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Research article

Aquatic High-Intensity Interval Training Improves Vascular Function, Whereas Aquatic Moderate-Intensity Continuous Training Lowers Resting Heart Rate in Overweight and Obese Young Adults: A Randomized Controlled Trial

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Abstract

We investigated the effects of 8-week aquatic moderate-intensity continuous training (aMICT) and aquatic high-intensity interval training (aHIIT) on body composition, aerobic fitness, arterial stiffness, and endothelial function in overweight and obese young adults (OOYA). Sixty-one OOYA were randomly assigned to aHIIT, aMICT, or Control group. aHIIT group underwent twelve 30-second exercise bouts with the intensity of 85-95% HR_{max}, with a 60-second rest between each bout. aMICT group underwent an uninterrupted exercise with the intensity of 70-75% HR_{max} for 30 minutes. Endothelial function was assessed using brachial artery flow-mediated dilation (FMD) and arterial stiffness was evaluated through pulse wave velocity (PWV) and ankle-brachial index (ABI). Results revealed that aHIIT but not aMICT decreased ABI and increased FMD and skeletal muscle mass, whereas only aMICT decreased resting heart rate. A positive correlation was found between the change in weight with the change in FMD ($r = 0.527$, $p = 0.020$) after aHIIT. Following subgroup analysis, a positive correlation between change in weight and change in FMD was also found in participants with increased skeletal muscle mass in aHIIT group ($r = 0.665$, $p = 0.002$). Moreover, the change in VO_{2max} was positively correlated with the change in FMD ($r = 0.568$, $p < 0.001$). In conclusion, both aHIIT and aMICT can raise aerobic capacity among OOYA. Importantly, aHIIT offers a time-efficient option to improve vascular function in OOYA, whereas aMICT may be preferable when the primary goal is to lower resting heart rate.

Key words: High-intensity interval training, moderate-intensity continuous training, aquatic exercise, vascular function, obesity, overweight.

Introduction

In 2022, more than one billion people were living with obesity, representing 16% of the world's adults, which was more than doubled since 1990 and quadrupled among adolescents (Collaboration, 2024). It indicates that there is a trend of obesity at a younger age, which can increase the risk of chronic diseases, such as hypertension, diabetes mellitus, and cardiovascular disease (CVD) during adulthood (Mezhal et al., 2023; Volpe and Gallo, 2023), and may even influence offspring risk for overweight and obesity (OO) (Bush et al., 2011). In other words, weight management should also be taken seriously in young adults, as health status at this age can affect the health trajectory for the rest of life.

Abnormalities in vascular function are associated with increased risk of cardiovascular events in obese people (Caballero, 2003). Evidence has shown that excess adiposity promotes chronic low-grade inflammation, oxidative stress, and insulin resistance, leading to reduced nitric-oxide bioavailability and endothelial dysfunction and increased arterial stiffness in young adults (Bessesen and Van Gaal, 2018; Caballero, 2003; Roberts and Porter, 2013). Obesity-induced atherosclerosis can be characterized by arterial stiffness, which could be assessed by ankle-brachial index (ABI) and pulse wave velocity (PWV) (Giugliano et al., 2012; Laurent et al., 1994; Laurent et al., 2006). Enhanced ABI and PWV have been reported in people with OO (Jefferson et al., 2016; Signorelli et al., 2011). Additionally, endothelial function is essential for the appropriate maintenance of cardiovascular health, and endothelial dysfunction has been considered as the first step in the progression of atherosclerosis (Gutierrez et al., 2013). Obesity has been demonstrated to be correlated with endothelial dysfunction (Caballero, 2003). Moreover, weight loss in people with OO positively improves vascular endothelial function as reflected by increased flow mediated dilation (FMD), and thus decreases cardiovascular risks (Joris et al., 2015).

Land-based exercise is widely recommended for its demonstrated non-pharmacological effects on improving body composition and cardiovascular health in the population with OO (Batrakoulis et al., 2022). In addition, to those with or without moderate-to-high risk of CVD, high-intensity interval training (HIIT) showed superior or similar improvements in cardiovascular function and aerobic fitness, compared to traditional moderate-intensity continuous training (MICT) (Luo et al., 2024; Ramos et al., 2015). Nevertheless, land-based HIIT may not be an appropriate choice for people with OO, because of the increased risk for knee- and other injuries in people with OO while

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performing HIIT (Nagle et al., 2017). As an alternative safe and effective exercise modality, aquatic exercise could minimize weight-bearing stress and therefore reduce the risk for joint injuries (Nagle et al., 2017), therefore, is particularly suitable for the population with OO. Furthermore, due to the fact that immersion in water leads to hydrostatic pressure gradient, which enhances venous reflux and the blood volume of heart and intrathoracic vessels by augmenting the pressure on immersed body surface, aquatic exercise is beneficial for improving cardiovascular health (Epstein, 1976; Tang et al., 2022; Weenink and Wingelaar, 2021). However, it remains unclear whether aquatic exercise is effective at improving the vascular health as well as aerobic fitness in people with OO. Therefore, the present study aimed to investigate the effects of 8-week aquatic HIIT (aHIIT) and aquatic MICT (aMICT) on body composition, arterial stiffness, endothelial function, and aerobic fitness in overweight and obese young adults (OOYA). We hypothesized that 8 weeks of aHIIT would produce improvements in endothelial function and arterial stiffness, while both aHIIT and aMICT would enhance aerobic fitness in OOYA.

