).

and hip) were analyzed by a paired-t test, which compared conditions corresponding to before and after the 6-week study in subjects for the IG and CG groups. The level of significance was set at $P<0.05$ for all measurements, excepting the muscle mass analysis where the assessment P level is specified.

EPOC evaluation as a function of intervention

Paired t-tests comparing $\Delta EE_{imm\text{-}post}$ of the IG on a HIIT day *vs*. a non-HIIT day as well as t-tests comparing $\Delta EE_{imm\text{-}post}$ of IG on a HIIT day *vs*. $\Delta EE_{imm\text{-}post}$ of CG in a measurement day were performed to evaluate EPOC.

Additional EPOC evaluations from daily baseline EE fluctuations

Before starting the study, five daily EE measurements for all 29 subjects were assessed. The EE measurements were averaged with standard deviations to elucidate "normal" fluctuations of EE throughout a normal day routine for each individual. The fluctuation values, named Fluctuation index, were assessed from the EE's standard deviation and multiplied by 1.96 to set the confidence interval to 95%. The fluctuation index values were compared to the HIIT-induced EPOC index to determine whether significant changes were self-measured in the IG when compared to a HIIT day *versus* a baseline day. A similar comparison was performed in the CG, comparing study measurement days *versus* a baseline day.

Results

Work and power progression

Figure 2 summarizes the HIIT workload and power averaged in the IG subjects at the beginning (S1 through S3) *vs*. the end of the study (S16 through S19). Prior to beginning the intervention, maximum workload density was estimated by the NASM-certified professional for each subject. As shown in Figure 2, three distinct "HIIT-capacity" groups emerged from the IG group according to each work capacity. On average, "low-", "medium-", and "high"-capacity subjects began the study lifting sandbags (or kettle bells) of 21%, 32%, and 36% of body mass, respectively. During each session, the subjects were closely monitored for safe squat or thruster technique while being verbally encouraged to reach maximum quality reps per set. All 19 HIIT sessions were calculated for work and power (Supplementary Digital Material 2: Supplementary Figure 2). All the IG subjects, except one, responded positively to the progressive loading adjustments, thereby

Table III.—*Body perimeters' analysis.*

Perimeter	Control			HIIT		
	Before	After	Test statistics	Before	After	Test statistics
Arm	24.3±2.8	24.4±2.9	t=-0.76, P=0.46	24.4±3.4	25.0±3.5	t=-5.46, P=3.5E-5*
Upper arm	27.7±4.0	27.9±4.0	t=-0.74, P=0.48	27.0±4.1	27.4±4.1	t=-2.39, P=0.03*
Thigh	47.1±5.7	48.6±4.7	t=-1.80, P=0.10	47.0±5.7	48.7±4.3	t=-2.36, P=0.03*
Calf	36.3±2.8	36.7±3.0	t=-0.85, P=0.41	35.7±3.1	35.4±3.2	t=0.97, P=0.34
Waist	77.9±14.3	77.1±14.9	t=1.42, P=0.19	74.3±8.1	74.8±8.1	t=-0.97, P=0.34
Hip	97.8±8.4	97.6±8.2	t=0.29, P=0.78	95.9±7.1	96.9±7.1	t=-1.41, P=0.17

*Significant difference (P<0.05).

Table IV.—*Body composition analysis.*

Parameter	Control			HIIT		
	Before	After	Test statistics	Before	After	Test statistics
% fat	22.4±10.8	21.4±10.2	t=1.63, P=0.13	17.7±8.5	16.1±7.5	t=2.25, P=0.04*
% LBM	77.6±10.8	78.6±10.2	t=-1.63, P=0.13	82.3±8.5	83.9±7.5	t=-2.25, P=0.04*
% muscle	25.2±5.0	27.4±4.3	t=-1.66, P=0.13	25.6±4.8	28.1±2.7	t=-2.42, P=0.03*
Weight	65.6±13.6	65.6±14.3	t=-0.04, P=0.97	66.6±12.8	67.7±13.5	t=-2.71, P=0.01*
BMI	23.3±5.0	23.3±5.1	t=0.06, P=0.95	22.2±3.4	22.5±3.6	t=-2.72, P=0.01*

LBM: lean body mass.
*Significant difference (P<0.05).

