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Suitability of Modified Tandem-Bicycle Ergometer during Submaximal and Maximal Exercise

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ABSTRACT

We have developed a tandem-bicycle ergometer, allowing two riders to synchronize pedalling movement sharing one load. We summarize fundamental data concerning cardiorespiratory responses during submaximal and maximal exercise by means of the tandem-bicycling ergometer, compared to those obtained using a single-bicycle ergometer. Heart rate (HR), oxygen uptake (VO_2) and ratings of perceived exertion (RPE) showed no significant differences. Observed coefficient of variations (CVs) ranged from 2.8% to 7.3%. To clarify whether two riders shared one load equally up to maximal exercise and whether exact maximal physiological responses of two riders are obtained during tandem-bicycle exercise, maximal values during tandem-bicycle exercise were compared. When variables were compared among the three conditions, no significant differences were noted. CVs were 2.2 ± 1.0% for peak heart rate (HR peak) and 3.1 ± 1.6% for peak oxygen uptake (VO_2 peak). Finally, we examined cardiorespiratory responses during maximal tandem-bicycle ergometer exercise in riders at different levels of physical fitness. Time to exhaustion of the low-VO_2 peak participant was longer in tandem-bicycle exercises, despite the VO_2 peak of a pair of riders differing by 10%. An advantage of the tandem-ergometer is significant extension of the time to exhaustion of the rider with lower peak VO_2 given a difference of 10%. From the perspective of cardiorespiratory responses to submaximal and maximal exercise, the newly developed tandem-bicycle ergometer can provide an equal exercise load to submaximal and exhaustion to double riders, at least when the physical fitness of a pair of riders is very close. We speculate that the tandem-bicycle ergometer could improve not only health promotion but also athletic ability.

Keywords: Tandem-bicycling ergometer, Cardiorespiratory responses, Heart rate, Oxygen uptake

INTRODUCTION

Physiological responses to exercise are generally measured while a single person is performing exercise using a bicycle ergometer, treadmill, or the like [1-6]. Relatively little is actually known about the physiological responses while multiple persons are engaged in synchronized exercise such as tandem road cycling [7]. The physiological responses of each person during exercise performed by multiple people represent an interesting topic for investigation. However, evaluation of true physiological responses in field studies is extremely difficult because we cannot regulate environmental conditions (climate, wind, temperature, etc.) and cannot impose arbitrary, precise, or constant intensities of work on the exercising individuals.

To overcome such methodological problems, use of an ergometer in the laboratory is helpful. For this reason, we developed a tandem-bicycle ergometer (Figure 1).

Figure 1: Tandem-bicycle ergometer

The tandem-bicycle ergometer was principally constructed by coupling one conventional Monark ergometer (Monark, Sweden) with another. This ergometer has a fixed-gear system (pist-type braking). The ergometer thus allows two riders to synchronize pedalling movements while sharing one load. To the best of our knowledge, this represents the first design for a double-rider bicycle ergometer. This ergometer allows regulation of exercise intensity with great accuracy and reproducibility. Furthermore, riders on the ergometer are unaffected by factors such as environmental conditions, handlebar operation, brake operation, and so on. We therefore considered that the tandem-bicycle ergometer would provide a helpful instrument for simultaneously evaluating the physiological responses of two individuals during exercise.

This study comprised three experiments, and we summarize herein the fundamental data concerning cardiorespiratory responses during submaximal and maximal exercise by means of tandem-bicycle ergometer, compared to results obtained using a single-bicycle ergometer. We also discuss future perspectives of how the tandem-bicycle ergometer can be used for training.

MATERIALS AND METHODS

All procedures were approved by the Ethics Committee of the Kawasaki University of Medical Welfare (Approval number 306) and were conducted following the guidelines of the Declaration of Helsinki.

Experiment 1: Cardiorespiratory responses during submaximal single- and tandem-bicycle ergometer exercise

As a first approach, we examined whether the loads with conventional single and tandem-bicycle ergometers were equal or not, comparing cardiorespiratory responses during submaximal exercise between the two ergometers.