Methods

Participants

Sample size was estimated with G*Power 3.1 for a two-way repeated-measures ANOVA (within-between interaction, 3 groups × 2 time points). An effect size of 0.30 was taken from the between-group difference in FMD observed by a meta-analysis (Joris et al., 2015). With $\alpha = 0.05$, $\beta = 0.80$, correlation among repeated measures = 0.60, and $\varepsilon = 1.00$, the required total sample size was 54 participants.

A total of sixty-eight volunteers were screened and seven of them were excluded. The remaining sixty-one either overweight or obese participants between the ages of 18 and 45 years were initially recruited from local community, and five participants withdrew during the intervention (minor illness = 2, lack of time = 3), with 56 participants (23.4 ± 5.1 years, 1.72 ± 0.1 meters, 80.9 ± 11.9 kg, 27.3 ± 1.9 kg/m²) completing the experiment (Figure 1).

The inclusion criteria were adults with body mass index (BMI) ≥ 25 kg/m², skilled in swimming yet absented from regular physical exercise (equating to less than 90 minutes per week) over the last three months. Eligible participants had not adhered to any specific dietary programs or nutritional supplement protocols within the past six months, and did not suffer any sport injuries during this period. The participants who were diagnosed with metabolic, cardiac, gastrointestinal or neurological diseases, current use of stimulants or psycho-active medications, as well as with a history of severe surgical procedures, were excluded. This study was approved by the Ethics Committee of Guangzhou Sport University (2023LCLL-28) and executed in accordance with the Declaration of Helsinki. Prior to participation, each individual voluntarily signed written informed consent.

Study design

The protocol for this study was modified based on a previous description (Tang et al., 2022). Specifically, a statistician generated a sequence with the *RAND* function in Microsoft Excel 2016, using a 3: 3: 2 ratio (aHIIT: aMICT: Control) to preserve statistical power in the intervention arms while allowing for expected 10% attrition. Eligible participants were listed in the order of screening completion and assigned sequentially according to the random list. Group codes were placed in opaque, sealed envelopes that were opened only after baseline measurements, thereby ensuring allocation concealment. All supervised sessions were conducted from 5 pm to 6 pm on Mondays, Wednesdays, and Fridays, trained in a 25°C constant temperature pool for 8 weeks, with a total of 24 training sessions. The late-afternoon was selected to standardize circadian influence across participants since core body temperature, muscle flexibility, and aerobic performance are typically considered to peak at this time, potentially reducing injury risk and inter-session variability (Atkinson and Reilly, 1996). During the training periods, participants were asked to maintain their usual dietary habits and physical activities. Body composition, aerobic fitness, and vascular function were measured before and after the training program in a quiet room at 25°C temperature with an average humidity of 50%. Participants were not allowed to consume alcohol and caffeine for 24 hours before the measurement, and were requested to fast for 8 hours before the vascular function test, as well as were instructed to obtain ≧ 7 hours of sleep on the preceding night of the test.

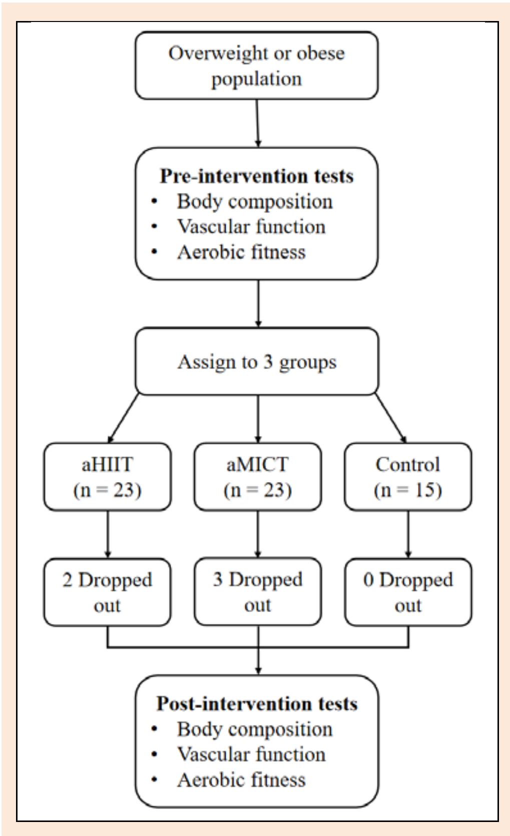

Figure 1. **Flow chart.**

Before the first training class, all participants attended a 30-minute familiarization session in the pool including (a) safety instructions and pool rules, (b) fitting and calibration of heart-rate straps, and (c) a walk-through of the complete session at low intensity with 50-55% HR_{max}.

