Cardiac Output Dependency on Exercising Muscle Mass

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ABSTRACT

Matthews EL, McConnell TR, Rawson ES, Andreacci JL. Cardiac Output Dependency on Exercising Muscle Mass. The purpose of this study was to determine the relationship between cardiac output (CO) and muscle mass engaged during submaximal steady-state exercise. JEPonline 2012;15(5):88-95. Fifteen young adult males participated in leg and arm ergometry with CO measured throughout incremental workloads. No significant difference exists for COabs (L·min⁻¹) during leg ergometry between larger (14.34±4.93) and smaller (12.68±4.47) leg musculatures (P=0.067). During arm exercise, COabs was greater in participants with larger (20.25±9.60) versus smaller (13.73±4.89) arm musculatures (P<0.01). During both exercise modalities, no difference exists between the subjects with larger and smaller musculatures for COrel (mL·kg⁻¹·min⁻¹). We conclude that differences exist in the CO response to matched submaximal exercise between larger and smaller muscle mass.

Key Words: Bioreactance, Bioimpedance, Ergometry
INTRODUCTION

Cardiac output (CO) is a direct measure of overall cardiac performance. It is directly related to the metabolic activity of active body tissue (2). Hence, at the onset of exercise, CO must rapidly increase to meet the metabolic demand. This is especially true during intensive bouts of exercise to maintain blood pressure in the presence of vasodilation in the working muscle. When large muscle groups are involved in exercise, the increase in local blood flow to the working muscle due to local vasodilation would result in a decrease in blood pressure if not for the rapid sympathetic vasoconstriction in areas of non-active tissue (4).

Accordingly, one would assume that the larger exercising muscle mass during leg ergometry will produce a greater vasodilation and decrease in total peripheral resistance (TPR) when compared to the smaller muscle mass involved during arm ergometry. Consequently during leg ergometry, you would then expect greater muscle blood flow to working muscle, followed by a greater venous return and greater stroke volume (SV) response to the increasing CO demand. Conversely, during arm exercise, there would be less vasodilation, greater TPR, smaller venous return, and smaller SV response. Thus, during arm exercise, CO must then be maintained by a greater increase in heart rate (HR). This premise is supported by multiple studies in which TPR and intra-arterial blood pressure are significantly greater during arm ergometry when compared with leg or combined leg and arm ergometry (1,14).

However, there is a limit to the muscle mass induced increase in CO (6,10). Koch, Newcomer, and Proctor (2005) explained that it is not possible to fully dilate large muscle mass. During exercise incorporating very large muscle mass, full dilation would result in an abnormally large decrease in TPR that an increase in CO could not overcome in order to maintain adequate blood pressure (8). In healthy sedentary individuals the dilation capabilities of muscle surpass the maximum CO capability when one-third or more of the total body muscle mass or approximately 10 kg of muscle mass is used during intense exercise (3,12). During high intensity large muscle mass exercise, once the maximum muscle perfusion is reached, further increases in work rate are accomplished through a partial redirection of blood flow from currently active exercising muscle fibers to newly recruited muscle fibers within the same working muscle (8). Therefore, it could be anticipated that CO relative to limb muscle mass (ml·kg⁻¹·min⁻¹) may level off during incremented leg exercise but continue to increase during arm exercise throughout a range of incremented work rates. This leads one to believe that there is greater anaerobic demand in working skeletal muscle of larger muscle masses than smaller muscle masses.

The purpose of this investigation was to determine differences in the CO response to incremented work rates during leg versus arm exercise. We hypothesized that there would be a decrease or no difference in CO with increasing exercise intensity during leg ergometry in those with larger leg muscle mass compared with those with smaller leg muscle mass. In contrast, we anticipated that CO would be greater in those with larger arm muscle mass versus those with smaller arm muscle mass.