Materials

Participants comprised 23 healthy men, 21.8 ± 1.7 years of age (mean ± SD), with a height of 171.9 ± 5.5 cm, body mass of 67.0 ± 7.6 kg and peak oxygen uptake (VO_2 peak) of 47.1 ± 5.3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (Table 1).

Table 1: Physical characteristics of subjects

Subjects	Age	Height	Weight	VO_2 peak
	(Years)	(cm)	(Kg)	($ml.\ kg^{-1}.\ min^{-1}$)
A	24	175	74	46.9
B	21	165	62	48.7
C	20	166	68	49.5
D	23	169	61	39.2
E	22	161	56	51.9

F	23	171	69	45.7
G	23	174	65	47.3
H	21	170	64	48.9
I	21	169	78	52.1
J	21	173	66	58.5
K	21	177	65	52.1
L	22	185	66	46.7
M	21	176	65	38.4
N	27	176	78	46.3
O	20	165	61	52.4
P	20	164	60	47.1
Q	20	173	64	46.3
R	22	175	73	41.8
S	21	168	70	46.9
T	21	176	62	47.4
U	21	178	66.3	50.7
V	25	174	90.3	33.9
W	22	173.5	57.5	44.6
Mean	22	171.9	67	47.1
SD	2	5.5	7.6	5.2

Experimental procedure

Each subject exercised under three conditions: using a conventional single-bicycle ergometer (SIN) and in the front (FRO) and rear (REA) positions on the tandem ergometer. The order of these three conditions was randomized. Load was set at 1.5, 2.0 and 2.5 kp and exercise was performed for 5 min under each load. The pedalling rate was maintained at 60 rpm with the aid of a metronome.

Experiment 2: Cardiorespiratory responses during maximal single- and tandem-bicycle ergometer exercise

Next, to clarify whether two riders shared the one load equally up to maximal exercise, and whether exact maximal physiological responses of the two riders were obtained during tandem-bicycle exercise, maximal values during tandem-bicycle exercise were compared between riders, and then compared to values obtained during maximal exercise by means of the single-bicycle ergometer.

Materials

Participants comprised 18 healthy men, 21 ± 2 years of age, with a height of 172.2 ± 6.4 cm and body mass of 66.4 ± 5.9 kg (Table 2).

Table 2: Physical characteristics of subjects (pairs)

Subjects (Pair)	VO_2 peak (ml. kg^{-1}. min^{-1})	Weight (Kg)
a-b	49.7-46.9	82.0-73.5
c-d	48.1-47.4	64.0-71.2
e-f	49.1-51.2	62.6-62.9
g-h	46.8-47.6	74.9-62.4

i-j	42.6-44.7	67.7-62.9
k-l	48.3-47.1	61.2-60.3
m-n	47.3-44.9	60.6-64.4
o-p	40.5-40.3	65.2-61.2
q-r	53.9-50.1	69.5-69.2

Experimental procedure

First, participants performed incremental exercise to exhaustion using a conventional single-bicycle ergometer (SIN). The test began at initial power output of 1.5 kp and the workload was increased until exhaustion. Peak HR (HR peak) and peak VO_2 peak were recorded, and participants with similar VO_2 peaks were paired to perform incremental exercise with the tandem-bicycle ergometer. Subjects then underwent testing twice under each condition of the FRO and REA positions. The CV of each variable at exhaustion was calculated.

Experiment 3: Cardiorespiratory responses during maximal tandem-bicycle ergometer exercise in subjects with different levels of physical fitness

Finally, we examined cardiorespiratory responses during maximal tandem-bicycle ergometer exercise in riders with different levels of physical fitness.

Materials

Fourteen healthy men performed maximal incremental exercise test on a conventional single-bicycle ergometer and HR peak and VO_2 peak were determined. Following the test, subjects were divided into seven pairs and differences in VO_2 peak between two subjects of each pair corresponded to >8.7% (range, 8.7%-15.1% range) (Table 3).