Evidence suggests that 10-15 minutes of progressive low-intensity warm-up can raise core body temperature, enhance neuromuscular readiness, and acclimatize the body to water temperature without inducing fatigue (Bishop, 2003). Accordingly, during the 8-week protocol every training session started with a 5-minute land-based warm-up comprising dynamic calisthenics (arm circles, trunk rotations, leg swings) and dynamic hamstring and quadriceps stretches, followed by a 10-minute aquatic warm-up at 50-55% HR_{max}, which included (a) slow water jogging, (b) sculling and flutter kicks, (c) breaststroke technique drills, and (d) treading water and breathing-pattern practice, concluded with a 10-minute cool-down of stretching and slow water walking. Polar heart rate monitors were applied to continuously monitor heart rate. HR_{max} was obtained by a formula: 220 minus age. The details of exercise protocol are shown in Figure 2.

aHIIT session consisted of twelve sprint bouts (breaststroke), each lasted 30 seconds, with an intervening rest period of 60 seconds between bouts, and 18-20 minutes (6 minutes of effective swimming) in total. In the first week, 8-10 bouts were performed following 80-85% HR_{max}. Participants completed the sprints with 85-95% HR_{max} from the second week until the end of the 24th session. This aHIIT program was developed based on our previous study of inactive adults and a study which showed that 5 weeks of aHIIT training increased VO_{2max} of OOYA by 5% (McDaniel et al., 2020; Tang et al., 2022).

aMICT session performed the intensity of 70-75% HR_{max}, 30 minutes of uninterrupted swimming (breaststroke) for 20 minutes in the first week and maintained 30 minutes from the second week. The intensity was checked every 5 minutes during the session. The intensity and duration of aMICT program is recommended by the American College of Sports Medicine for weight management and cardiovascular health (Medicine, 2021). In addition, a recent randomized controlled trial in OOYA reported that 10 weeks of thrice-weekly water-based aerobic exercise produced significant improvements in body composition and resting heart rate (Ben Cheikh et al., 2025).

Participants in the control group were requested to maintain their current daily lifestyle as much as possible and avoid regular exercise during this study.

Body composition

Body composition measurements were performed between 8 am and 10 am after an overnight fast of ≧ 8 h. Height and weight were determined to calculate BMI. Fat mass (kg and %) and skeletal muscle mass (kg) were recorded using a bio-eletrical impedance analyzer (InBody 370, Korea). All Participants were instructed to stand-barefooted with upright position in minimal clothing on the analyzer until the completion of the records.

Aerobic fitness

Aerobic fitness was assessed using a MasterScreen CPX equipment (CareFusion, Hochberg, Germany) connected to a cycle ergometer (Ergoline, Bitz, Germany). Recent evidence shows that bicycle and tethered swimming tests demonstrated high validity with comparable VO_{2max} estimates, explaining a large proportion of differences in endurance performance (de Haan et al., 2024). In this cardiopulmonary test, a modified protocol (Andersen, 1995) was applied in which the warming up was designed as 25 watts (W) and the workload was then increased by 25 W every 2 minutes until one of the following occurs: (1) participants have a palpitations or chest tightness; (2) maximal oxygen uptake (VO_{2max}) does not increase with increasing workload; (3) exhausted before the 1 or 2 are reached. In addition, a continuous electrocardiography was conducted to record heart rate but its abnormalities were not used to terminate the test.

Vascular function

ABI was measured by an oscillometric device (bosoABI-system 100; BOSCH & SOHN, Germany) which was able to simultaneously record the systolic blood pressure of four extremities. Before the measurement, all participants familiarized with the procedures: upper arms and both ankles were bounded by four cuffs, maintained a supine position for 5 minutes, the changes of pulse wave and blood pressure were then transmitted to a microprocessor.