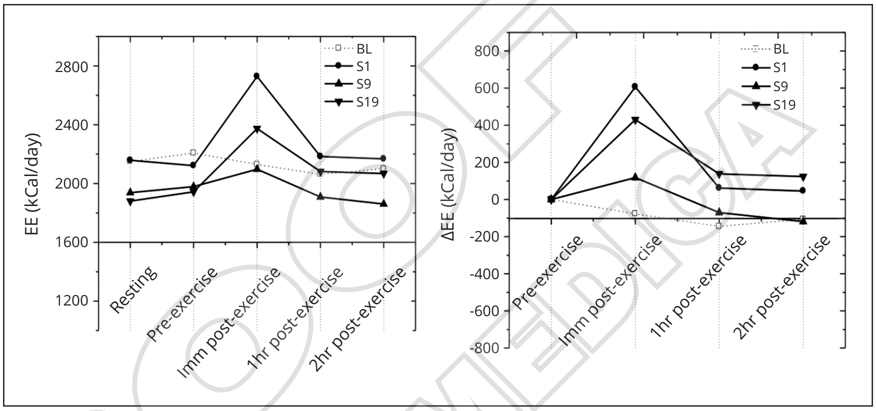

Figure 3.—Energy expenditure measurements from an IG individual at sessions S1, S9, and S19 of HIIT protocol, and on a non-HIIT day. BL is baseline or resting energy expenditure. Absolute energy expenditure from resting condition throughout the day (A), and corresponding differential energy expenditure (B) using pre-exercise energy expenditure as reference (0).

became "trained" by regularly completing high quality reps in each of 8 sets. Throughout the six weeks, each subject avoided injury and improved both form and rep quantity, while maintaining or increasing sandbag (or kettle bell) mass, and increasing averaged load to 25%, 35%, and 43% of body mass, for low-, medium-, and high- HIIT capacity groups, respectively. Specifically, work capacity per 4-minute intervention increased in all groups, as follows: from 271 to 361 J in the low capacity group; from 391 to 505 J in the mid capacity group; and from 548 to 622 J in the high capacity group, which represented increases of 34%, 29%, and 13%, respectively.

Anthropometric and physiological measurements

Anthropometric measurements

Table III and IV summarize the results of paired t-test comparisons of anthropometric changes in the IG and CG subjects before and after the study period. Details of individual changes in fat, muscle, and lean body percentage for the IG and CG subjects are presented in Supplementary Digital Material 3 (Supplementary Figure 3). While the CG subjects showed no significant changes in the anthropometric measurements (P>0.05), the IG subjects showed significant changes in seven anthropometric parameters. Perimeters of the body, including upper- and forearm and thigh, and muscle, lean body mass, fat, BMI (which includes weight) showed statistically significant increases (P≤0.04, α=0.05). Of the 19 IG subjects, five showed significant increases in muscle mass percentage equal or greater than 6%. This group was specifically studied in connection to measured EPOC.

Energy expenditure measurements

Before the study intervention started, the following measurements and protocols were conducted: 1) training of the study subjects for device use; 2) baseline measurements by each of 29 study subjects.

During the intervention part of the study, "session days" with 5 measurements per day were

