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ORIGINAL ARTICLE

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Does the amount of exercising muscle alter the aerobic demand of dynamic exercise?

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Abstract The primary purpose of this study was to determine if the aerobic demand for production of specified power outputs is altered by distribution of work between the arms and legs compared with when all the work is performed by the legs. Because of the important exercise training implications, a secondary purpose of this study was to determine if the exercising muscle mass affects the cardiorespiratory demands at specified rating of perceived exertion (RPE) levels and blood lactate concentrations. Nine healthy adults completed leg cycling and combined arm and leg exercise on an Airdyne using a discontinuous protocol. Repeated measures ANOVA revealed that oxygen uptake for the combined arm and leg exercise averaged 0.04 $1 \cdot min^{-1}$ greater ($p < 0.05$) than for leg cycling at the same external power outputs. However, RPE levels at specified power outputs were lower ($p < 0.05$) with combined arm and leg exercise than leg cycling. At specified RPE levels and blood lactate concentrations, oxygen uptake and heart rate values were higher ($p < 0.05$) for combined arm and leg exercise than leg cycling. From these findings we conclude that: (1) the addition of arm exercise to leg cycling results in a reduction in RPE, but a minimal increase in oxygen consumption to perform a given power output, and (2) if training intensity is established by RPE or blood lactate concentration, use of a muscle mass larger than that used in leg cycling should allow a greater cardiorespiratory training effect.

Key words Blood lactate · Ergometry · Oxygen consumption · Rating of perceived exertion

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Introduction

It is often assumed that dynamic exercise distributed between the arms and legs requires a greater oxygen uptake ($\dot{V}O_2$) than when the same external power output is produced with the legs alone. This belief has merit since it would be expected that there is a metabolic requirement for movement of additional body parts that should increase the overall aerobic demand. However, the scientific literature has not supported such a theory. Unfortunately, the previous studies addressing this question (Hagerman et al. 1988; Reybrouck et al. 1975; Stenberg et al. 1967; Toner et al. 1983) used separate ergometers which limited the ability to assure that workloads were identical for the exercises being compared. We reasoned that an ergometer that couples arm and leg exercise to the same resistance mechanism would be required for a definitive assessment of the effect of varying muscle mass on aerobic demand for performing specified external power outputs.

The primary objective of this investigation was to determine if the exercising muscle mass influences the aerobic demand of dynamic exercise. To accomplish this, we compared the aerobic demands for performing specified external power outputs with the legs to that when the identical work rate was distributed between the arms and legs. We hypothesized that if the $\dot{V}O_2$ for combined arm and leg exercise was greater than for leg work at a given power output, the additional metabolic cost could be accounted for by the $\dot{V}O_2$ required for movement of the arms. A secondary objective of this investigation was to examine if the cardiorespiratory demands at specified rating of perceived exertion (RPE) levels and blood lactate concentrations differ based upon the amount of exercising muscle. We hypothesized that the $\dot{V}O_2$ would be higher with combined arm and leg work than with leg work when compared at specified RPE levels or blood lactate concentrations.

Methods

Subjects

Nine healthy subjects (five male and four female) participated in the study. The subject group had a mean (SD) age of 32 (7) years, body mass of 66.4 (10.2) kg and height of 173 (9) cm. None of the subjects was taking medications known to affect cardiorespiratory responses. The female subjects were screened to avoid testing from 72 h of beginning menses and the completion of menses because of the previous suggestion that perceived effort associated with exercise might be altered during this time phase (Higgs and Robertson 1981). All subjects provided written informed consent before participation. A monetary reward was given to the subjects for completion of the investigation.

Test protocols

All testing was performed in a laboratory of mean (SD) temperature of 23.4 (1.1)°C and free of significant external distractions. Each subject reported to the laboratory for testing on three separate days. On different days, the subjects underwent testing of combined arm and leg exercise, leg cycling, and arm-only movement without added external resistance. For a given subject, all tests were performed within a 9-day time span and at approximately the same time of day. The order of testing was randomized.

