Physiological Responses and Mechanical Efficiency during Different Types of Ergometric Exercise

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Abstract. This study compared the physiological responses and the mechanical efficiency during both arm cranking exercise and leg pedaling exercise with identical work loads, and determined whether arm cranking or unilateral leg pedaling performance could be used to estimate bilateral pedaling exercise capacity. Seven healthy adult males [mean age: 32 (27–36) years old] participated in this study. Arm cranking and leg pedaling exercise tests were carried out using an identical electrically controlled bicycle ergometer. The cranking/pedaling rate was set at 60 rpm. Exercise was performed under the following conditions: Bilateral leg pedaling (BLP), Unilateral leg pedaling (ULP), Bilateral arm cranking (BAC), and Unilateral arm cranking (UAC). By ramp load protocol in gradually increasing 20 W/min stages, peak oxygen uptake (peak VO$_2$) and peak heart rate (peak HR) were obtained using BLP, ULP, BAC, and UAC. The oxygen uptake and heart rate obtained using BLP, ULP, BAC, and UAC were compared under three exercise work loads (20 W, 40 W, 60 W). In comparison with ULP and UAC, the values of peak VO$_2$ and peak HR in BLP and BAC were high, and the response to the 20 W to 60 W exercise intensities rose in tandem with work load. Differences in physiological response due to disparities in the exerted muscle mass became large and showed a rising trend, particularly in ULP and UAC. There were no significant correlations between BLP and the other types of exercise (BAC, ULP, UAC) in peak VO$_2$ and peak HR. In conclusion, the physiological responses in bilateral and unilateral arm/leg exercise at an identical work load depend on the amount of muscle mass exerted. It is hard to estimate the aerobic work capacity (peak VO$_2$) using BLP from the results of exercise performed with BAC, ULP, and UAC.

Key words: Ergometric exercise, Physiological response, Mechanical efficiency

(This article was submitted Feb. 14, 2000, and was accepted May 20, 2000)

INTRODUCTION

The bicycle ergometer is widely used as an aerobic exercise machine for the evaluation of exercise capacity. Aerobic exercises in which both legs and arms are used are becoming more popular for conditioning and rehabilitation. Arm ergometry is used less frequently, but maybe a useful alternative for evaluating patients who have limited use of their legs.

According to previous studies, the maximum oxygen uptake (peak VO$_2$) is less in the exercise of both arms than in the exercise of both legs, and less in the exercise of one leg than in the exercise of both legs$^{1–3}$). Therefore, the peak VO$_2$ is proportional to the amount of muscle mass involved in exercise, and in the case where arm exercise and
leg exercise are combined, the peak VO\textsubscript{2} becomes even greater. Numerous studies have been conducted on the effect of training of the arms on the legs and vice versa, and it is reported that a transfer of training effect is observed between the arms and legs\textsuperscript{4–8}). Also, there have been a few studies, which examined whether leg work capacity can be estimated from the test results of the arm exercise. Similarly, Schwade et al.\textsuperscript{10}) reported that there is only a low correlation between the maximum work loads in the arm exercise and the leg exercise of ischemic heart disease patients.

In this study, while driving a bicycle ergometer with bilateral lower limbs, unilateral lower limb, bilateral upper limbs, or unilateral upper limb, we examined the physiological responses and calculated the mechanical efficiency in each case at the maximal work and submaximal work, and compared the work conditions. Further, we determined whether arm cranking or unilateral leg pedaling performance could be used to estimate bilateral pedaling exercise capacity.

**METHODS**

**Subjects**

The subjects were seven healthy male adults with a mean age of 32.1 (27–36) years old, mean height of 169.9 (163–180) cm, and mean weight of 64.1 (54–73) kg. No subject had had the habit of taking regular exercise, and none had developed an orthopedic disease. Subjects received no special training for this test. Each subject was subjected to the test at least two hours after a meal, and was instructed to avoid intense exercise before the test. Informed consent was obtained from all subjects.

**Testing procedures**

The test was conducted in an air-conditioned laboratory with a room temperature of 20–22°C and an atmospheric pressure of 769–773 mmHg.