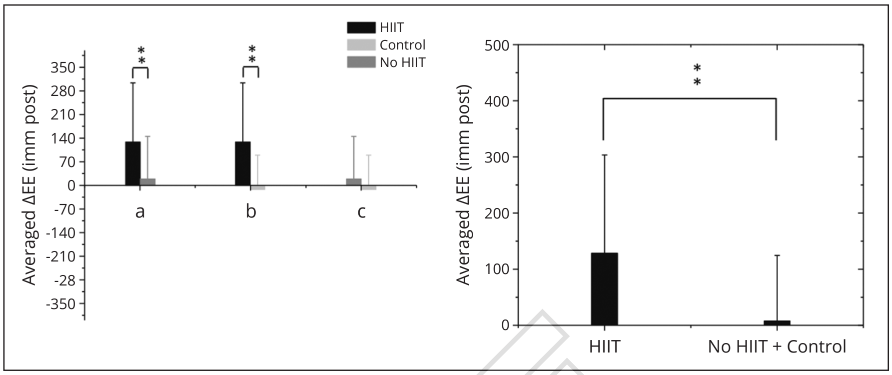

Figure 4—Comparison of changes in energy expenditure for IG subjects (during HIIT days and Non-HIIT days) *vs*. CG subjects. All subjects' ΔEE were measured at the same times of the day during the 1st (S1), 4th (S9), and final week (S19) of the study. A) Three comparisons were performed: a) within the IG, HIIT day *vs*. non-HIIT day; b) between IG and CG, HIIT day *vs*. control measurement day; and c) between IG and CG, non-HIIT day *vs*. control measurement day. B) ΔEE for CG and Non HIIT day from IG were combined and compared to those measured under HIIT conditions for IG. **P=0.01, and α=0.05.

assessed. Figure 3 shows an example of the EE and ΔEE measurements performed by three study subjects from the IG during both a HIIT day and a non-HIIT day. The figure shows A) absolute energy expenditure from resting condition throughout the day, and B) differential energy expenditure from pre-HIIT (near-resting conditions) using pre-exercise energy expenditure as reference (0). As it can be observed, EPOC was evidenced on HIIT days (S1, S9, and S19) with the highest energy expenditure changes measured for immediate post-exercise conditions ($\Delta EE_{imm\text{-}post}$).

Statistical analysis of averaged $\Delta EE_{imm\text{-}post}$ throughout S1, S9, and S19 in the IG and CG (Figure 4A, case a) further indicated average differences of ~110 kcal/day from EPOC in IG HIIT days vs. IG non-HIIT days. In addition, average differences of the IG HIIT days were ~141 kcal/day vs. CG measurement days in Figure 4A, case b. Both comparisons indicated significant differences with P=0.01, and α=0.05. As a control, comparison of IG non-HIIT days vs. CG days did not show significant differences in Figure 4A, case c.

Lastly, EPOC evaluation as a function of HIIT intervention incorporated fluctuation index as defined in the experimental section. Fluctuation index is considered as the physiological fluctuation of EE values in an individual measured throughout different times of a day. The fluctuation index values averaged 216±89 kcal/day for IG, and 286±58 kcal/day for CG. EE values of $\Delta EE_{imm\text{-}post}$ (evaluating the presence or absence of positive EE changes immediately after HIIT) and EPOC index values (evaluating the presence or absence of positive EE changes over 2.5-h post-exercise period) were compared with the individual's fluctuation index. HIIT-effect positive cases were defined as both $\Delta EE_{imm\text{-}post}$ and EPOC index values were larger than the fluctuation index. As explained before, these levels indicate the maximum expected daily physiological fluctuation in energy expenditure based on 95% confidence interval (1.96SD). Nevertheless, 50%, and 8% of IG cases in a HIIT day showed $\Delta EE_{imm\text{-}post}$ and EPOC index values higher than fluctuation index values, respectively. On the contrary, 0% of CG cases in a measurement day had $\Delta EE_{imm\text{-}post}$ or EPOC index values larger than the corresponding fluctuation index values. This fact corroborated the higher probability of a positive impact of HIIT intervention on the energy expenditure for IG subjects on a HIIT day. In addition, it indicated that EPOC is higher for immediate post-exercise.

Correlation of EE changes and muscle mass

The change of muscle mass over the 6 weeks emerged as a consequence of HIIT training in the IG, significantly increasing for the IG (t=-2.42, P=0.03) *vs*. the CG (t=-1.66, P=0.13) (Table IV). Within the IG, two subgroups were identified. Subjects with 6% or larger increase in muscle mass, and subjects with 1% or no change in muscle mass. Analysis of EPOC effect via $\Delta EE_{imm\text{-}post}$

in the subgroup with 6% muscle increase (N.=5) had an averaged $\Delta EE_{imm\text{-}post}$ of 241 kcal/day (SEM=77), whereas in the subgroup showing 1% increase or no change in muscle mass (N.=7) had an average 70 kcal/day (SEM=58).