METHODS

Subjects

The subjects consisted of 15 healthy, male volunteers between 18 to 26 yrs of age. All subjects had to be free of known health complications that would influence their tolerance or response to exercise. Subjects were excluded if they had regularly trained for cardiovascular endurance 3 or more d·wk⁻¹, for 30 min or more in the previous 5 yrs. All subjects read and signed an Institutional Review Board approved consent form that explained all testing purposes, procedures, benefits, and risks associated
with the study. In addition, each subjects completed a Physical Activity Readiness Questionnaire (PAR-Q). All experiments associated with this study complied with the current laws of the United States of America and with the Helsinki Declaration of 1975, as revised in 1983. This study was approved by the Bloomsburg University IRB.

Procedures

**Testing Sequence**
All subjects underwent one segmental body composition analysis and two incremented ergometry tests (one using arms and one using legs). All testing was completed over 2 days of testing with a minimum of 48 hrs between test days. The subjects were asked to arrive well rested after eating a small meal ~2 hrs prior to testing and to refrain from over the counter drugs, stimulants such as caffeine, showering or bathing within 4 hrs prior, sauna use, and excessive food or beverage consumption. They were also asked to avoid alcohol and heavy exercise at least 24 hrs preceding testing. None was allowed to wear metallic clothing or electronic devices during testing to eliminate potential electrical interference with electrodes. On the 1st day of testing, the subjects had their body composition assessed and, then, they performed one of the ergometry tests. During the 2nd day of testing, they performed the other ergometry test. The testing sequence (arm vs. leg) was randomly assigned for each subject.

**Body Composition Analysis**
Body composition assessment was performed using single frequency, segmental bioelectrical impedance analysis (SBIA) (BC-418 Bioelectrical Impedance Segmental Body Composition Analyzer, Tanita Corporation of America, Inc., Arlington Heights, IL). The body was positioned on the contact electrode platform so that each foot had an electrode positioned at the toes and heel. The participant held two electrode implanted handles so that each hand had electrodes approximately positioned at the finger tips and thenar (muscle of the palm proximal to the thumb) portion of the hand. Legs and arms were kept straight during the test. The inner thighs were not allowed to touch and the arms were abducted so as to not be in contact with the torso. Impedance was measured between electrodes in such a way that impedance of the whole body and each segment were determined. Body composition was measured before any exercise was performed during the first visit.

**Cardiorespiratory Measures**
Both leg and arm ergometry were performed using the Warren E. Collins Company (Braintree, MA) Pedal Mate electronically braked ergometer. A Parvo Medics (Sandy, Utah) TrueMax 2400 Metabolic Measurement System cart measured expired air volume, analyzed O₂ and CO₂ concentrations in expired gases, and then calculated oxygen consumption (VO₂) and carbon dioxide production (VCO₂). The Cheetah Medical, Inc. (Portland, Oregon) noninvasive CO monitoring (NICOM) system utilizing bioreactance determined CO as described elsewhere (12). In brief, blood flow within the aorta was calculated based on an assessment of the phase shifts in an alternating radiofrequency electrical current (d² · dmax⁻¹) measured across the thorax. CO was subsequently determined from:

\[
CO = [C \cdot VET \cdot (dF \cdot dmax^{-1})] \cdot HR
\]

Where C is a constant of proportionality (based upon participant age, gender and body size) and VET is ventricular ejection time determined from the NICOM and electrocardiograph signal. The system was auto-calibrated and an adequate electrocardiograph signal and NICOM waveform were established prior to the acquisition of data. The NICOM system uses four surface electrodes. One electrode was placed on each side of the torso over the spine of the scapula. The second set of electrodes was placed on the sides of the torso level with the umbilicus. Electrode connections were secured with medical tape and all connecting wires supported to insure minimal movement artifact.
Blood pressure was measured on the left brachial artery with a blood pressure cuff and standard sphygmomanometer.