An Airdyne (Schwinn Cycling and Fitness, Boulder, Colo., USA) was chosen as the testing apparatus because it couples the arm and leg exercise components to the same resistance mechanism (Fig. 1). The device is designed so that the legs perform a cycling motion and the arms alternate in a push–pull motion. The movements of the upper and lower body are coupled so that when one leg is extending the contralateral arm is also extending. The loading force is generated by air resistance applied through linkage of the ergometer to a fanwheel. The force imposed on the ergometer fanwheel is that necessary to overcome atmospheric drag, so the external power output is exponentially related to the speed of the fanwheel. Since there is no adjustable gearing system, power output is also exponentially related to the rate of performing a complete movement cycle (or pedaling rpm). Based upon data supplied by the manufacturer, the external power output of the Airdyne (in watts) was defined by the equation $y = 0.00072x^{3.02}$, where x is the pedaling rpm.

Before testing, subjects were familiarized with the exercise testing device and the 6–20 RPE scale (Borg 1970). A standard statement describing the RPE scale (American College of Sports Medicine 1991) was read to each subject indicating that the rating should represent an integration of all exercise sensations. For each subject, seat height was adjusted appropriately and was the same for the three tests performed. Toe clips were not used with any of the exercise tests.

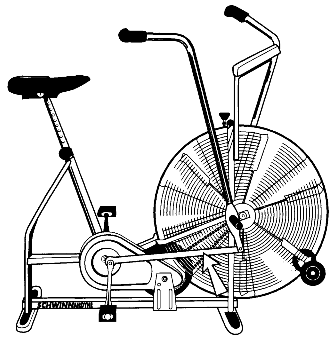

Fig. 1 The Airdyne upper and lower body ergometer. When arm-only movement without added external resistance was performed, the connecting rods (*arrow*) were disconnected from the arm levers so that movement of the arm levers was isolated from the pedals and fanwheel

For the combined arm and leg exercise, the subjects were instructed to distribute the work comfortably between their arms and legs. When performing the leg cycling exercise, the subjects let their arms hang to their sides or lightly gripped their hands behind them. The same graded discontinuous exercise protocol was used for the testing of combined arm and leg exercise and leg cycling. Exercise stages were 4 min, and rest periods of 2 min separated the stages. The first stage was performed at a pedaling rpm of 27 resulting in an external power output of 15 W. The desired workload was maintained through the use of an audio-visual metronome and the digital rpm display on the Airdyne. The incremental increases in workload between stages were established with limitations in the available metronome settings and averaged 23 W.

During each test of combined arm and leg exercise and leg cycling, $\dot{V}O_2$ and heart rate were measured continuously. RPE values and blood samples for determination of whole blood lactate concentration were obtained immediately after each stage. Exercise tests were continued until the subject achieved a blood lactate concentration over 4.0 $\text{mmol} \cdot \text{l}^{-1}$.

The testing of the arm-only motion was performed with the subjects first sitting quietly without distractions for 15 min on the Airdyne for resting $\dot{V}O_2$ measurement. After a 1-min period allowing a brief removal of the mouthpiece the subjects then completed a continuous test. During this test, the arm movement of the Airdyne was performed with no external load imposed. This was accomplished by disconnecting the connecting rod linking the arm levers with the pedals and fanwheel (Fig. 1). Soft bumpers were positioned so that the same excursion of the arm levers occurred as during the combined arm and leg exercise. The movement rate began at 27 rpm and increased every 2 min using the same rpm settings as for the other exercise tests. An audio-visual metronome was used to maintain the desired rpm. $\dot{V}O_2$ and heart rate were measured continuously during this test.

Measurements

Metabolic measurements were performed with an automated open-circuit spirometry system, which averaged values over 1-minute sample periods. Inspired ventilation was determined with a previously calibrated dry gas meter (Rayfield Equipment, Waitsfield, Vt., USA) fitted with a potentiometer that was integrated into a computer (Apple IIE, Cupertino, Calif., USA). Expired ventilation was directed from a high-velocity valve (Hans Rudolph, Model 2700, Kansas City, Miss., USA) into a 4-l mixing chamber. Concentrations of oxygen and carbon dioxide in the mixing chamber were continuously sampled by calibrated oxygen (Beckman OM-11, SensorMedics, Anaheim, Calif., USA) and carbon dioxide (Beckman LB-2, SensorMedics) analyzers integrated into the computer. For each exercise test, the metabolic data from the last minute of each stage were used in data analysis. During the resting portion of the arm-only test, the last 5 min of the 15-min rest was averaged for data analysis.