Discussion

Impact of the HIIT protocol

For the present study, HIIT was chosen as the best practice to fit the busy schedule of office workers. All subjects were sedentary and worked in office jobs requiring minimal movement and physical activity. They arrived at work early in the morning, took a lunch break, which included the HIIT training, and continued working into later in the afternoon. Convenient exercise times and settings plus available personal mobile trackers that the subjects easily engaged with indicated the potential sustainability of the HIIT practice.

EE measurements

The mobile IC device (Breezing®) used in this study was a suitable tool for measuring changes in VO_2 and VCO_2 under free-living conditions. To start with, the mobile IC device has an app that enabled friendly guidance and assessment of EE. Furthermore, due to the relatively low cost of the device (over a full magnitude cheaper than conventional instrumentation), simultaneous measurements from multiple users were enabled all at once since the study could provide one mobile IC device to each participant. Overall, the mobile IC devices provided over 340 measurements of REE and EE under pre- and post-HIIT exercise conditions throughout the six-week study. To our knowledge, there is no previous report of such a study protocol design and execution, which makes this aspect of the study innovative.

Though no statistically significant changes of REE were observed over the 6 weeks for CG and IG subjects, HIIT exercise protocol did increase post-exercise oxygen consumption and carbon dioxide production, which were recorded using the mobile IC devices. As shown in Figure 3 and 4, EPOC was evidenced in the IG during HIIT days compared to changes assessed in IG during non-HIIT days, and those assessed in the CG measurement days. Furthermore, the EPOC effect was significantly above the maximum fluctuation indexes estimated for each participant at the baseline period of the study in 50% of the cases for post-HIIT short periods of 30 min ($\Delta EE_{imm\text{-}post}$), and 8% of the cases for post-HIIT 2.5-hour period (EPOC index). This observation is in line with work published in the literature.[15, 33] The EPOC effect has been documented for HIIT protocols as producing increased levels of catecholamines and growth hormone as the body responds to reach metabolic physiological functions equilibrium and rebuilds its mechanism to counter muscle damage induced by HIIT training.[18, 33, 34]

EE and body composition

HIIT has been shown to increase mitochondrial biogenesis,[19, 35-37] muscle oxidative capacity,[28] exercise performance,[19, 20, 38] and cardiovascular functions.[39-42] All of these above factors are physiological adaptations that correlate with higher oxygen consumption.[27] In this study, HIIT-derived benefits evidenced as post-exercise energy expenditure was used instead as a predictor of muscle change over six weeks. We reported significant increases in muscle mass and perimeters associated to HIIT training (Table III, IV); therefore the body composition change in the IG participants (after 6-week training) was correlated to $\Delta EE_{imm\text{-}post}$ measures averaged from single HIIT sessions (S1, S9, and S19) of 4 min each. As shown in the Results section of this paper, the work demonstrates that subjects with greater gains in muscle mass (>6%) showed higher measurements of energy expenditure $\Delta EE_{imm\text{-}post}$, indicating that the post-exercise energy expenditure effect could be used to predict greater or lesser muscle mass change in similar 6-week training regimens.

Conclusions

Increasingly, sophisticated consumers, as well as personal trainers seek meaningful feedback for planning and maintaining effective routines that include post-exercise recovery and long-term muscle change strategies. Nineteen IG sedentary office workers experienced a time saving, low-cost, safe, and effective training protocol. We demonstrated that it is feasible for 29 study participants to independently use a mobile IC device to measure energy expenditure. Furthermore, we demonstrated that the mobile IC device application recorded and tracked the direct relevant measurement of gas exchange, REE, and EPOC-like measurements used in elucidating EPOC immediately following HIIT training.

Another interesting fact of the mobile IC device is that it enabled less than 2-minute EE measurements to show evidence of EPOC, a highly dynamic measure that may be difficult to attain from measurement protocols taking 10 minutes or longer. The EPOC measurements were evaluated against individual participants, correlated with their body composition changes, and were subsequently shown predictive muscle mass change. It is worth noting that not all subjects show muscle mass change, which indicates that EPOC cannot be calculated but has to be tracked. This study also shows that the study of EPOC effect can be, for the first time, easily detected with the help of a mobile metabolic tracker.