Table 3: Physical characteristics of subjects (pairs)

Subjects (Pair)	**VO_2 peak (ml. kg^{-1}. min^{-1})**	**Weight (kg)**
1-2	44.9-40.5 (9.8%)	63.6-65.2
3-4	46.3-39.4 (14.9%)	78.1-78.8
5-6	48.4-43.3 (10.5%)	61.5-62.7
7-8	42.5-36.7 (13.6%)	63.5-65.2
9-10	48.3-41.9 (13.3%)	61.4-60.4
11-12	44.9-38.1 (15.1%)	72.3-70.6
13-14	50.5-46.1 (8.7%)	65.7-64.0

Mean HR peak and VO_2 peak among subjects with higher physical fitness (Hfit) were 195.1 ± 9.5 beats·min^{-1} and 46.6 ± 2.7 ml^{-1}. kg^{-1}·min, respectively, while mean values of those subjects with lower physical fitness (Lfit) were 193.0 ± 9.5 beats·min^{-1} and 41.2 ± 3.0 ml^{-1}·kg^{-1}·min, respectively.

Experimental procedure

Incremental exercise was then performed using the tandem-bicycle ergometer with incremental loading and HR peak and peak VO_2 peak were measured. Two riders performed the test twice, in both FRO and REA positions, and the order of FRO and REA conditions was randomized.

Measurements

Heart rate (HR): HR was measured using a heart rate monitor (RS800CX; POLAR, Japan) to record each intensity during every 1 min of exercise.

Oxygen uptake

Oxygen uptake (VO_2) was analysed using the Douglas bag method. Expired gases were collected in a Douglas bag during the last 30 s of each intensity. Gas fractions were analysed by mass spectrometry (ARCO-2000; ARCO

SYSTEM, Japan) that was calibrated before each test. The expired gas volume was measured using a certified dry gas meter (DC-5; SHINAGAWA, Japan).

Rating of perceived exertion (RPE) was scored using the Borg scale [8]. RPE was measured during the last minute of exercise at each intensity.

Coefficients of variation (CVs) of the SIN, FRO and REA measurements and RPE scores were calculated.

Statistical analyses

All data are expressed as mean and standard deviation. Changes in all measurements during bicycle ergometer exercise were compared by one-way analysis of variance (ANOVA). When differences were found to be significant, comparisons were made using Bonferroni's post hoc test. Values of $P<0.05$ were considered statistically significant.

RESULTS AND DISCUSSION

Experiment 1

Table 4 shows mean values and CVs for HR, VO_2 and RPE for each exercise load. When HR, VO_2 and RPE in the three riding conditions were compared at the same exercise load, no significant differences were found among three conditions. Observed CVs ranged from 2.8% to 7.3% (All data are expressed as means ± standard deviations (SD). SIN: Single saddle condition; FRO: Front saddle condition, and REA: Rear saddle condition).

Table 4: Heart rate, oxygen uptake and RPE under each load

Index	Load (kp)/Condition	SIN	FRO	REA	CV (%)
HR (beats·min^{-1})	1.5	115.2 ± 12.5	117.0 ± 8.9	116.1 ± 10.6	4.7 ± 2.8
	2	134.4 ± 13.4	135.0 ± 9.7	134.2 ± 12.1	3.1 ± 2.4
	2.5	151.9 ± 14.3	154.6 ± 11.8	154.8 ± 13.4	2.8 ± 2.1
VO_2 (ml. kg^{-1}. min^{-1})	1.5	18.9 ± 1.6	19.3 ± 1.8	19.4 ± 1.9	4.6 ± 3.0
	2	24.0 ± 2.3	24.6 ± 2.4	25.0 ± 2.6	4.8 ± 2.3
	2.5	29.4 ± 2.9	30.4 ± 3.7	31.1 ± 3.1	4.8 ± 2.2
RPE	1.5	8.0 ± 1.3	7.9 ± 1.3	8.0 ± 1.3	6.5 ± 4.2
	2	10.4 ± 1.6	10.3 ± 1.5	10.2 ± 1.8	7.3 ± 5.8
	2.5	12.5 ± 2.0	12.6 ± 2.0	12.7 ± 2.0	5.8 ± 4.8