A telemetry system (Polar, Vantage XL, Stamford, Conn., USA) was used to obtain averaged heart rates over 15-s intervals. Heart rate values were averaged over the final minute of each stage for data analysis.

The subjects were instructed to determine their RPE during the last minute of exercise during each stage for the combined arm and leg exercise and leg cycling tests. RPE was then requested from the subject immediately after completion of each stage.

Immediately after each exercise stage during the combined arm and leg exercise and leg cycling tests, 30–40 μl of blood was collected into a heparinized capillary tube from a finger using an automatic lancet device (Ames finger sticks, Miles, Elkhart, Ind., USA). Samples were analyzed immediately for whole-blood lactate concentration with an automated lactate analyzer (Yellow Springs Instruments, Model 27, Yellow Springs, Ohio, USA) after aspiration from the capillary tube using a 25-μl "syringepet".

Statistical analysis

Two-way repeated measures analysis of variance (ANOVA) was used to analyze the $\dot{V}O_2$, heart rate, RPE and blood lactate concentration data across the workloads that were completed by all subjects. $\dot{V}O_2$ values for combined arm and leg exercise were also compared across stages with the sum of the $\dot{V}O_2$ for leg cycling and the arm-only motion after correcting for resting $\dot{V}O_2$. Comparisons of $\dot{V}O_2$, heart rate and blood lactate concentration with RPE were performed by first determining individual values for each dependent variable at RPE levels of 8, 10, 12, 14 and 16 from individual linear regressions using the data points on either side of the specified RPE values. These calculated individual values were then analyzed using two-way repeated measures ANOVA. Similarly, comparisons of $\dot{V}O_2$, heart rate and workload with blood lactate concentration were made at concentrations of 2.0, 2.5 and 4.0 $\text{mmol} \cdot \text{l}^{-1}$, and comparisons of heart rate with $\dot{V}O_2$ were made at $\dot{V}O_2$ values of 0.75, 1.00, 1.25, 1.50, 1.75 and 2.00 $\text{l} \cdot \text{min}^{-1}$. In all cases, significant *F*-values were followed by a Newman-Keuls *post-hoc* analysis. A probability value of 0.05 was set as the level of statistical significance.

Results

Comparisons of $\dot{V}O_2$ among the different test conditions are presented in Fig. 2. $\dot{V}O_2$ was found to be significantly ($p = 0.016$) greater for combined arm and leg exercise compared with leg cycling. However, this difference averaged only 0.04 $\text{l} \cdot \text{min}^{-1}$ across the workloads. The mean (SD) $\dot{V}O_2$ for sitting at rest on the Airdyne was 0.25 (0.04) $\text{l} \cdot \text{min}^{-1}$. Performing the arm motion without added external resistance increased the mean (SD) $\dot{V}O_2$ above resting levels form 0.07 (0.03) $\text{l} \cdot \text{min}^{-1}$ at 27 rpm (corresponding to the first workload) to 0.19 (0.08) $\text{l} \cdot \text{min}^{-1}$ at 58 rpm (corresponding to the ninth workload). The $\dot{V}O_2$ values for combined arm and leg exercise were found to be significantly lower ($p = 0.0015$) than the sum of the $\dot{V}O_2$ values for leg cycling and arm-only motion after correcting for resting $\dot{V}O_2$.

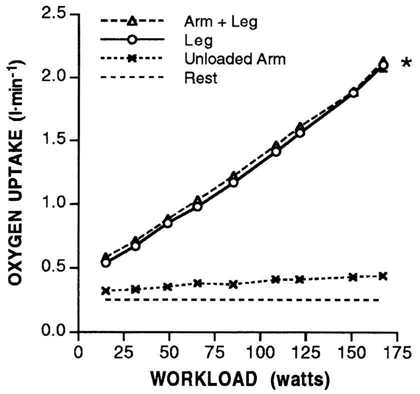

Fig. 2 Comparisons between combined arm and leg exercise (*Arm + Leg*) and leg cycling (*Leg*) for oxygen uptake across workloads. Also shown are the oxygen uptakes for seated rest on the Airdyne (*Rest*) and arm-only movement without added external resistance (*Unloaded Arm*) plotted at the workload that corresponds with the tested rpm. $*p < 0.05$ for comparison of Leg with Arm + Leg. *Brackets* represent 1 SE. Note that the SE values for oxygen uptake were small enough that brackets frequently do not appear on the graph

