Sports Medicine and Health Science 7 (2025) 185–189

Contents lists available at ScienceDirect

Sports Medicine and Health Science

journal homepage: www.keaipublishing.com/smhs

Original Article

Effects of high-intensity intermittent cross-training on maximal oxygen uptake

Xin Liu, Katsunori Tsuji, Yuzhong Xu, Motoyuki Iemitsu, Izumi Tabata *

Faculty of Sport and Health Science, Ritsumeikan University, Kusatsu, Shiga, Japan

ARTICLE INFO

Keywords:
Maximal oxygen uptake
Bicycling
Running
Cross-training
High intensity

ABSTRACT

We investigated the effects of high-intensity intermittent cross-training (HIICT) on maximal oxygen uptake ($\dot{V}O_2$max). The HIICT consisted of alternating intermittent 20-s treadmill running (1st, 3rd, 5th, and 7th bouts) and 20-s bicycle exercise (2nd, 4th, and 6th bouts) with a 10-s rest period. Each intensity for running and bicycling of the HIICT corresponded to an oxygen demand of ~160% and ~170% of the $\dot{V}O_2$max, respectively. Fifteen healthy young males (aged [24 ± 1] yrs) were randomly assigned to training (TG, $n = 8$) and non-training control (CG, $n = 7$) groups. The TG completed this HIICT daily 4 days/week for 6 weeks. Significant group × time interactions were observed for both the running and bicycling $\dot{V}O_2$max ($p < 0.001$ each). After the training, the $\dot{V}O_2$max for both running ([57.4 ± 4.8] mL·kg^{-1}·min^{-1}) and bicycling ([50.6 ± 3.7] mL·kg^{-1}·min^{-1}) in the TG were significantly higher than those for running ([50.1 ± 3.1] mL·kg^{-1}·min^{-1}) and bicycling ([43.7 ± 3.6] mL·kg^{-1}·min^{-1}) in the CG, respectively ($p < 0.01$ each). Post-hoc tests revealed a significant increase in $\dot{V}O_2$max for running and bicycling in the TG after the HIICT ($p < 0.001$ each) but no significant difference in the CG. These results demonstrated that the newly developed HIICT increases the $\dot{V}O_2$max for both running and bicycling.

1. Introduction

The type of high-intensity intermittent/interval training (HIIT) known as "Tabata training"[1–4] is an intense form of physical training that has been shown to improve an individual's maximal oxygen uptake ($\dot{V}O_2$max)[5] and maximal accumulated oxygen deficit (MAOD).[6] Many athletes have adopted the Tabata training method to improve their performance, which depends on the aerobic and anaerobic energy supply during specific sport activities. Since the high-intensity intermittent exercises (HIIEs) used with Tabata training are extremely demanding and exhaust the participant, even elite athletes should use caution when undergoing authentic Tabata training during a tapering period prior to participating in their main competitions.

We have thus designed a non-exhaustive high-intensity intermittent cross-exercise (HIICE) protocol that may have the same effects on aerobic energy-releasing systems as the exhaustive HIIE.[7] The HIICE protocol consists of four 20-second (s) running periods on a treadmill for the 1st, 3rd, 5th, and 7th bouts and 20-s periods of a bicycle ergometer exercise for the 2nd, 4th, and 6th bouts. The exercise intensity for the HIICE is the intensity that exhausts the participant after the completion of the 6th set or during the 7th set of the exercise with 10-s rests between exercise sets, corresponding to ~160% of the $\dot{V}O_2$max for the running exercise and ~170% of the $\dot{V}O_2$max for the bicycle ergometer exercise.[7]

The rating of perceived exertion (RPE)[8] after the HIICE protocol was reported to be simply 'hard' (15 ± 2), suggesting that the HIICE is not exhaustive.[7] The peak blood lactate concentration after the HIICE in that study ([12.8 ± 1.0] mmol/L) was significantly lower than those observed after authentic Tabata training using only running ([15.8 ± 1.4] mmol/L) or only bicycling ([15.6 ± 1.5] mmol/L).[7]

One of our research group's earlier studies also showed that the $\dot{V}O_2$ during the last bout of the bicycle ergometer exercise was significantly higher than the $\dot{V}O_2$max of the same exercise mode and similar to that of running.[7] The oxygen uptake during the last (7th) bout of the running exercise nearly reached the $\dot{V}O_2$max measured for running, suggesting that the HIICT virtually maximally stimulated aerobic energy-releasing systems for the running and bicycle ergometer exercises. These results further suggested that a HIICT protocol adopting the HIICE may improve the $\dot{V}O_2$max measured for both running and bicycle ergometer exercise.