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Conflicts of interest.—Xiaojun Xian, Francis Tsow, David Jackemeyer, Ashley Quach, Nongjian Tao, and Erica Forzani are employees of Breezing Co. All other authors have no conflicts of interest to disclose.

Authors' contributions.—Xiaojun Xian, Francis Tsow: study and experiment. Samita Rai, Ashley Quach, Amlendu Prabhakar: diet management and data collection. Troy Anderson: exercise design and coordinator. David Jackemeyer, Mirna Terrera: discussion on understanding of EPOC and mobile indirect calorimeter, subject recruitment. Erica Forzani: design of study, logistics (IRB), discussion. Nongjian Tao: support and discussion.

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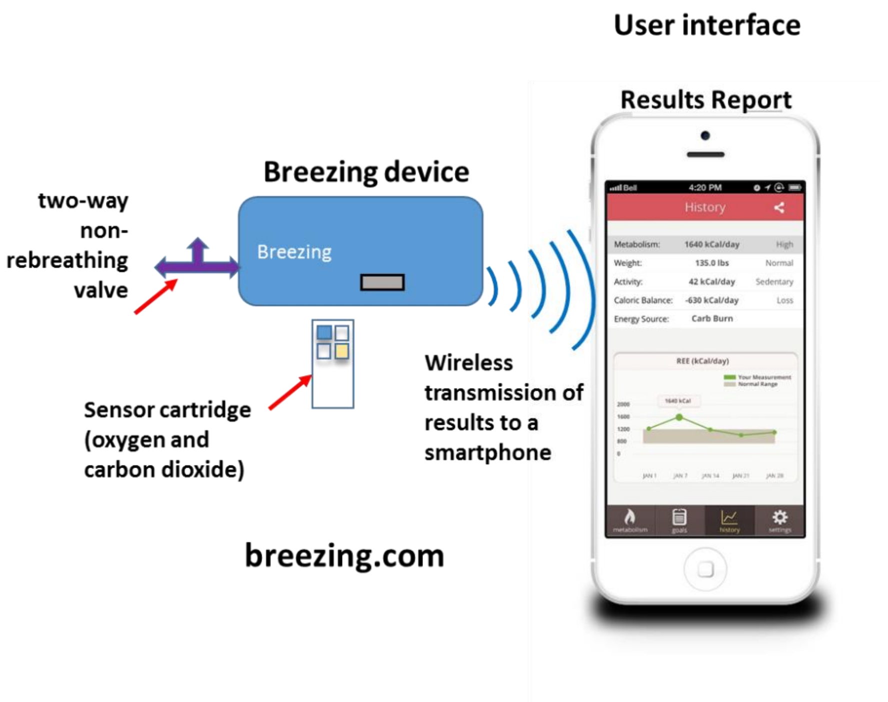
For supplementary materials, please see the HTML version of this article at www.minervamedica.it