Figure 3 displays the comparisons between combined arm and leg exercise and leg cycling for the heart rate, RPE and blood lactate concentration values across workloads. The relationship of heart rate with workload was similar for combined arm and leg exercise and leg cycling. However, leg cycling was found to elicit a significantly higher ($p = 0.049$) RPE than combined arm and leg exercise. The presence of a significant interaction effect ($p = 0.022$) suggests that the higher RPE values with leg cycling were at the greater workloads. For blood lactate concentration, the comparison of combined arm and leg exercise with leg cycling approached, but did not reach, a statistical significance ($p = 0.08$).

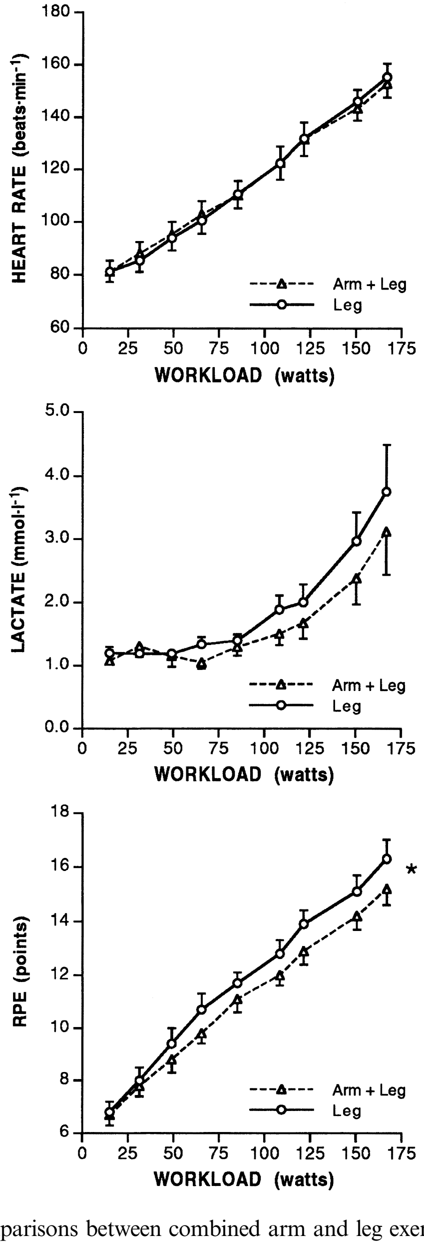

Fig. 3 Comparisons between combined arm and leg exercise (*Arm + Leg*) and leg cycling (*Leg*) for heart rate, blood lactate concentration and rating of perceived exertion (*RPE*) across workloads. $^*p < 0.05$ for the comparison of the two modes of exercise. *Brackets* represent 1 SE

The relationships of $\dot{V}O_2$, heart rate, and blood lactate concentration with RPE are presented in Fig. 4. The combined arm and leg exercise resulted in significantly higher values for $\dot{V}O_2$ ($p = 0.017$) and heart rate ($p = 0.010$) at a given RPE compared to leg cycling. No significant difference existed between combined arm and leg exercise and leg cycling for the relationship of blood lactate concentration with RPE.

The relationships of $\dot{V}O_2$, heart rate and workload with blood lactate concentration are displayed in Fig. 5. Combined arm and leg exercise resulted in significantly higher values for $\dot{V}O_2$ ($p = 0.0010$), heart rate ($p = 0.044$) and workload ($p = 0.0027$) at a given blood lactate concentration.