However, our search of the relevant literature identified no published report of the effects of these types of high-intensity cross training on $\dot{V}O_2$max. We conducted the present investigation to evaluate the effects of the HIICT method on the $\dot{V}O_2$max for both running and a bicycle

* Corresponding author. Faculty of Sport and Health Science, Ritsumeikan University, 1Noji-higashi, Kusatsu City, Shiga, 525-8577, Japan.
E-mail address: tabatai@fc.ritsumei.ac.jp (I. Tabata).

https://doi.org/10.1016/j.smhs.2024.11.003
Received 20 June 2024; Received in revised form 3 November 2024; Accepted 7 November 2024
Available online 9 November 2024

Abbreviations

ANOVA	analysis of variance
HIIE	high-intensity intermittent exercise
HIICE	high-intensity intermittent cross exercise
HIIT	high-intensity intermittent training
HIICT	high-intensity intermittent cross training
IVST	interventricular septum thickness
LVEDD	left ventricular end-diastolic diameter
LVEDV	left ventricular end-diastolic volume
LVESD	left ventricular end-systolic diameter
LVESV	left ventricular end-systolic volume
LVPWT	left ventricular posterior wall thickness
MAOD	maximal accumulated oxygen deficit
min	minute
MHz	mega Herz
rpm	revolutions per minute
R	running
RPE	rating of perceived exertion
SV	stroke volume
s	seconds
$\dot{V}O2$	oxygen uptake
$\dot{V}O2max$	maximal oxygen uptake
yr	years

ergometer exercise.

The question of whether central factors (e.g., the maximal cardiac output) or peripheral factors (e.g., skeletal muscle's oxygen consumption) exert dominant role in the elevation of $\dot{V}O_2$max after endurance training has been a matter of debate.[9] The HIICT protocol has not been studied from this point of view. Since we were able to measure only the stroke volume (SV) at rest and the thickness of cardiac walls in the present study, we observed changes in these central parameters before and after the HIICT to help clarify the mechanism(s) that underlie the increase in $\dot{V}O_2$max after the training.

2. Participants and methods

2.1. Ethical approval

The protocols for the experiments and procedures involved in the present investigation were approved by the Ethics Committee of Ritsumeikan University (no. BKC-IRB-2011-05). After receiving a detailed explanation of the purpose, potential benefits, and risks of participating in the study, 16 participants gave their written informed consent. The study was implemented in accordance with the Declaration of Helsinki.

2.2. Participants

Healthy males were recruited through advertisements with posters. We excluded individuals who were performing vigorous exercise training; taking anti-hyperlipidemic, anti-hypertensive, or anti-hyperglycemic medication; or had a joint disorder or mental disorder. A sample size that was sufficiently large for a two-way analysis of variance (ANOVA) was calculated. This calculation considered the effect size (Cohen's *f*), the significance level (α), the power, and the number of levels for each factor. The effect size was set based on data obtained from a related meta-analysis, and Cohen's $f = 0.62$ was adopted.[10] This value is based on the effect size (standardized mean difference [*SMD*] = 1.24) for sprint interval training (SIT) in healthy adults. The significance level (α) was set at 0.05, and the power was set at 0.80. The number of levels for each factor was assumed to be 2, representing "group allocation (training vs. control)" and "time point (pre-vs. post-training)." The required sample size was manually calculated using the F distribution. The calculation results indicated that each group required a sample size of eight participants, with a total of 16 participants needed overall.