The conditions of exercise were bilateral leg pedaling (BLP), unilateral leg pedaling (ULP), bilateral arm cranking (BAC), and unilateral arm cranking (UAC) of the bicycle ergometer. The same ergometer was used for each exercise condition, and the arm cranking was performed by mounting the ergometer on a stable table. For leg pedaling, the height of the saddle was adjusted so that the knee at extension was slightly flexed. For ULP all the subjects were instructed to pedal with the right leg, the left pedal was removed for this purpose, and during pedaling the left leg was put on a bench 20 cm in height. For both BLP and ULP, the subjects were instructed to grasp the handle grips with both hands while pedaling. For arm cranking, the posture was that of sitting in a chair; the pedals were replaced by hand grips, and the position of the chair was adjusted so that the arm crank axis was level with the shoulder, the shoulder flexion was approximately 90°, and the elbow joint was extended when the hand grips were at the furthest distance. For BAC, arm crank rotation with 180° phase shift was performed, and for UAC all the subjects were instructed to rotate the arm crank with the right arm within the plane parallel to the sagittal plane of each subject. The cycle ergometer was an electronically braked type (Isopower Ergometer, Takei, Tokyo, Japan). The crank arm length was 17 cm, and the pedaling or cranking rate was set to 60 rpm by an electronic metronome.

For the maximal exercise, five minutes rest was allowed on the chair or saddle, and the point where the arm crank or pedal ceases to be driven at a fixed revolution using the ramp protocol, consisting of minute increments of 20 W, was determined as the end point. For the ramp protocol a dedicated ramp controller (Takei, Tokyo, Japan) was used, and its output waveform was displayed on an oscilloscope to ensure the linearity of the incremental work load. For the submaximal exercise, after five minutes rest an incremental stress consisting of three stages (four minutes each) of exercise stress work load, that is, 20 W, 40 W, and 60 W, was performed.

Each subject first undertook the measurement of the maximal exercise by BLP, ULP, BAC, and UAC. The order of execution of each exercise type was random for each subject, and each exercise took place at intervals of seven days. Then submaximal exercise by BLP, ULP, BAC, and UAC was carried out. The order of tests was the same as that for the maximal exercise, and each exercise took place at intervals of at least 48 hours. The test for the maximal exercise and the test for the submaximal exercise took place on different days.

For maximal exercise, peak power output (peak PO), peak oxygen uptake (peak VO\textsubscript{2}), and peak
heart rate (peak HR) were measured, and for submaximal exercise oxygen uptake (VO₂) and heart rate (HR) were measured at each stage.

Peak PO was calculated from the time taken to reach the end point by each exercise type. Expired gas was collected from a face mask continuously at rest and during exercise for measurements of VO₂ using the Oxycon beta system (Mijnhardt, Netherlands). The gas analysis system was calibrated before each test. Oxygen uptake was measured every 30 seconds and adjusted for body weight (ml/kg/min). The peak VO₂ was determined from data obtained during the final 30 seconds of exercise. The peak HR was the peak value obtained during the session. Heart rate was recorded via three chest electrodes (CM5) and displayed on an ECG monitor (Cardiocare-uni ECU-10, Fukudadenshi, Tokyo, Japan), which was interfaced to the Oxycon system.

Gross efficiency (Gross E) and net efficiency (Net E) of the submaximal exercise for each exercise type were calculated using the following equations:

**Gross efficiency** = work/energy consumption = \[ \frac{\text{power (W) × 60 (sec) / 4.18 (cal/J)}}{\text{VO₂ at exercise (ml/min) × 5 (cal/ml) × 100%}} \]

**Net efficiency** = \[ \frac{\text{power (W) × 60 (sec) / 4.18 (cal/J)}}{\text{(VO₂ at exercise - VO₂ at rest) × 5 (cal/l) × 100%}} \]

### Data Analyses

For maximal values (PO, VO₂, and HR) one-factor repeated measures of analyses of variance (ANOVA) [exercise type (BLP, ULP, BAC, UAC) × maximal values] were performed to detect differences in the dependent variables (p<0.05). Similarly, for submaximal values (VO₂, HR, Gross E, and Net E) two-way ANOVA [exercise type (BLP, ULP, BAC, UAC) × work loads (20, 40, 60 W)] was performed to detect differences in the dependent variables (p<0.05). When a significant F ratio was found, a post-hoc procedure (Student Newman Keuels) was employed to compare the means (p<0.05).