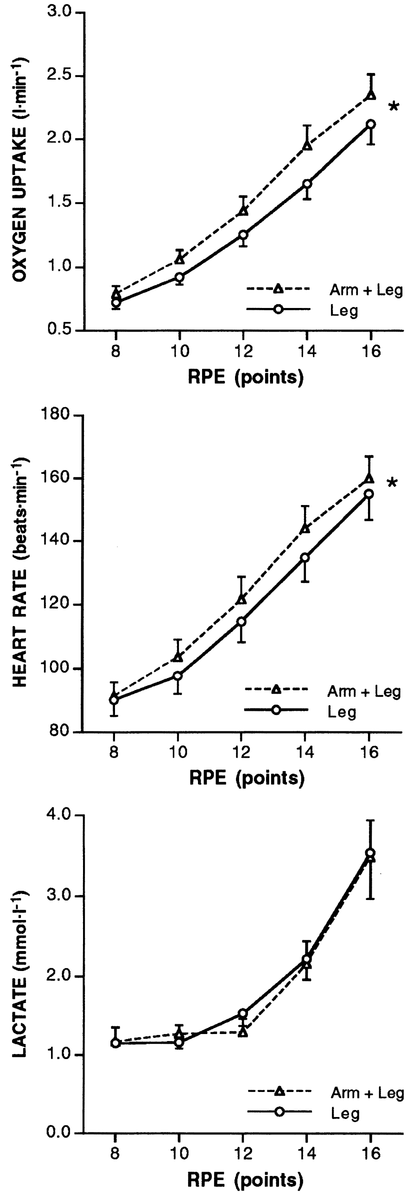

Fig. 4 Relationships for oxygen uptake, heart rate and blood lactate concentration with RPE for combined arm and leg exercise (*Arm + Leg*) and leg cycling (*Leg*). $^{*}p < 0.05$ for the comparison of the two modes of exercise. *Brackets* represent 1 SE

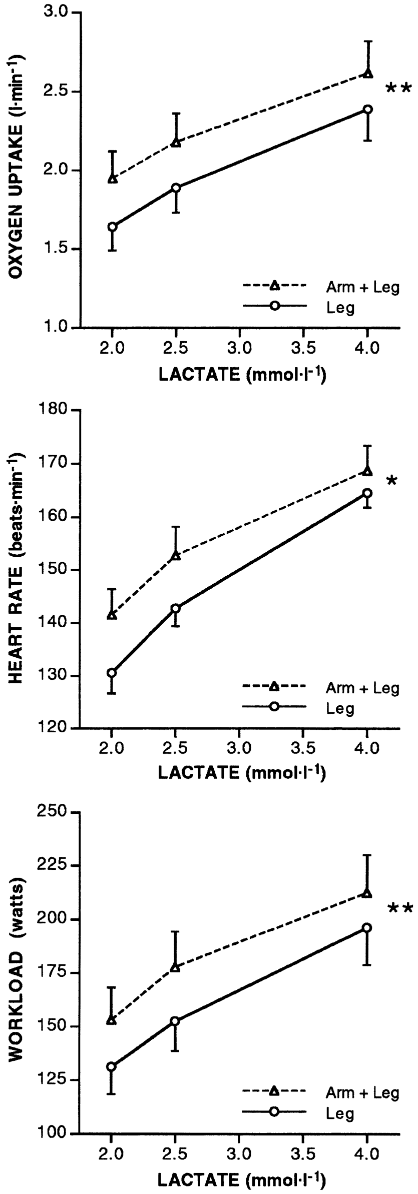

Fig. 5 Relationships for oxygen uptake, heart rate and workload with blood lactate concentration for combined arm and leg exercise (*Arm + Leg*) and leg cycling (*Leg*). $^{*}p < 0.05$ and $^{**}p < 0.01$ for the comparison of the two modes of exercise. *Brackets* represent 1 SE

Discussion

Oxygen uptake relative to power output

The primary focus of this investigation was to compare the aerobic demands for leg cycling and exercise that distributes the same external power output between the upper and lower body. A major strength of the study is the utilization of a single exercise device for performing the leg exercise and the combined arm and leg exercise. This assured that the external work rates were identical for those two exercise conditions. The results demonstrate that increasing the exercising muscle mass by inclusion of the upper body results in a minimal, but statistically significant, increase in the $\dot{V}O_2$ for performing a given external power output. However, the additional $\dot{V}O_2$ resulting from incorporation of the upper body in the exercise was found to be significantly less than would be expected from the added $\dot{V}O_2$ required to move the additional body parts (i.e., arms) against no resistance.