The allocation of the participants was then performed using computer-generated random numbers. The participants were randomly divided into two groups: the training group ($n = 8$) and the control group ($n = 8$). Before starting the training, one individual seceded from the control group for personal reasons, making the control group ($n = 7$). The mean ± standard deviation (*SD*) values for all 15 participants were age (24 ± 1) years, height (1.74 ± 0.06) m, and weight (67.7 ± 6.4) kg.

The assessors who measured these parameters were blinded to the group allocation in the present investigation.

The study was registered in the University Hospital Medical Information Network Clinical Trials Registry (UMIN-CTR; UMIN000055772)

2.3. Pretest

The bicycle exercise was conducted on a mechanically braked cycle ergometer (Monark, Stockholm, Sweden) at 90 revolutions per minute (rpm). The running was done on a motor-driven treadmill at 6° (10.5%) inclination.[1,2,6] First, to determine a linear relationship between the submaximal intensity of running (m·min^{-1}) and bicycling (watts, W) and the steady-state oxygen uptake (L·min^{-1}) for each individual, we measured the participants' oxygen uptake during the last 1 or 2 minutes (min) of six to nine different 10-min bouts of running and bicycling at a constant power between 35% and 90% of the $\dot{V}O_2$max.

Next, to determine the $\dot{V}O_2$max, we measured the participants' oxygen uptake during the last two or three 30-s intervals during several bouts of supramaximal-intensity exercises that exhausted the participants within 2–4 min.[1,2,6] For the bicycle exercise, the criterion for exhaustion was that the participant was unable to maintain the pedaling frequency at ≥ 85 rpm near the end of the bout. The criterion for exhaustion on the treadmill exercise was determined by the participant when he was unable to follow the given speed. After we confirmed a leveling-off in the oxygen uptake by increasing the intensity, the highest oxygen uptake measured was taken as the participant's $\dot{V}O_2$max for each exercise.[1,2,6]

As a pretest to determine the exercise intensity for the HIICT, the participants performed 20-s intermittent exercises at an oxygen demand of 160% and 170% of the $\dot{V}O_2$max for the running and bicycling exercise, respectively with 10-s rest intervals until exhaustion.[7] If a participant was not able to complete the 6th bout or did complete the 7th bout of exercise during this pretest, for the next pre-test he again performed the same high-intensity intermittent exercise at a lower or higher intensity than the first test. The purpose of these pre-tests was to determine the exercise intensity for the HIICT, i.e., the intensity that exhausts the participant after the completion of the 6th set or during the 7th set of the 20-s running or bicycle exercises with 10-s rests between the bouts.

2.4. Training procedure

The HIICT consisted of alternating 20-s running periods on a treadmill (for the 1st, 3rd, 5th, and 7th bouts) and the cycle ergometer exercise (the 2nd, 4th, and 6th bouts). The bouts were separated by a 10-s rest period. The exercise intensities for the running and the bicycle ergometer exercise were determined by the pre-tests as those exhausting the participant just after the completion of the 6th set or during the 7th set of the exercise. The participants completed the above-described HIICT protocol 1 × /day, 4 days/week for 6 weeks. The $\dot{V}O_2$max was determined before and at 1, 3, and 5 weeks after the completion of the training. If a participant's

$\dot{V}O_2$max for either type of exercise was observed to have increased during the training period, the power and/or the running speed was elevated. In this study, if the participation rate of 24 training sessions was $\leq$ 90%, we excluded the participant's data from the statistical analyses as "Low adherence to the exercise."

2.5. Gas analysis

The fractions of oxygen and carbon dioxide in the expired air were measured by a mass spectrometer (Arco 2000; Arcosystems, Kashiwa, Chiba, Japan). The gas volume was measured by a gasometer (Shinagawa Seisakusho, Shinagawa, Tokyo).