A previous study reported CVs of daily HR and VO_2 during submaximal and maximal exercise as corresponding to 1.0%-10.7% and 1.9%-11.6% during treadmill running, respectively [9]. CVs obtained in the present study were quite comparable or smaller, and strongly support that the ability of this newly developed tandem-bicycle ergometer to provide identical loads with great reproducibility, compared to that from a conventional single-bicycle ergometer regardless of saddle position. The CV of RPE scores were higher than those of VO_2 and HR measurements. However, little change in the RPE index was seen when scaled up or down. Accordingly, RPE might be widely distributed rather than a physiological index during exercise [10].

Experiment 2

In the SIN condition, HR peak and VO_2 peak were 193.7 ± 7.0 beats·min^{-1} and 47.0 ± 3.5 ml^{-1}·kg^{-1}·min, respectively (Figures 2 and 3).

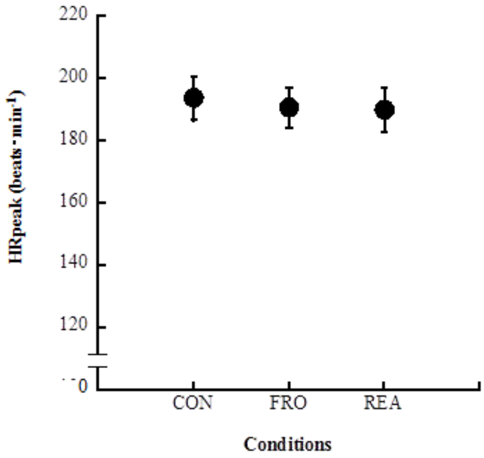

Figure 2: HR peak in each condition

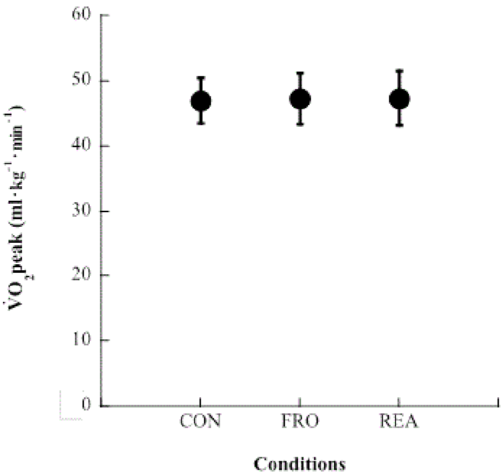

Figure 3: VO_2 peak in each condition

Corresponding values obtained during the tandem-bicycle exercise were 190.7 ± 6.5 beats·min^{-1} and 47.3 ± 3.9 ml^{-1}·kg^{-1}·min in the FRO and 190.1 ± 7.2 beats·min^{-1} and 47.3 ± 4.2 ml^{-1}·kg^{-1}·min in the REA condition, respectively. When variables were compared among the three conditions, no significant difference was observed. The CV was 2.2 ± 1.0% for HR peak and 3.1 ± 1.6% for VO_2 peak.

In previous studies, intra-subject variation of maximum oxygen uptake was 3.8%-8.3% during treadmill running exercise [11]. In this study, intra-subject variation was quite similar when saddle position was changed. In addition, the same results were obtained when values obtained during the tandem-ergometer exercise were compared. Therefore, findings thus reveal that the tandem-bicycle ergometer could provide equal loads to double riders from submaximal to maximal intensities. These data also indicate that maximal physiological responses during the tandem-bicycle ergometer exercise could be quite comparable to those during the single-bicycling ergometer exercise when subjects with a similar VO_2 peak were paired.