**Exercise Tests**
Both leg and arm tests used an intermittent protocol using 3-min work periods interspersed with 1-min rest periods. The initial work load was 25 Watts with 25 Watt increments for each ensuing work stage. The work increments were continued until the subjects could no longer complete the 3-min increment. All measures were obtained during the last 15 sec of the rest period and each work increment. CO and VO$_2$ measures were the average of three consecutive measures obtained during the 15-sec measurement period.

**Statistical Analyses**
A power analysis established that 14 subjects would provide an 80% chance of detecting a correlation coefficient of $r = .70$ between CO and muscle mass that would be statistically significant at the $P=0.05$ level. A two-way-analysis of variance (ANOVA) determined the significance of differences between main effects, which were muscle mass (high and low) and Watts for absolute values of CO (COabs; L·min$^{-1}$) and CO relative to muscle mass (COrel; mL·kg$^{-1}$·min$^{-1}$). Any significant interactions of main effects were determined, and were visually analyzed through graphical interpretation. The analyses were performed for arm and again for leg work. The high and low muscle mass groups were determined as the upper and lower 50th percentile for muscle mass for arms and again for legs. Estimates of CO were correlated using Pearson’s product-moment correlation to measured VO$_2$ in order to confirm validity of CO values obtained (5).

**RESULTS**
The specific aim of this study was to determine whether muscle mass had an effect on CO during incremental exercise. Fifteen young adult males served as volunteers for the study. Demographics for the study participants are listed in Table 1. During both arm and leg exercise a strong correlation between estimated CO and measured VO$_2$ was obtained (arm exercise: $r(6) = .67$, $P<0.001$; leg exercise: $r(8) = .84$, $P<0.001$)

<table>
<thead>
<tr>
<th>Table 1. Descriptive Data of the Subjects.</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>22.2 ± 1.5</td>
<td>20.0 - 26.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.0 ± 9.7</td>
<td>156.0 - 196.0</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>89.8 ± 19.9</td>
<td>71.1 - 132.6</td>
</tr>
<tr>
<td>Body Mass Index (kg·m$^{-2}$)</td>
<td>28.2 ± 4.7</td>
<td>22.2 - 40.0</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>16.4 ± 6.2</td>
<td>8.2 - 29.9</td>
</tr>
<tr>
<td>Fat Mass (kg)</td>
<td>15.5 ± 9.2</td>
<td>6.2 - 39.7</td>
</tr>
<tr>
<td>Fat Free Mass (kg)</td>
<td>74.3 ± 12.8</td>
<td>58.5 - 98.5</td>
</tr>
<tr>
<td>Total Muscle (kg)</td>
<td>70.9 ± 12.1</td>
<td>55.9 - 94.0</td>
</tr>
<tr>
<td>Body Surface Area (m$^2$)</td>
<td>2.1 ± 0.3</td>
<td>1.7 - 2.5</td>
</tr>
<tr>
<td>Leg Peak (Watts)</td>
<td>166.8 ± 29.4</td>
<td>125.0 - 200.0</td>
</tr>
<tr>
<td>Leg Peak VO$_2$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>36.2 ± 7.1</td>
<td>22.6 - 49.6</td>
</tr>
<tr>
<td>Arm Peak (Watts)</td>
<td>113.3 ± 28.1</td>
<td>75.0 - 175.0</td>
</tr>
<tr>
<td>Arm Peak VO$_2$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>27.5 ± 6.9</td>
<td>14.8 - 37.7</td>
</tr>
</tbody>
</table>

Values are means ± standard deviations for 15 volunteers.
There was no significant difference for COabs (L·min\(^{-1}\)) during leg ergometry between larger (14.34 ± 4.93) and smaller (12.68 ± 4.47) muscle mass (P=0.067). As expected, COabs did increase with increasing workload (P=0.001), but there was no interaction between main effects. During arm exercise, there was a significant interaction between main effects for COabs, (P<0.01). It appears that both groups increased COabs (larger 20.25 ± 9.60; smaller 13.73 ± 4.89) throughout the test, but the large muscle mass group showed a greater and more rapid increase than the small muscle group (Figure 1).