2.6. Echocardiographic measurement

Since one training-group participant had started the HIICT before he underwent the echocardiographic measurements, the seven other training-group participants were analyzed. We measured the stroke volume (SV), left ventricular end-systolic and end-diastolic diameters (LVESD and LVEDD, respectively), left ventricular posterior wall thickness (LVPWT), and interventricular septum thickness (IVST) with the participant at rest in the supine position by using an ultrasound system with a 2.5-MHz probe (Vivid S6, GE Healthcare Japan, Tokyo) as described.[11]

The IVST and LVPWT were determined by measuring the diameter at the point of the maximum long-axis diameter of the left ventricle where the mitral valve tip could be observed by M-mode echocardiography on the left sternal border of the 4th rib. The end-diastolic and systolic volumes were derived from Simpson's biplane analysis of two-dimensional echocardiographic images of the left ventricle that were obtained from the apical four-chamber and two-chamber views on B-mode echocardiography. Endocardial borders were automatically traced at both end-diastole (maximum dimension; LV end-diastolic volume [LVEDV]) and end-systole (minimum dimension; LV end-systolic volume [LVESV]). We calculated the SV by subtracting the LVESV from the LVEDV. The average of a minimum of five cardiac cycles was used.

All of the data (including echo images) were analyzed in a blinded fashion.

2.7. Statistical analyses

The participants' data are presented as the mean $\pm$ *SD*. The data were analyzed by a repeated-measures two-way analysis of variance (ANOVA) to determine differences between and within the training and control groups. When statistical significance ($p < 0.05$) was indicated by the ANOVA, a post-hoc test (multiple comparison) was used to compare the mean values between pre- and post-training and between the control and training groups. The significance level for all comparisons was set at $p <$ 0.05.

3. Results

All participants of the training group fulfilled all 24 training sessions (4 $\times$ week for 6 weeks) and measurements during the training period. All of the control-group participants also underwent all of the measurements that were performed for the training-group participants.

The post-training weights of the training group ([69.4 $\pm$ 4.9] kg) and control group ([67.3 $\pm$ 7.2] kg) were not significantly different from their pre-training values at ([69.3 $\pm$ 5.3] kg) and ([66.6 $\pm$ 7.5] kg), respectively.

The pre-training $\dot{V}O_2$max values for both running and bicycling did not differ between the training and control groups (Figs. 1 and 2). A significant group $\times$ time interaction was observed for both the running $\dot{V}O_2$max and the bicycling $\dot{V}O_2$max (both $p < 0.001$).

After the training, the $\dot{V}O_2$max for running ([57.4 $\pm$ 4.8] mL·kg^{-1}·min^{-1}) in the training group was significantly higher than that of the control group (50.1 $\pm$ 3.1 mL· kg^{-1}·min^{-1}, $p < 0.01$). Post-hoc tests revealed a significant increase in the $\dot{V}O_2$max for running (pre: [53.4 $\pm$ 5.3] mL·kg^{-1}·min^{-1}, post: [57.4 $\pm$ 4.8] mL·kg^{-1}·min^{-1}) in the training group ($p < 0.001$) but no significant difference (pre: [50.1 $\pm$ 2.0] mL·kg^{-1}·min^{-1}, post: [50.1 $\pm$ 3.1] mL·kg^{-1}·min^{-1}) in the control group ($p = 1.00$).

After the training, the $\dot{V}O_2$max for bicycling ([50.6 $\pm$ 3.7] mL·kg^{-1}·min^{-1}) in the training group was significantly higher than that of the control group ([43.7 $\pm$ 3.6] mL·kg^{-1}·min^{-1}, $p < 0.01$). A significant group $\times$ time interaction was also observed for the bicycling $\dot{V}O_2$max ($p < 0.001$). Post-hoc tests revealed a significant increase (pre: [45.6 $\pm$ 4.7] mL·kg^{-1}·min^{-1}, post: 50.6 $\pm$ 3.7 mL·kg^{-1}·min^{-1}) in the $\dot{V}O_2$max for bicycling of the training group ($p < 0.001$) but no significant difference (pre: [43.5 $\pm$ 2.9] mL·kg^{-1}·min^{-1}, post: [43.7 $\pm$ 3.6] mL·kg^{-1}·min^{-1}) in the control group ($p = 1.00$).