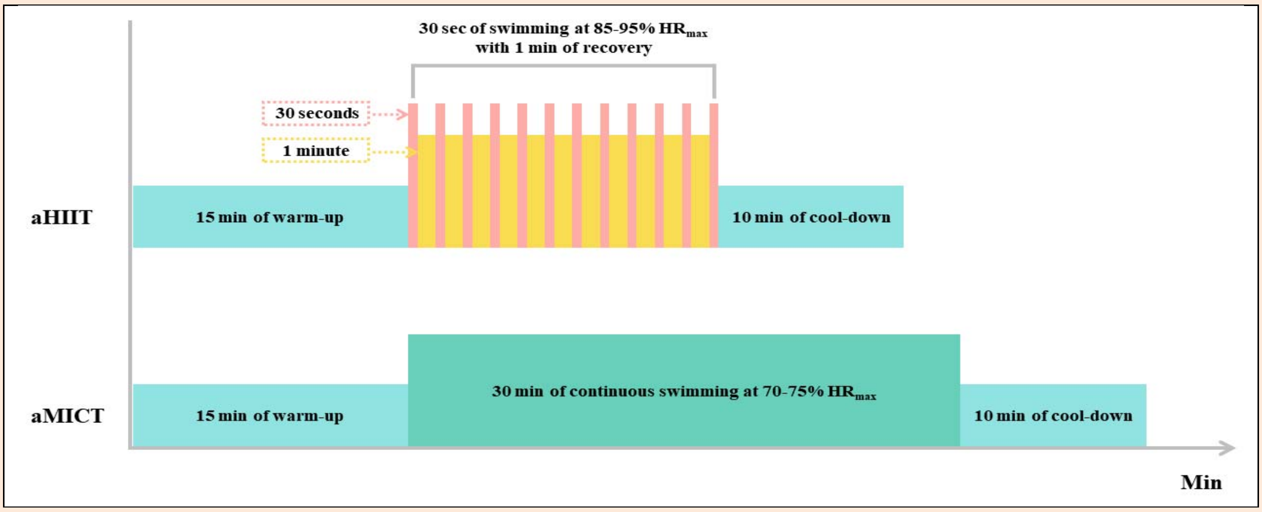

Figure 2. Exercise protocol.

ABI was subsequently calculated as the systolic blood pressure at the ankle (the mean of systolic blood pressure of the posterior tibial artery and anterior tibial artery) divided by the higher value of systolic blood pressure at the arm. An ABI value of 0.9 or less indicates the presence of peripheral arterial disease, while an ABI value above 1.4 indicates stiffness or calcified arteries (Song et al., 2019). All the procedures were operated by a trained researcher to reduce operating error.

Brachial-ankle pulse wave velocity (baPWV) was measured as a previously described technique (Sugawara et al., 2019). A SphygmoCor device (AtCor Medical, Australia) was used to determine carotid-femoral pulse wave velocity (cfPWV) which was defined as the gold-standard for the evaluation of arterial stiffness (Laurent et al., 1994; Laurent et al., 2006). All participants approved of the following procedures: three disposable electrodes connected to the ECG were placed on the sternum, suprasternal notch, and above the left hip, followed by a supine position for 10 minutes to obtain a stable ECG. The distance from the suprasternal notch to the right common femoral artery site (D1) and from the suprasternal notch to right common carotid artery site (D2) was measured using a measuring tape. The strongest femoral and carotid pulse points were sequentially explored and then lightly pressed by a pressure-sensitive tonometer. Subsequently, the transit time of the strongest pulse wave between the left ventricle and the femoral artery (T1) as well as between the left ventricle and the carotid artery (T2) were generated. The cfPWV was calculated by a formula: $\Delta D1\text{-}D2/\Delta T1\text{-}T2$. A trained researcher operated all the procedures to ensure error reduction.

Prior to assessment of FMD, participants were assigned to a quiet and air-conditioned room with 22-25℃. A blood pressure cuff was placed around the right forearm of participants and ECG clips were positioned around their left wrist and right wrist, then rested in a supine position for 15 minutes to obtain a stable ECG signal. FMD of the brachial artery diameter was measured by an ultrasound equipment with a software which generates the two-dimensional images including one longitudinal and two transverse sections (UNEX, Nagoya, Japan). The brachial artery was positioned 5 to 10 cm above the elbow and was manually scanned using a stereotactic probe with a couplant. In order to obtain the clearest vascular intimal images, an edge-tracking function from the software were applied to adjust the positions of two transverse sections. Subsequently, the vascular diameter was automatically tracked based on the longitudinal section, and the waveform of the changes in diameter within the cardiac cycle was displayed in real-time through a UNEXEF38G system. After the baseline diameter was measured, the blood pressure cuff was compressed above 50 mmHg of systolic blood pressure for 5 minutes, followed by continuous recording of change in brachial artery diameter within 2-minute decompression period. FMD was calculated as change in maximum arterial diameter of compressed period from the baseline diameter. All the procedures were completed by a professional operator.

Statistical analysis

All analyses at the baseline and at the end of the program were performed. Normality assumption and homogeneity of variance test were assessed from all data. If applicable, a two-way repeated-measures ANOVA was employed to compare the factors [group (aHIIT vs. aMICT vs. Control)], time (0 vs. 8 weeks). Mauchly's test assessed sphericity, when violated, Greenhouse–Geisser correction was used. Where the group × time interaction was not significant, but we had a priori interest in the simple time effect within each group, paired-samples t-tests were performed (pre vs post). Between-group differences in change-scores (Δ = post - pre) were examined with independent-samples t-tests. To limit inflation of type-I error, p-values from these follow-up comparisons were adjusted with the Holm-Bonferroni procedure. Non-normally distributed variables across time and between groups were compared using Wilcoxon test and Mann-Whitney U test, respectively. Covariance analysis was applied to control baseline characteristics that were not balanced between the groups. Bonferroni post-hoc test was used to adjust for multiple comparisons. For outcomes that violated normality or exhibited baseline imbalance between groups, a rank-based analysis of covariance was applied (Conover and Iman, 1981; Quade, 1967). Raw scores were converted to mid-ranks across all participants, the ranked variable served as the dependent variable in an ANCOVA with group as the fixed factor and the baseline value as covariate. Homogeneity of regression slopes was verified by the non-significant group × baseline interaction (all $p > 0.10$). The correlations between the changes of weight and FMD were assessed using partial correlation coefficients. Statistical analyses were performed with IBM SPSS Statistics V.29 and significance was set at 5% level.