The previous scientific literature has demonstrated that the $\dot{V}O_2$ for producing a given external power output is greater for arm ergometry than for leg exercise (Moldover and Downey 1983; Taguchi and Horvath 1987; Toner et al. 1983; Vokac et al. 1975). This is thought to be largely due to the unmeasured "internal" work that is performed in stabilizing the body when performing upper body work. However, the scientific literature seems conflicting with regard to the effect on aerobic demand of increasing the exercising muscle mass above that used with leg cycling. Using separate arm and leg ergometers, some investigators (Reybrouck et al. 1975; Stenberg et al. 1967) have concluded that the $\dot{V}O_2$ for performing a specified power output is the same with leg ergometry compared with combined arm and leg ergometry. Toner et al. (1983) concluded that the $\dot{V}O_2$ for a given power output did not increase with combined arm and leg ergometry compared with leg ergometry until the arms contributed over 50% of the total power output. Using separate ergometers for rowing and cycling, Hagerman et al. (1988) have reported that the $\dot{V}O_2$ at a given power output was greater for rowing ergometry than for cycle ergometry. These authors concluded that the greater muscle mass involved in rowing is part of the explanation for their finding. In the present study, distributing the work between the upper and lower body increased the aerobic demand above that required for performing the same external work with the legs alone. The relative contribution of the upper body to the total power output was not measured. Although the present results are consistent with the fundamental notion that increasing the exercising muscle mass above that used in leg cycling elevates the $\dot{V}O_2$ for performing a specified external power output, it is important to recognize that the effect was found to be very small.

We hypothesized that if the $\dot{V}O_2$ for combined arm and leg exercise was greater than for leg cycling at a given power output, the finding could be explained by the additional $\dot{V}O_2$ associated with movement of the arms. To determine the added $\dot{V}O_2$ required for the arm movement against no resistance, we subtracted the $\dot{V}O_2$ for resting on the Airdyne from that for the arm movement at frequencies matching those of the other exercise tests. Interestingly, we found that the sum of $\dot{V}O_2$ values for leg cycling and that for movement of the arms above resting requirements was significantly greater than the $\dot{V}O_2$ for combined arm and leg exercise. In other words, our findings show that the combined arm and leg exercise required a lower $\dot{V}O_2$ than was expected from summation of the separate components.

The possibility must be considered that the added $\dot{V}O_2$ associated with movement of the arms was overestimated by the methods used in this study. Measures were taken to assure that the upper extremity excursion and rate of movement were comparable with the upper body movement performed during the combined arm and leg exercise. However, it is possible that, while performing the arm movement without external resistance, there were additional aerobic demands from muscular contractions in the lower extremities and trunk for stabilization of the body that were not present during the resting measurements.

Another possible explanation for our finding of a lower $\dot{V}O_2$ than expected for the combined arm and leg exercise might be that the combined arm and leg movement pattern is inherently more efficient than might be expected. It has previously been suggested that neural pathways for reciprocal innervation might allow for improved efficiency with asynchronous movement patterns compared with synchronous movement patterns (Glaser et al. 1980). It could be speculated that inherent or learned neural pathways also allow the combined arm and leg movement examined in this study to be performed at a lower $\dot{V}O_2$ than calculated as the sum of the aerobic demands for the arm movement and leg movement when performed separately.

Physiological demands relative to RPE

Another focus of this investigation involved analysis of the relationships of several physiological variables and power output with RPE. We hypothesized that the $\dot{V}O_2$ at a given RPE would be higher with combined arm and leg exercise compared with exercise just using the legs. The results support this hypothesis. In addition, this study demonstrates that distribution of work between the arms and legs allows one to exercise at a higher heart rate and external power output for a given RPE than when all the work is performed by the legs.

Previous studies have also demonstrated that the $\dot{V}O_2$ at a given RPE is increased when the work is distributed over a larger muscle mass. Ekblom and Goldbarg (1971) compared arm ergometry with leg ergometry and found that the $\dot{V}O_2$ at a given RPE was higher for leg ergometry. Sargeant and Davies (1973) compared single and double upper extremity work and single and double lower extremity work and found that, for a given RPE, the $\dot{V}O_2$ and power output increased with the muscle mass participating in the exercise. A study of Butts et al. (1995) compared the exercise of walking with walking combined with arm exercise. These authors also found that the $\dot{V}O_2$ at a given RPE was higher for the exercise using the larger muscle mass. In other investigations (Ekblom and Goldbarg 1971; Hetzler et al. 1991; Skinner et al. 1973; Zeni et al. 1996b) walking and running have been demonstrated to induce a higher $\dot{V}O_2$ than cycle ergometry at a given RPE, presumably because walking and running use a larger muscle mass than cycling. Finally, our comparisons of cross-country skiing techniques (Hoffman et al. 1990, 1992, 1994) have also demonstrated that the $\dot{V}O_2$ for a given RPE is higher for the techniques using a larger muscle mass.