Experiment 3

When time to exhaustion from the incremental test was compared between different types of ergometer exercise, time in Hfit was significantly shorter with tandem ergometer exercise than with single-bicycle ergometer exercise, regardless of front or rear saddle position (Table 5) (All data are expressed as means ± standard deviations (SD), SIN: Single saddle condition; FRO: Front saddle condition; and REA: Rear saddle condition. $^{*}P<0.05$, vs. SIN).

Table 5: HR peak and VO_2 peak in each condition (subjects with higher physical fitness)

Parameters\Conditions	SIN	FRO	REA
HR Peak (beats·min^{-1})	195.1 ± 9.5	191.1 ± 8.2	190.1 ± 8.6
VO2 peak (ml. kg^{-1}. min^{-1})	46.6 ± 2.7	45.4 ± 2.8	44.8 ± 3.5*
Exhaustion time (s)	1054.2 ± 68.0	947.1 ± 41.9*	955.7 ± 61.1*

Mean VO_2 peak in Hfit tended to be lower with tandem-ergometer exercise when compared to that with single-ergometer exercise, and the value obtained in the REA position was significantly lower. On the other hand, in Lfit, no significant difference in VO_2 peak was observed between different types of ergometer exercise or between FRO and REA positions.

Time to exhaustion of the low-VO_2 peak participant was longer in tandem-bicycle exercises (Table 6) (All data are expressed as means ± standard deviations (SD), SIN: Single saddle condition; FRO: Front saddle condition; and REA: Rear saddle condition. $^*P<0.05$, vs. SIN), despite the VO_2 peak of a pair of riders differing by 10%. This finding suggests that even with a 10% difference in VO_2 peak, the maximal cardiorespiratory responses of the two subjects obtained during tandem-bicycle exercise could be the same as those obtained during use of the single-bicycle ergometer. The tandem-bicycle ergometer functions much the same as a single-rider bicycle ergometer. An advantage of the tandem-ergometer is a significant extension of the time to exhaustion of the rider with lower peak VO_2, assuming a difference of 10%.

Table 6: HR peak and VO_2 peak in each condition (subjects with lower physical fitness)

Parameters/Conditions	SIN	FRO	REA
HR Peak (beats·min^{-1})	193.0 ± 9.5	190.6 ± 9.2	191.1 ± 7.9
VO_2 peak (ml. kg^{-1}. min^{-1})	41.2 ± 3.0	41.5 ± 2.9	41.7 ± 3.6
Exhaustion time (s)	891.4 ± 41.4	955.7 ± 61.1*	947.1 ± 41.9*

Future perspectives

A previous study reported that exhaustion time for two subjects was extended during maximal trial using the single-bicycle ergometer sitting in a parallel standing position [12]. This suggests that the physiological responses are appropriate for an incentive situation such as a competitive race between two individuals.

There are two differences when working pedals using the two ergometers sitting at a parallel standing position and using the tandem bicycle ergometer with two riders. The first difference concerns physics. When two ergometers are sitting in a parallel standing position, each rider has an individual load. When riders cycle using a tandem ergometer, the riders share a load. The second difference concerns exercise psychology. When two ergometers are sitting parallel in a standing position, the riders have an individual consciousness of a competitive situation. When riders work the pedals using a tandem ergometer, we suppose that they have a cooperative consciousness.

Three areas of usefulness are apparent for using a tandem bicycle ergometer with two riders. First, the tandem-ergometer is useful tool to clarify physiological responses during passive exercise, when one rider pedals voluntarily and the other rider pedals passively. Similarly, passive exercise would be useful for rehabilitation of patients who are unable to walk. In addition, tandem-ergometer exercise is useful in training for athletes with visual disorders, keeping them physically safe. Actually, a previous study [13,14]. Reported the efficacy of tandem cycling for improvement of exercise capacity in visual disorders. We speculate that the tandem-bicycle ergometer could improve not only health promotion but also athletic ability.

CONCLUSION

From the perspective of cardiorespiratory responses to submaximal and maximal exercise, this newly developed tandem-bicycle ergometer can provide equal exercise loads to submaximal and exhaustion to two riders, at least when the physical fitness of the pair of riders is very close.

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