Results

Effects of aHIIT and aMICT on anthropometric and aerobic fitness

The characteristics of participants are shown in Table 1. Prior to the interventions, there were no significant differences in gender, age, height, body weight, BMI, systolic pressure, diastolic pressure, and VO_{2max} among aHIIT, aMICT, and Control groups.

As shown in Table 2, after 8 weeks of intervention, BMI, and fat percentage significantly decreased in both aHIIT and aMICT groups but not in the Control group ($p < 0.05$, $p < 0.01$, or $p < 0.001$). Notably, significant group × time interaction was detected in fat percentage ($F_{(2,48)}$ = 5.54, $p = 0.007$, partial $\eta^2 = 0.19$), and significant differences in fat percentage were specifically observed in the aHIIT and aMICT groups compared to the Control group (both $p < 0.01$). Moreover, Mann-Whitney U test showed change in body weight was marginally significant between the aHIIT group and the Control group ($p = 0.063$). In addition, 8 weeks of aHIIT but not aMICT significantly reduced body weight and increased skeletal muscle mass ($p < 0.01$ and $p < 0.001$, respectively). However, no significant difference was found for fat mass among any of the groups after 8 weeks of intervention period.

Table 1. Baseline characteristics of participants. Data are shown as mean (SD).

Parameters	aHIIT	aMICT	Control
Gender (m/f)	17/4	15/5	12/3
Age (yr)	22.0 (2.0)	23.8 (5.4)	24.9 (7.1)
Height (m)	1.72 (0.10)	1.71 (0.08)	1.72 (0.08)
Weight (kg)	80.5 (13.6)	80.7 (10.6)	81.8 (10.8)
Body mass index (kg/m²)	27.1 (1.8)	27.4 (2.0)	27.4 (2.0)
Systolic pressure (mmHg)	116.2 (10.2)	109.3 (13.4)	119.7 (14.7)
Diastolic pressure (mmHg)	63.2 (7.5)	59.8 (11.8)	70.3 (10.2)
VO_{2max} (mL/kg/min)	32.1 (5.7)	29.4 (4.1)	31.3 (10.8)

VO_{2max}, maximal oxygen uptake; SD, standard deviation.

While the value of VO_{2max} was adjusted by using a rank transformation and covariance analysis, significant improvements in VO_{2max} were detected after both aHIIT and aMICT ($p < 0.01$, $d = 0.15$ and $p < 0.001$, $d = 0.13$ respectively) interventions, however, there was no difference between groups.

Table 2. Correlations of change in weight with change in FMD. Results from controlling for age and pre-test FMD.

Group	Variables	Correlation (r)	p
aHIIT	Weight, FMD	0.527	0.020
aMICT	Weight, FMD	-0.007	0.977
CON	Weight, FMD	-0.315	0.346

Effects of aHIIT and aMICT on vascular function

Significant group × time interaction was detected in RER ($F_{(1,52)} = 14.5$, $p < 0.001$, partial $\eta^2 = 0.36$). As seen in Table 2, compared to the baseline, resting heart rate significantly decreased in the aMICT group ($p < 0.001$, $d = -1.48$) rather than in the aHIIT group or the Control group. Notably, changes in resting heart rate were significantly different between the aMICT group and the Control group ($p < 0.01$) as well as between the aMICT group and the aHIIT group ($p < 0.01$). In addition, a significant group × time interaction also was detected in right ABI ($F_{(2,52)} = 4.11$, $p = 0.03$, partial $\eta^2 = 0.19$), which was significantly decreased after 8 weeks of aHIIT but not aMICT. A significant difference in right ABI between the aHIIT group and the aMICT group ($p < 0.01$), and a marginal difference in right ABI between the aHIIT group and the Control group ($p = 0.06$) were observed. Although there were no changes in left ABI and diastolic pressure after aHIIT and aMICT, significant differences in both left ABI and diastolic pressure were found between the aHIIT group and the aMICT group (both $p < 0.05$). However, no significant differences were found for systolic pressure, baPWV, and cfPWV among any groups after the 8-week intervention period. Furthermore, a marginal significance was found in basal brachial artery diameter after 8 weeks of aHIIT intervention ($p = 0.078$). In addition, aHIIT rather than aMICT significantly increased peak brachial artery diameter ($p < 0.001$, $d = 0.21$) and FMD ($p < 0.001$, $d = 0.73$) after controlled the baseline of FMD.

Supplementary analyses

Sex-specific analysis revealed no significant sex × group interaction for VO_{2max}, resting heart rate, PWV, and ABI (all $p > 0.15$). Effect-size estimates were similar in men and women ($d \leq 0.20$ for VO_{2max} and approximately 1.0 for the resting heart rate reduction observed with aMICT). For FMD, the exercise interventions produced a moderate improvement in men but only a small change in women. Nonetheless, the interaction term did not reach significance (partial $\eta^2 < 0.05$).