Before the training period started, the LVEDV, LVESV, SV, LVPWT,

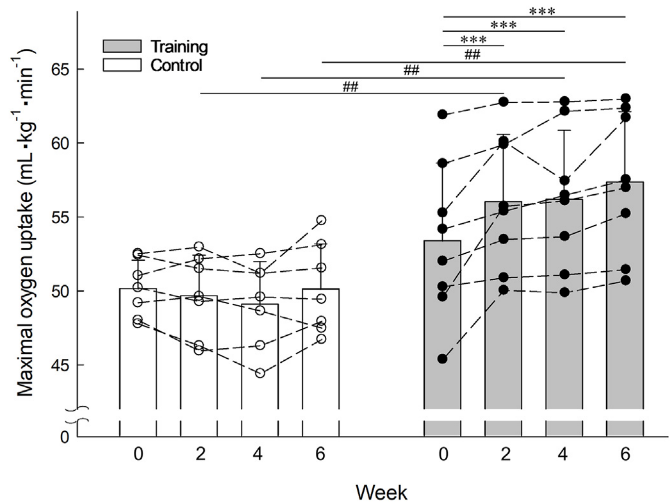

Fig. 1. Changes in the $\dot{V}O_2$max for bicycling in the control (○: $n = 7$) and training (●: $n = 8$) groups during the 6-week HIICT (high-intensity intermittent cross-training) period. ##: $p < 0.01$ between the control and training groups' values. ***: $p < 0.001$ from the pre-training values.

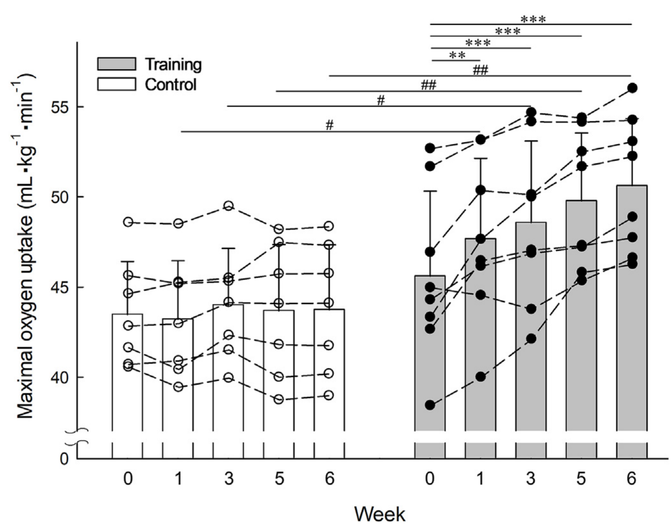

Fig. 2. Changes in the $\dot{V}O_2$max for running in the control (○: $n = 7$) and training (●: $n = 8$) groups during the 6-week HIICT period. #: $p < 0.05$, ##: $p < 0.01$ between the control and training groups' values. **: $p < 0.05$, ***: $p < 0.001$ from pre-training values.

and IVST at rest were not significantly different between the control and training groups. A significant group × time interaction was identified for the LVEDV ($p < 0.01$). After the HIICT, the LVEDV of the training group was significantly higher than that of the control group ($p < 0.05$) (Table 1). Post-hoc tests revealed a significant increase in the training group ($p < 0.01$) after the HIICT but no significant difference in the control group ($p = 0.38$). A significant group × time interaction was observed for the SV ($p < 0.004$). The SV of the training group was significantly higher than that of the control group after the HIICT ($p < 0.05$) (Table 1). Post-hoc tests revealed a significant increase in the training group ($p < 0.001$) after the HIICT but no significant difference in the control group ($p = 0.46$). The % changes in the participants' SV (mL) at rest after the training were significantly related to the % changes in the $\dot{V}O_2max$ of running (L/min; $r = 0.79$, $p < 0.05$; Fig. 3).

No significant differences in the post-training LVPWT or IVST at rest was observed between the training and control groups (Table 1).