### RESULTS

Table 1 shows each measured value at maximal exercise and submaximal exercise.

For peak PO, and peak VO₂, BLP showed the largest values followed by ULP, BAC, and UAC (p<0.01). For the peak HR, BLP showed the largest value followed by BAC, ULP, and UAC (p<0.05), but there was no significant difference between ULP and UAC.

At submaximal exercise, both VO₂ and heart rate values increased with the increase in the work load, but the rate of the increase differed according to the type of exercise. At low work load (20 W) no conspicuous difference was observed among exercise types for both VO₂ and HR, but with the increase in the work load (40 W and 60 W), VO₂ and heart rate tended to increase in the ULP and UAC. There were significant differences among the exercise types and work loads, respectively (p<0.05).

Table 2 shows the regression lines and correlation coefficients between each exercise type at peak VO₂ and peak HR. For maximal exercise there was a significant correlation between VO₂ and HR at each type of exercise. For submaximal

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**Table 1.** Maximal exercise and submaximal exercise values (Mean ± standard deviation) during different types of exercise

<table>
<thead>
<tr>
<th></th>
<th>BLP</th>
<th>ULP</th>
<th>BAC</th>
<th>UAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power output (W)</td>
<td>240.6 ± 31.9</td>
<td>144.7 ± 14.6</td>
<td>124.1 ± 13.7</td>
<td>88 ± 8.7</td>
</tr>
<tr>
<td>VO₂ (ml/min/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak</td>
<td>45.6 ± 5.1</td>
<td>33.6 ± 5.6</td>
<td>29.2 ± 2.3</td>
<td>22.1 ± 3.2</td>
</tr>
<tr>
<td>20 W</td>
<td>9.5 ± 0.8</td>
<td>9.9 ± 1.9</td>
<td>8.3 ± 0.9</td>
<td>8.7 ± 0.7</td>
</tr>
<tr>
<td>40 W</td>
<td>11.7 ± 1.1</td>
<td>14.6 ± 1.7</td>
<td>12.0 ± 1.1</td>
<td>13.4 ± 1.0</td>
</tr>
<tr>
<td>60 W</td>
<td>13.5 ± 1.2</td>
<td>18.9 ± 2.0</td>
<td>17.1 ± 3.1</td>
<td>20.5 ± 1.6</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak</td>
<td>180.9 ± 8.9</td>
<td>150.6 ± 10.8</td>
<td>167.0 ± 6.0</td>
<td>148.1 ± 8.6</td>
</tr>
<tr>
<td>20 W</td>
<td>84.7 ± 6.1</td>
<td>96.4 ± 8.7</td>
<td>88.7 ± 3.9</td>
<td>96.4 ± 7.9</td>
</tr>
<tr>
<td>40 W</td>
<td>91.0 ± 4.8</td>
<td>106.6 ± 9.1</td>
<td>100.0 ± 5.9</td>
<td>110.7 ± 5.3</td>
</tr>
<tr>
<td>60 W</td>
<td>98.9 ± 4.9</td>
<td>122.7 ± 5.4</td>
<td>114.6 ± 7.6</td>
<td>132.7 ± 8.5</td>
</tr>
</tbody>
</table>
exercise, however, there were significant correlations between \( VO_2 \) and HR at each type of exercise. Table 3 shows the correlation coefficients between each exercise type for \( VO_2 \) and HR at maximal exercise. For the peak \( VO_2 \) values, there was a significant positive correlation between BAC and UAC \((p<0.01)\), but no significant correlation existed among the other exercise types. For the peak HR values, there was a significant positive correlation between BLP and BAC \((p<0.05)\), but no significant correlation existed among the other exercise types. Table 4 shows the correlation coefficients between each type of exercise for \( VO_2 \) and heart rate values at submaximal exercise. For \( VO_2 \) the correlation coefficients between each exercise type were 0.79–0.90; that is, a significant correlation existed between each type of exercise \((p<0.001)\). Similarly, for HR the correlation coefficients between each exercise type were 0.76–0.92; that is, a significant correlation existed between each exercise type \((p<0.001)\).