Analyses of the correlations between different variables

Our correlation analyses showed that a significantly positive correlation ($r = 0.568$, $p < 0.001$) was found between change in VO_{2max} and change in FMD after 8 weeks of interventions (Figure 3). In addition, change in weight was positively correlated with change in FMD ($r = 0.527$, $p = 0.020$) after aHIIT intervention (Table 3). Notably, following subgroup analysis, a positive correlation between change in weight and change in FMD was also found in participants with increased skeletal muscle mass in the aHIIT group ($r = 0.665$, $p = 0.002$).

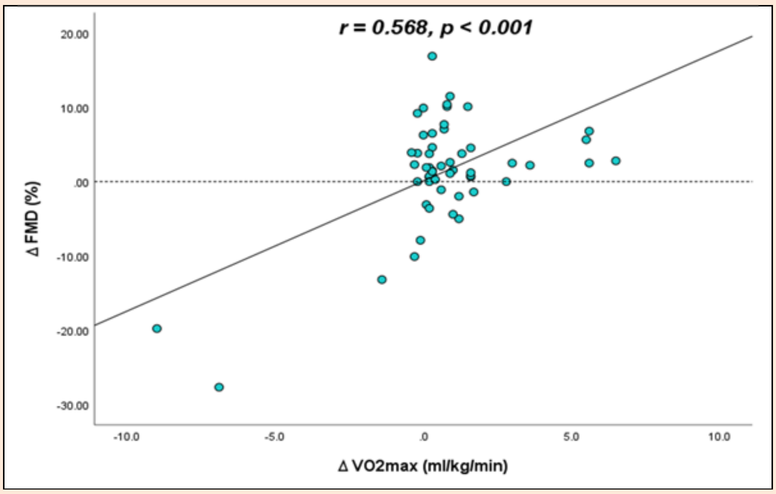

Figure 3. A correlation between change in VO_{2max} and change in FMD.

Table 3. The anthropometric, aerobic fitness, and vascular function parameters of participants pre- vs. post-training programs. Data are shown as mean (SD).

Parameters	aHIIT		aMICT		Control	
	Pre	Post	Pre	Post	Pre	Post
Weight (kg) [n]	80.5 (14.0)	78.9 (14.4) **	80.7 (10.8)	79.7 (10.7)	81.8 (10.8)	82.5(10.9)
Body mass index (kg/m²) [n]	27.1 (1.8)	26.6 (2.1) **	27.4 (2.1)	27.1 (1.9) *	27.4 (2.0)	27.5 (2.0)
Fat (kg)	20.3 (4.8)	18.8 (5.9)	22.9 (5.6)	21.2 (6.9)	21.6 (7.0)	20.9 (5.4)
Fat (%)	26.1 (6.0)	24.2 (6.6)***,[a]	27.9 (7.1)	25.7 (8.3) **,[a]	24.1 (7.5)	25.2 (5.5)
Skeletal muscle (kg)	33.5 (7.4)	34.4 (7.4) ***	33.0 (6.5)	33.9 (6.6)	34.7 (6.0)	35.8 (7.2)
VO_{2max} (mL/kg/min) [n]	32.1 (5.9)	33.0 (6.1) **	28.9 (4.2)	29.5 (4.7) ***	31.3 (10.8)	32.5 (9.1)
Resting heart rate (bpm)	70.7 (6.7)	68.5 (6.6) [b]	77.7 (7.7)	66.6 (7.3) ***,[a]	67.9 (9.7)	67.1 (9.8)
Systolic pressure (mmHg)	116.2 (10.5)	114.5 (11.3)	109.2 (14.5)	111.9 (12.5)	119.7 (14.7)	116.7 (9.2)
Diastolic pressure (mmHg) [n]	63.2 (7.7)	62.1 (7.3) [b]	60.3 (12.7)	67.8 (8.4)	70.3 (10.2)	67.7 (9.7)
ABI Left	1.07 (0.06)	1.04 (0.05) [b]	1.02 (0.10)	1.07 (0.06)	1.02 (0.09)	1.00 (0.09)
ABI Right	1.08 (0.04)	1.02 (0.05)**,[b]	1.02 (0.09)	1.04 (0.07)	1.02 (0.08)	1.01 (0.07)
Pulse wave velocity						
baPWV Left (m/s)	9.83 (0.83)	9.68 (1.13)	9.55 (1.79)	9.80 (0.99)	9.66 (1.01)	9.48 (1.16)
baPWV Right (m/s)	9.81 (0.98)	9.88 (1.34)	9.76 (1.82)	9.80 (0.99)	9.83 (1.17)	9.68 (1.32)
cfPWV (m/s)	6.07 (0.64)	6.12 (0.99)	6.04 (1.47)	6.05 (0.83)	6.01 (1.11)	5.91 (0.95)
Brachial endothelium						
Basal diameter (mm)	3.94 (0.54)	3.96 (0.54)	3.98 (0.56)	3.95 (0.42)	3.89 (0.68)	3.88 (0.81)
Peak diameter (mm)	4.40 (0.60)	4.53 (0.64)***	4.51 (0.60)	4.56 (0.54)	4.42 (0.75)	4.36 (0.90)
FMD	11.52 (3.13)	14.23 (4.19)***	13.92 (3.62)	15.79 (3.38)	14.11 (9.52)	12.50 (8.99)