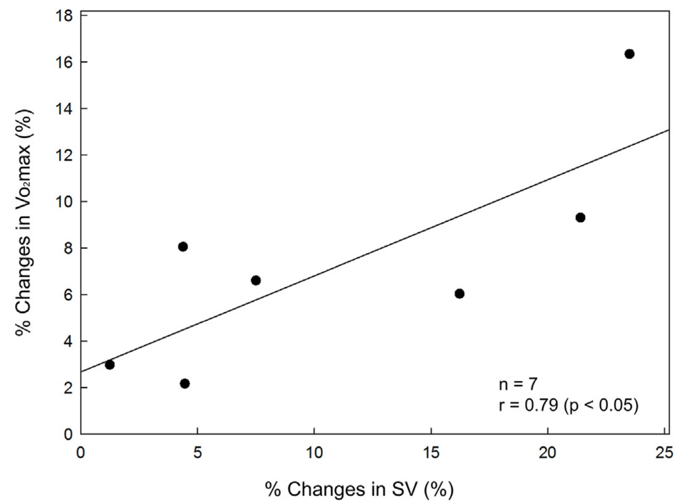

Fig. 3. The relationship between the % changes in the stroke volume (SV, mL) and ●VO_2max (L/min) after the HIICT.

4. Discussion

The main finding of this study was that the 6-week high-intensity intermittent cross-training brought about a significant increase in the $\dot{V}O_2max$ for both running and bicycling. In one of our group's previous studies,[2] we attributed the significant increase in $\dot{V}O_2max$ after an exhaustive bicycle HIIT protocol (Tabata training) to the fact that the $\dot{V}O_2$ during the last bout of the HIIT bicycle exercise reached the VO_2max that had been achieved for bicycling, suggesting that the HIIT resulted in a high aerobic energy demand for the bicycle exercise. Since the magnitude of the increase in the $\dot{V}O_2max$ for bicycling after the HIICT training in the present study (~11%) is comparable to the ~14% obtained by the HIIT in another of our group's studies,[1] we speculate that the HIICT maximizes oxygen uptake during bicycling exercise.

There is a specificity of the cardiorespiratory adaptation to different types of training.[12,13] In another words, improvement of the $\dot{V}O_2max$ is limited mostly to that measured during the same exercise as that used for the training exercise. In light of this, the present investigation revealed an advantage of HIICT in terms of dual effects on the $\dot{V}O_2max$ measured during different exercises, because the HIICT elevated the $\dot{V}O_2max$ measured during both running and bicycling. This type of HIICT may elevate the $\dot{V}O_2max$ for different types of exercise simultaneously and consequently enhance the performance in sports that involve different exercises, e.g., a triathlon.

The RPE after the HIICT exercise was reported to be (15 ± 2), suggesting that the training exercise was not exhaustive.[7] The magnitude of increase in the $\dot{V}O_2max$ for bicycling after the HIICT training in the present study (11%) is comparable to the value obtained by the high-intensity exhaustive intermittent exercise training (14%).[1] Since exhaustion after the HIIT induces stress in athletes and further limits other training after HIIT, an advantage of the HIICT investigated in the present study is the participants' ability to achieve the same level of improvement of maximal aerobic power after non-exhaustive HIICT as that obtained after conventional HIICT. The HIICT protocol can thus provide effective training for improving aerobic power, and it could be adopted as an additional tool for athletes.[1–4]

Mutton et al. trained participants with a 5-week high-intensity cross-training protocol consisting of running for 2 days/week and bicycling for 2 days/week,[14] and they reported that the $\dot{V}O_2max$ measured during both running (5.9%) and bicycling (8.4%) were similar to the values observed after 4-day running-only training in a protocol that was identical to the cross-training used, suggesting the effectiveness of their cross-training. The number of training days per week in our study is the same as that in the Mutton et al. study,[14] but the improvement in the $\dot{V}O_2max$ measured during both running (8%) and bicycling (11%) in the present investigation is greater than that observed in Mutton et al.'s study.[14] The difference may be attributed to the longer training period (6 weeks) and the higher intensity in the present protocol. The superiority of the present study might be based on its inclusion of both running and bicycling exercise for 4 days/week.