Table 5 shows each proportion of ULP, BAC, and UAC for \( VO_2 \) and HR in BLP. For peak \( VO_2 \), ULP showed the largest value followed by BAC and UAC \((p<0.05)\), but for \( VO_2 \) at 20 W, 40 W, and 60 W, BAC showed the smallest value \((p<0.05)\). On the other hand, for peak heart rate BAC showed the largest value \((p<0.05)\) and UAC showed the smallest value \((p<0.05)\). Heart rate at a given level of \( VO_2 \) was higher in arm exercise than in leg exercise \((p<0.05)\), and the highest value was shown in UAC and the lowest value was shown in the BLP \((p<0.05)\).

Table 6 shows the mean values and the standard deviations of Gross E and Net E for each exercise type. Each efficiency value was within the range.

\[\begin{array}{ccc}
\text{Maximal oxygen uptake} & \text{Maximal heart rate} \\
\text{ULP} & 0.51 & 0.75 & 0.62 & - & 0.44 & 0.87 & 0.42 \\
\text{ULP} & 0.53 & 0.68 & - & 0.65 & 0.31 \\
\text{BAC} & 0.92 & 0.23 \\
\end{array}\]

\[\begin{array}{ccc}
\text{Submaximal oxygen uptake} & \text{Submaximal heart rate} \\
\text{ULP} & 0.86 & 0.78 & 0.83 & 0.88 & 0.76 & 0.84 \\
\text{ULP} & 0.79 & 0.90 & 0.90 & 0.90 & 0.88 \\
\text{BAC} & 0.83 & 0.83 \\
\end{array}\]
of general exercise efficiency for each exercise type. During leg exercises (BLP and ULP) both Gross E and Net E became large with increases in work load (p<0.05), and during arm exercises (BAC and UAC) the Net E remained unchanged or tended to decline. Also, for both the leg and arm exercises the Net E tended to decline more in unilateral exercises than in bilateral exercises.

DISCUSSION

1) Relation between oxygen uptake and heart rate by exercise type at maximal exercise and submaximal exercise

The main result in this study is that the mechanical work for four different exercises was the identical but the unilateral limb movement associated with higher VO$_2$ and HR compared to the bilateral limb movements when the exercise work load was larger.

For peak power, peak VO$_2$, and peak heart rate, BLP showed the largest values followed by ULP, BAC, and UAC. The proportions of ULP, BAC, and UAC to the peak VO$_2$ obtained at BLP were about 76%, 64%, and 48%, respectively. Previous studies have shown that VO$_{\text{max}}$ measured during BAC and ULP is about 70–78% of peak VO$_2$ measured during BLP$^{11, 12}$. Bond et al.$^{13}$ also reported that BAC and ULP were found to be 55 and 66% of VO$_{\text{max}}$ in BLP, respectively.

Similarly, the proportions of ULP, BAC, and UAC to the peak heart rate obtained at BLP were lower by 17%, 8%, and 18%, respectively. This means that the limb regions and the muscle mass participating in exercise are the limiting factors of peak VO$_2$.

At submaximal exercise, for VO$_2$ and heart rate BLP showed the smallest values followed by BAC, ULP, and UAC. At maximal exercise, for VO$_2$ and heart rate BLP showed the largest values (Table 1), followed by ULP or BLP and UAC; BLP values were the largest and UAC values were the least. The reason that VO$_2$ value was small at the light work load (20 W) arm exercise seems to be that driving (rotation) was possible with small force due to inertia at the rotating part of the crank of the ergometer.

The proportion of heart rate value to VO$_2$ value was higher in arm exercises (BAC, UAC) than leg exercises (BLP, ULP). The observed differences in responses between arm and leg exercises at a given work load appear to have been influenced by differences in sympathetic outflow due to the greater level of static contraction of the relatively
small muscle groups required for arm exercise\(^{14}\). The reasons for this seem to be the increase in peripheral vascular resistance due to the increase in intramuscular pressure during arm exercise, and the decrease in stroke volume due to the decrease in the returned blood flow caused thereby.