VO_{2max}, maximal oxygen uptake; ABI, ankle-brachial index; baPWV, brachial-ankle pulse wave velocity; cfPWV, carotid-femoral pulse wave velocity; FMD, flow-mediated dilation. [n] Non-parametric tests, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ vs. pre-training. [a] Significantly difference from Control, b Significantly difference from aMICT.

Discussion

The results of the current study showed that 8 weeks of aquatic exercise led to improved body composition, vascular function, and aerobic fitness in OOYA, which validating our hypothesis. Importantly, to the best of our knowledge, this was the first study to examine the effects of aHIIT and aMICT on arterial stiffness, endothelial function, and aerobic fitness in OOYA. Our results revealed that aHIIT and aMICT produced different vascular adaptations in OOYA, with aHIIT increasing brachial diameter and FMD and decreasing ABI and aMICT reducing resting heart rate. In addition, both aHIIT and aMICT improved body composition and VO_{2max}.

Numerous previous studies have shown that physical exercise increases VO_{2max} in humans across all ages, despite healthy or chronic medical conditions (Lahart and Metsios, 2017; Ramos et al., 2015). Consistently, the results of the present study provide the evidence that both aHIIT and aMICT increased VO_{2max} in OOYA, suggesting that aquatic exercise is beneficial for improving aerobic fitness in this population. However, although both aHIIT and aMICT reduced body weight, BMI, and body fat percentage, only aHIIT increased skeletal muscle mass in OOYA. These data are consistent with previous studies which reported that HIIT has more potential to increase skeletal muscle mass compared to MICT (Ravnholt et al., 2018). Conversely, a systematic review of 20 randomized trials reported that aMICT increased skeletal muscle mass, whereas aHIIT appeared less effective (Zhu et al., 2023). Likewise, another study found no additional lean mass gain after 12 weeks of deep-water HIIT compared with continuous water cycling, despite identical weekly exposure (Kanitz et al., 2015). Differences in program duration, water depth, and participant characteristics may account for these divergent results.

Arterial stiffness was commonly assessed by ABI and PWV, which are independent risk factors for predicting CVD. Regarding the effects of physical exercise on ABI are still vague (Aboyans et al., 2012), the present study reported that ABI was decreased after aHIIT and change in ABI was significantly different between aHIIT and aMICT, suggesting that aHIIT is superior to improve lower limb vascular tone than aMICT. Our finding is similar to a study showed that an incremental exercise decreased ABI in healthy young adults (Kyte et al., 2023). In addition, both land-based HIIT (Luo et al., 2024) and MICT (de Oliveira et al., 2020) have been shown to decrease PWV in individuals at risk for CVD. Moreover, we previously showed that 6 weeks of land-based exercise training with dietary restriction decreased baPWV and cfPWV in obese adolescents (Huang et al., 2019). Different from previous studies, the present study was the first attempt to investigate the response of PWV to 8 weeks of aquatic exercise in OOYA and demonstrated that neither HIIT nor MICT elicited changes in baPWV and cfPWV of OOYA. A plausible explanation could be that the participants in the present study are young adults and their PWV values maintain in normal range, therefore, aquatic exercise interventions for 8 weeks might not significantly improve PWV. Accordingly, in this population, a training related decline in ABI is more plausibly attributed to peripheral vasodilation or altered limb vascular resistance than to a reduction in arterial stiffness.

Elevated resting heart rate has been recognized as an independent risk factor for CVD in healthy individuals (Cooney et al., 2010). In addition, a network meta-analysis compared the efficacy of 5 exercise types in OO adults and reported that the significant decrease in resting heart rate were observed in MICT and multicomponent training rather than combined training, interval training, or resistance training (Batrakoulis et al., 2022). Furthermore, our previous study of inactive adults also found that 6 weeks of aMICT but not aHIIT decreased resting heart rate (Tang et al., 2022). These previous observations are consistent with the present study and suggest that aMICT is more effective than aHIIT at reducing resting heart rate in OOYA. Head-out immersion redistributes blood centrally under hydrostatic pressure, thereby increasing stroke volume and eliciting a vagally mediated bradycardia. Evidence demonstrates a pronounced parasympathetic dominance during brief immersion periods and even after six hours of continuous immersion (Florian et al., 2013; Perini et al., 1998). Moderate-intensity continuous exercise permits this immersion-induced vagal predominance to persist whereas the pronounced sympathetic activation to high-intensity interval exercise counteracts it, which may explain the reduction in resting heart rate was only observed in the aMICT group in the present study.