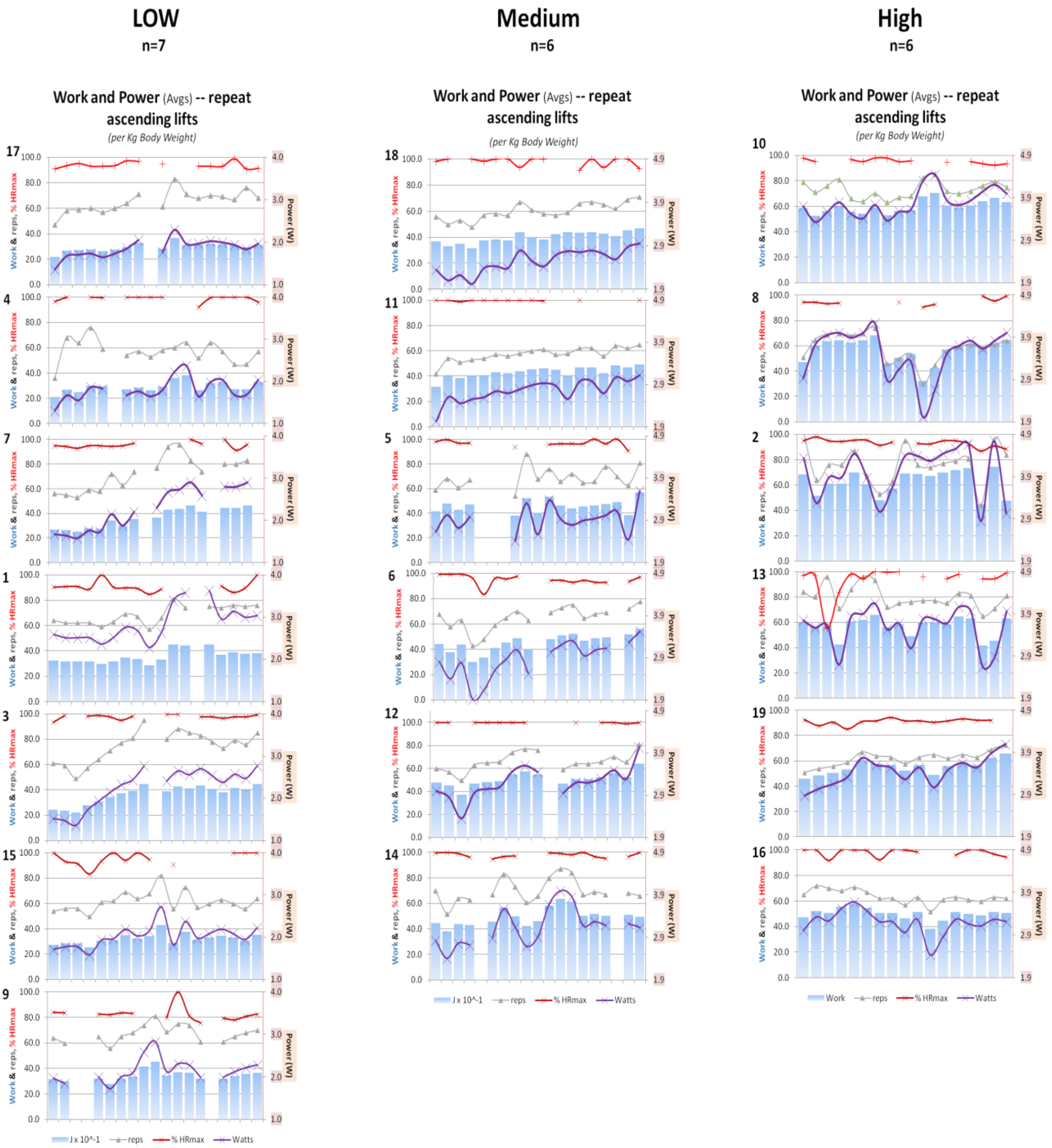
SUPPLEMENTARY DIGITAL MATERIAL 1

Supplementary Figure 1.—The mobile indirect calorimeter device, Breezing® is an indirect calorimeter that measures the rate of O_2 consumption (VO_2) and CO_2 production (VCO_2) by exhaled breath analysis. It is a portable, pocket-sized device that is intended for personal use. It synchronizes with a mobile device through a dedicated phone/table application. The application guides the user for accurate sample delivery, receives the data from the device *via* Bluetooth® chip and displays it to the user in real time. After the test is done, the application calculates the values of energy expenditure based on Weir Equation.[43]



SUPPLEMENTARY DIGITAL MATERIAL 2

Supplementary Figure 2.—Session-by-session progression of work (J/kg), heart rate (bpm), repetition (number), and power (W) for each study subject in the intervention group from session 1 (S1) through session 19 (S19). Subjects were divided into 3 sub-groups according to low, medium, and high workloads.



SUPPLEMENTARY DIGITAL MATERIAL 3

Supplementary Figure 3.—Fat, lean body mass (LBM), and muscle mass percentage (%) before (light grey) and after (dark grey) the HIIT intervention study for: A) the intervention group, and B) the control group.