Comparing between bilateral limbs exercises (BAC and BLP) and unilateral limb exercises (UAC and ULP), during BAC and BLP the muscles used to move the bilateral limbs are bilateral arm/leg extensor muscles, while during UAC and ULP not only the extensor muscle group but also the flexor muscle group of the exercise limbs are used for returning the grip/pedal, and this tendency becomes conspicuous with the increase in the work load. Above all, since the muscle force exerted is the weakest in UAC, the muscles in the trunk are used to compensate for this. As a result, it seems that VO\(_2\) and heart rate values increased conspicuously with the increase in the work load. However, in the case of UAC the proportion of trunk muscles involved in the exercise depends greatly on subjects, and accordingly the data varies. Also, since muscles are used more frequently in UAC and ULP than in BAC and BLP during exercise, the muscles are relaxed for a shorter period and intramuscular pressure remains high. As a result, it is presumed that oxygen delivery decreases and peripheral vascular resistance increases when the arm was involved in the exercise, and that these phenomena affect the muscular endurance.

The heart rate at the identical work load increased conspicuously in the arm exercise, above all in UAC. Since venous return is less and stroke volume is smaller during arm exercise than leg exercise, it is expected that heart rate would be conspicuously increased. Further, since the arm exercise induces a more conspicuous increase in blood pressure and peripheral vascular resistance than the leg exercise, it is said that higher sympathetic outflow is developed more by arm exercise\(^{8,10,11}\). For peak VO\(_2\), a significant correlation was observed between BAC and UAC, but among the other exercise types no significant correlation was observed. This result coincided the results of Birkett et al.\(^{16}\). They reported HR and VO\(_2\) were highly correlated, and there were no significant differences between the peak VO\(_2\) values during BAC and UAC. For peak HR no significant correlation was observed among exercise types, except between BLP and BAC. These results agree with the results of previous studies in which no correlation was observed between arms and legs for VO\(_2\) at the maximal exercise\(^{11}\). The 95% confidence intervals indicate that the error of estimate for estimating peak VO\(_2\) in BLP from that in ULP, UAC and BAC for an individual was large. This error varies depending on exercise duration.

Meanwhile, for VO\(_2\) and HR at submaximal exercise, there was a significant correlation among the exercise types, and a significant correlation existed also between VO\(_2\) and heart rate. This suggests that data obtained from an exercise type in submaximal exercise could be used to estimate the data of other exercise types.

The trunk muscles may be recruited for driving the ergometer during arm exercise (BAC and UAC), but the degree depends greatly on individuals. This is a possible explanation for the cause of widely varying data between the arms and between both sides and one side. The higher VO\(_2\) and HR in unilateral limb movements than in bilateral was considered to be attributed to a higher sympathetic outflow related to small bulk working.

2) Differences in mechanical efficiency by exercise type

Oxygen uptake at the identical submaximal work load became maximal in exercise by BLP, and also mechanical efficiency became maximal. These results agree with those of previous studies, and show that the mechanical efficiency becomes high in proportion to the amount of muscle mass and the number of muscle groups recruited during exercise\(^{17}\). Furthermore, exercise with small muscle groups is considered to be characterized by low mechanical efficiency compared with large muscle units\(^{18}\).

The mechanical efficiency is represented by the ratio of energy consumption to the external work, but it is known that the efficiency of arm exercise is lower than that of leg exercise. Also, in general within a specific range the higher the work load is, the higher the work efficiency is. It seems that the efficiency of the arm cranking in this study was low because the work load of the arm cranking was somewhat lower than that in previous studies. The results of this study showed that among all the driving types the greater the work load was, the higher the Gross E and Net E were, and in unilateral exercise, such as UAC and ULP, both
efficiencies were low, but the efficiencies were higher for the arms when the work load was low. These data may suggest that not only the number of muscles recruited but also the work load exerts an influence on the efficiencies.

For the Net E calculated from the net energy needed for the exercise, in BLP an increase in the efficiency was observed with an increase in work load, but in the other exercise types no conspicuous changes were observed. The reason for this seems to be that, as described above, as the work load became higher the muscles such as the trunk muscles, which were not involved in the direct exercise, participated in exercise, and the energy consumption increased, thus the efficiency was lowered. Moreover, in the arm exercises the ratio of isometric contraction of the muscles used such as the arm muscles and the trunk muscles is large, so the energy consumed during this is not converted to external work, resulting in energy loss. Furthermore, the efficiency was lowered in UAC and ULP, and it therefore seems that individual skill is involved in the efficiency; that is, the efficiency is affected by individual ability and the degree of proficiency in alternately using the flexors and extensors of unilateral arm or legs for the purpose of rotating the crank.

REFERENCES