FMD is considered as the most well-established method for assessing endothelial function. With the cuff pressure is released during the FMD test, the increased blood flow causes an increase in laminar shear stress, resulting in the release of nitric oxide (NO) and its associated endothelium-dependent vasodilation (Lekakis et al., 2011). Although previous studies had investigated the effects of land-based HIIT and MICT on endothelial function in obese people (Batrakoulis et al., 2022; Sawyer et al., 2016), studies comparing the impacts of aMICT with aHIIT on endothelial function in this population were lacking. In the present study, we reported that both peak brachial artery diameter and FMD significantly increased after aHIIT rather than aMICT. These results were consistent with a previous study which reported that 8 weeks of land-based HIIT rather than MICT enhanced FMD in obese adults (Sawyer et al., 2016). Furthermore, our previous study of inactive adults also proved that 6 weeks of aHIIT but not aMICT increased FMD (Tang et al., 2022). Interestingly, we found a positive correlation between change in weight and change in FMD after aHIIT. Following subgroup analysis, a positive correlation between change in weight and change in FMD was also found in participants with increased skeletal muscle mass in the aHIIT group. As mentioned above, aHIIT is more effective than aMICT to increase skeletal muscle mass, which could result in a higher intensity of laminar shear stress associated with a greater amount of NO release (Adams et al., 2017). In addition, our previous study in obese adults found that the increase in irisin was positively correlated with the increase in the number of endothelial progenitor cells, which is critical for vascular repair and angiogenesis and has been identified as an independent determinant of endothelial function (Huang et al., 2017). Therefore, we speculate that skeletal muscle-secreted myokines such as irisin may be involved in aHIIT-induced enhancement in FMD, but the underlying mechanisms need to be clarified in future studies.

In addition, our correlation analysis showed a positive correlation between change in VO_{2max} and change in FMD after 8 weeks of exercise interventions. The present study reported that both aHIIT and aMICT significantly increased VO_{2max} in OOYA. Moreover, both aHIIT and aMICT also increased FMD in OOYA (23.5% and 13.4%, respectively), although a significant difference was only seen after aHIIT. These results indicated the importance of aerobic fitness in regulating endothelial function. The significant correlation between VO_{2max} and FMD had been demonstrated in a study of an obese population performing land-based exercise (Schjerve et al., 2008). Other similar results were also reported in healthy people (Palmieri et al., 2005), people with diabetes (Regensteiner et al., 2005), and people with heart disease (Montero, 2015). As reviewed by Green et al., exercise training increases endothelial production of NO by increasing aerobic fitness while promoting vascular endothelial adaptation to shear stress (Green et al., 2004). This increase in shear stress is partly due to the increase in localized blood flow induced by skeletal muscle activity (Green et al., 2004). Consequently, the results of the present study emphasized the importance to enhance aerobic fitness in exercise training with the aim of improving endothelial function.

There are several limitations of the present study. Firstly, the sample size of this study is relatively small, which may limit the generalizability of the findings to a larger population. Secondly, although all participants were asked to maintain their habitual lifestyle during the intervention, we did not monitor how participants behaved on a daily basis. For instance, we did not administer a validated physical activity questionnaire (e.g., International Physical Activity Questionnaire), therefore we cannot exclude the possibility that unrecorded changes in habitual activity influenced some outcomes. On the other hand, the unrecorded data on smoking, alcohol consumption, hydration status, sleep quality, and quality and quantity of caloric intake before and during training programs may arouse lifestyle variance, although randomization should distribute these factors evenly across groups. Moreover, due to the lack of controlling over the menstrual cycle phase, potential phase-dependent changes in endothelial function and aerobic fitness could not be taken into account, which may influence the results for female participants. In addition, because our female sample size was small, sex stratified results are exploratory and should be interpreted with caution.

Conclusion

In conclusion, both 8-week aHIIT and aMICT improved body composition and aerobic fitness in OOYA. Importantly, the present study reported that aHIIT and aMICT resulted in different vascular adaptations in OOYA, with aHIIT improving lower limb vascular tone and endothelial function and aMICT reducing resting heart rate. Furthermore, aHIIT performed a total of 2.4 hours of effective exercise throughout the intervention period, comparing to aMICT which took 12 hours of effective exercise during the period. These findings highlight the potential of aHIIT as an alternative time-efficient exercise modality in OOYA. Future studies should extend the intervention beyond 8 weeks, include objective menstrual cycle tracking and additional stiffness indices (e.g., augmentation index), and examine whether similar benefits occur in older age groups.

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The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who was an organizer of the study.

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Key points

- aHIIT and aMICT resulted in different vascular adaptations in the OOYA, suggesting that aquatic exercise can be used as a preventive strategy to reduce the incidence of cardiovascular disease.
- aHIIT saves 5 folds of time over aMICT in effective exercise, which provides an alternative and time-strategized exercise mode.
- These present findings (including correlation analysis) warrant quantitative data in larger-scale related studies in the OOYA population in the future.

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