The present study was not directed at determining an explanation for the higher $\dot{V}O_2$ at a given RPE that results from distribution of work over a larger amount of muscle. However, we speculate that distribution of work over a larger muscle mass reduces the sensory input for RPE from sensations of strain in the working muscles and joints.

The practical benefits that might be achieved from exercising with a large muscle mass should be apparent. Since exercise intensity is commonly established from a subjective perception of exertion, dynamic exercise using a muscle mass larger than that used in leg cycling is likely to induce greater cardiorespiratory training adaptations.

Physiological demands relative to blood lactate concentration

Recent research has suggested that exercise training intensity should be based upon lactate threshold or fixed blood lactate concentrations (Henritze et al. 1985; Sjodin et al. 1982; Yoshida et al. 1982). With this theory in mind, the relationships of $\dot{V}O_2$, heart rate, RPE and workload with blood lactate concentration were examined in the present investigation. This study demonstrates that at a specified blood lactate concentration, $\dot{V}O_2$, heart rate and external power output are higher with combined arm and leg exercise compared with leg cycling.

Previous work has suggested that the mode of exercise can alter the relationship of $\dot{V}O_2$ with blood lactate concentration. Bevegard and coworkers (1966) demonstrated that the lactate concentration at a given $\dot{V}O_2$ was higher with arm ergometry compared to leg ergometry. However, in contrast to the findings in the present study, they found that leg ergometry and combined arm and leg ergometry had the same relationship of $\dot{V}O_2$ with blood lactate concentration. On the other hand, a comparison of treadmill walking/running with cycle ergometry by Hetzler and colleagues (1991) demonstrated that $\dot{V}O_2$ and heart rate were higher for a given blood lactate concentration with treadmill walking/running, presumably because of the use of a larger muscle mass.

A difference in the relationship of $\dot{V}O_2$ with blood lactate concentration has practical importance if blood lactate concentration is used to establish exercise intensity. The present findings suggest that dynamic exercise that distributes the work between the upper and lower body should induce a higher $\dot{V}O_2$, heart rate and external power output at a given blood lactate concentration compared with exercise that uses only the lower body.

The RPE with blood lactate relationship was found to be similar for leg cycling and combined arm and leg exercise. A similar relationship between RPE and blood lactate concentration has been found in previous investigations which have made comparisons among arm ergometry, leg ergometry and treadmill walking/running (Ekblom and Goldbarg 1971; Hetzler et al. 1991). We (Zeni et al. 1996a; 1996b) have also demonstrated that the relationship of RPE with blood lactate concentration is similar for cycle ergometry, Airdyne exercise, stairstepping, treadmill walking/running and rowing ergometry. However, our previous work also demonstrated that the blood lactate concentrations were lower at specified RPE values with simulated cross-country skiing compared with the other modes of exercise. Thus, while the findings of similar relationships of RPE with blood lactate concentration among several different modes of dynamic exercise make it appealing to emphasize the contribution of blood lactate concentration in mediating RPE, it must be recognized that other factors are involved in providing the stimulus for RPE.

In conclusion, this study demonstrates that the aerobic demands for combined arm and leg exercise are minimally, but significantly, greater than for leg cycling at the same external power output. In addition, the aerobic demands and heart rates at specified RPE values and blood lactate concentrations are higher for combined arm and leg exercise than leg cycling. From these findings it is concluded that: (1) increasing the exercising muscle mass above that used in leg cycling for generation of a given power output results in a reduction in RPE, but a minimal increase in $\dot{V}O_2$, and (2) use of a muscle mass larger than that used in leg cycling should allow a greater cardiorespiratory training effect if training intensity is established by RPE or blood lactate concentration.