Generally speaking, central adaptation measured as elevated maximal cardiac output after training has been regarded as a major contributor to an increased $\dot{V}O_2max$ after training.[9,15] Of the two parameters that comprise cardiac output (the SV and the maximal heart rate), an increased SV at maximal exercise after training was proposed as a key factor for elevated $\dot{V}O_2max$ after training because the maximal heart rate does not increase after training.[16] Spina et al. observed a significant increase in the SV at $\dot{V}O_2max$ after training,[16] whereas in the present investigation, the SV at rest was increased after the HIICT. This training-induced change in the SV at rest is comparable to that reported by Helgerud et al., who observed changes in the SV after high-intensity intermittent exercise training.[17] We also observed that the % changes in the participants' SV at rest were significantly related to the % changes in the $\dot{V}O_2max$ of running ($r = 0.79$, $p < 0.05$). Even though changes in the SV at rest may not necessarily reflect changes in the SV during maximal exercises, our results may indicate that the training-induced increase in the $\dot{V}O_2max$ is due to a possible increase in the

Table 1
Changes in the training ($n = 7$) and control ($n = 7$) groups' LVEDV, LVESV, SV, LVPWT, and IVST at rest after the 6-week HIICT training period.

	LVEDV, mL		LVESV, mL		SV, mL		LVPWT, cm		IVST, cm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Training group	116 ± 15	125 ± 16[a,b]	40 ± 8	41 ± 8	76 ± 13	84 ± 12[a]	0.84 ± 0.13	0.91 ± 0.09	0.79 ± 0.10	0.84 ± 0.09
Control group	108 ± 12	106 ± 6	37 ± 2	37 ± 7	71 ± 9	69 ± 8	0.81 ± 0.06	0.82 ± 0.07	0.74 ± 0.04	0.76 ± 0.04

HIICT: high-intensity intermittent cross training. IVST: interventricular septum thickness, LVEDV: left ventricular end diastolic volume, LVESV: left ventricular end systolic volume, LVPWT: left ventricular posterior wall thickness, SV: stroke volume.

[a] $p < 0.05$ between the training and control groups after training.

[b] $p < 0.01$ between the values obtained at pre- and post-training.

maximal-exercise SV, which may reflect the SV at rest.

Since both bicycles and treadmills are expensive and not easily accessible to all athletes, the training protocol described herein may not be preferable to conventional training that adopts only running or bicycling. However, our findings suggest cardiovascular training effects that are equal or superior to those of other types of non-equipped cross-exercise, e.g., exercise comprised of alternating lower-body exercises (burpees, jumping jacks, squats) and upper-body exercises (push-ups, crunches).

The COVID-19 outbreak-induced inactivity might have affected the respiratory, cardiovascular, and musculoskeletal systems, resulting in health problems.[18] Souza et al. suggested that HIIT, including Tabata training, is a potential strategy to prevent symptoms induced by reduced physical activity due to the COVID-19 pandemic.[19] Since the Tabata training is extremely demanding and exhausts the subjects,[1–4] it may not be safe for some individuals, especially who are not familiar with high intensity exercises, as it may result in physical accidents and/or increased blood pressure. Non-exhaustive Tabata cross training studied in the present investigation may have wider applications to populations, including not only health-oriented people and athletes but also people who may start exercise training under COVID-19 pandemic.

5. Conclusion

Our results demonstrated that 6 weeks of high-intensity intermittent cross-training elevates the $\dot{V}O_2$max significantly for both running and bicycling.

CRediT authorship contribution statement

Xin Liu: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Katsunori Tsuji:** Writing – review & editing, Validation, Methodology, Data curation. **Yuzhong Xu:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Motoyuki Iemitsu:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Izumi Tabata:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Ethical approval statement

The protocols for the experiments and procedures were approved by the Ethics Committee of Ritsumeikan University (approval no. BKC-IRB-2011-05). After receiving a detailed explanation of the purpose, potential benefits, and risks of participating in the study, each participant gave written informed consent. The study was implemented in accordance with the Declaration of Helsinki.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper entitled "Effects of high-intensity intermittent cross-training on maximal oxygen uptake".

Acknowledgement

We greatly appreciate the study participants. This study was supported in part by a Grant-in-Aid for Scientific Research (C) (no. 24K14417) from the Japan Society for the Promotion of Sciences (JSPS) KAKENHI.

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