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References

American College of Sports Medicine (1991) Guidelines for exercise testing and prescription. In: Guidelines for exercise test administration. Lea and Febiger, Philadelphia, pp 71

Bevegard S, Freyschuss U, Strandell T (1966) Circulatory adaptation to arm and leg exercise in supine and sitting position. J Appl Physiol 21: 37–46

Borg G (1970) Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 2–3: 92–98

Butts NK, Knox KM, Foley TS (1995) Energy costs of walking on a dual-action treadmill in men and women. Med Sci Sports Exerc 27: 121–125

Ekblom B, Goldbarg AN (1971) The influence of physical training and other factors on the subjective rating of perceived exertion. Acta Physiol Scand 83: 399–406

Glaser RM, Sawka MN, Young RE, Suryaprasad AG (1980) Applied physiology for wheelchair design. J Appl Physiol Respir Environ Exerc Physiol 48: 41–44

Hagerman FC, Lawrence RA, Mansfield MC (1988) A comparison of energy expenditure during rowing and cycling ergometry. Med Sci Sports Exerc 20: 479–488

Henritze J, Weltman A, Schurrer RL, Barlow K (1985) Effects of training at and above the lactate threshold on the lactate threshold and maximal oxygen uptake. Eur J Appl Physiol 54: 84–88

Hetzler RK, Seip RL, Boutcher SH, Pierce E, Snead D, Weltman A (1991) Effect of exercise modality on ratings of perceived exertion at various lactate concentrations. Med Sci Sports Exerc 23: 88–92

Higgs SL, Robertson LA (1981) Cyclic variations in perceived exertion and physical work capacity in females. Can J Appl Sports Sci 6: 191–196

Hoffman MD, Clifford PS, Foley PJ, Brice AG (1990) Physiological responses to different roller skiing techniques. Med Sci Sports Exerc 22: 391–396

Hoffman MD, Jones GM, Bota B, Mandli M, Clifford PS (1992) In-line skating: physiological responses and comparison with roller skiing. Int J Sports Med 13: 137–144

Hoffman MD, Clifford PS, Watts PB et al. (1994) Physiological comparison of uphill roller skiing: diagonal stride versus double pole. Med Sci Sports Exerc 26: 1284–1289

Moldover JR, Downey JA (1983) Cardiac responses to exercise: comparison of three ergometers. Arch Phys Med Rehabil 64: 155–159

Reybrouck T, Heigenhauser GF, Faulkner JA (1975) Limitations to maximum oxygen uptake in arm, leg, and combined arm-leg ergometry. J Appl Physiol 38: 774–779

Sargeant AJ, Davies CTM (1973) Perceived exertion during rhythmic exercise involving different muscle masses. J Hum Ergol 2: 3–11

Sjodin B, Jacobs I, Svendenhag J (1982) Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA. Eur J Appl Physiol 49: 45–47

Skinner JS, Hutsler R, Bergsteinova V, Buskirk ER (1973) Perception of effort during different types of exercise and under different environmental conditions. Med Sci Sports 5: 110–115

Stenberg J, Astrand P-O, Ekblom B, Royce J, Saltin B (1967) Hemodynamic response to work with different muscle groups, sitting and supine. J Appl Physiol 22: 61–70

Taguchi S, Horvath SM (1987) Metabolic responses to light arm and leg exercise when sitting. Eur J Appl Physiol 56: 53–57

Toner MM, Sawka MN, Levine L, Pandolf KB (1983) Cardiorespiratory responses to exercise distributed between the upper and lower body. J Appl Physiol Respir Environ Exerc Physiol 54: 1403–1407

Vokac Z, Bell H, Bautz-Holter E, Rodahl K (1975) Oxygen uptake/heart rate relationship in leg and arm exercise, sitting and standing. J Appl Physiol 39: 54–59

Yoshida T, Suda Y, Takeuchi N (1982) Endurance training regimen based upon arterial blood lactate: effects on anaerobic threshold. Eur J Appl Physiol 49: 223–230

Zeni AI, Hoffman MD, Clifford PS (1996a) Relationships among heart rate, lactate concentration, and perceived effort for different types of rhythmic exercise in females. Arch Phys Med Rehabil 77: 237–241

Zeni AI, Hoffman MD, Clifford PS (1996b) Energy expenditure with indoor exercise machines. J Am Med Assoc 275: 1424–1427