![Figure 1. Comparison of COabs between large muscle mass (light grey squares) and small muscle mass (dark grey diamonds) during arm ergometry. Error bars represent standard error of the measurement.](image)

A similar two-way analysis of variance (ANOVA) was also performed for COrel (ml·kg\(^{-1}\)·min\(^{-1}\)). During both leg (larger 0.55±0.18; smaller 0.61±0.20) and arm (larger 2.01±0.97; smaller 1.86±0.67) exercise, there was no significant difference between groups of larger and smaller muscle mass for COrel. In both exercise modalities, COrel increased (leg exercise: P<0.001; arm exercise: P<0.001) with increasing workloads as seen with absolute COabs. There was no significant interaction effects found for COrel across workloads in either modality.

**DISCUSSION**

If perfusion of muscle masses is inadequate during exercise exclusively in large muscle mass, we anticipated that CO would increase in a linear fashion during arm exercise for both those with smaller muscle mass and those with larger muscle mass but at a greater rate for those with the larger muscle mass. Conversely, during leg exercise we would expect that there would be no differences in the rate or magnitude of increase for those with the larger muscle mass due to the inability to perfuse larger muscle mass during higher intensity exercise. This is indeed what we found.
During arm exercise both the small and large muscle groups displayed an increase in CO throughout the test (Figure 1), but the rate of increase was greater in those with larger muscle mass and exceeded the CO of those with the smaller muscle mass at 25, 50, and 75 watts. This was expected, because during small muscle exercise the blood vessel perfusion capabilities of the cardiovascular system are not being overloaded (3,8-10,12). Therefore, CO was able to adequately perfuse the muscle mass of the arms even in those with larger muscle mass as exercise increased.

Although CO increased with increasing workloads during leg exercise, there were no differences in the CO response to exercise for the smaller muscle mass group when compared to the larger muscle mass group (Figure 2). This would suggest that the CO response had reached its capacity to perfuse the leg musculature during exercise in the smaller muscle mass group and was limited in its ability to perfuse the larger muscle mass even though you would expect a greater venous return and resultant enhanced CO. These findings are consistent with what others have demonstrated (1,14).

![Figure 2. Comparison of COabs between large muscle mass (light grey squares) and small muscle mass (dark grey diamonds) during leg ergometry. Error bars represent standard error of the measurement.](image)

The arms were expected to show greater CO in individuals with larger musculatures. This is because the arm muscle mass does not exceed the limits of perfusion capabilities. In healthy sedentary individuals, the dilation capabilities of muscle surpass the maximum CO capability when one-third or more of the total body muscle mass or approximately 10 kg of muscle mass is used during intense exercise (3,12). The larger muscle mass group for arm exercise consisted of eight subjects. Of these eight subjects in the larger muscle mass group, only four had arm muscle mass totaling greater than 10 kg (mean 10.2, SD 1.2). Therefore, CO was able to closely match the blood flow requirements of the arm, even in the subjects with larger muscle masses. Conversely, all of the subjects had a combined leg muscle mass of greater than 10 kg, with the lower muscle mass groups having a mean muscle of 20.7±1.1 kg and the larger muscle mass group having a muscle mass of 26.1±3.0 kg.
When CO was expressed relative to muscle mass, the COrel continued to increase through 75 Watts during arm exercise but leveled off during leg exercise. This finding suggests two considerations: (a) that once the maximum muscle perfusion is reached, further increases in work rate is accomplished through a partial redirection of blood flow from currently active exercising muscle fibers to newly recruited muscle fibers within the same working muscle; and (b) that the increase in work rate is not accomplished with a further increases in CO (8).

**Recommendations**

First, a future study may want to consider more strict controls for muscle mass by selecting participants with larger and smaller muscle masses within a predetermined inclusion/exclusion criterion of large muscle masses =10 kg and small muscle mass <10 kg (3). Second, newer noninvasive technologies such as bioreactance have enhanced the ability to study cardiovascular dynamics in humans while minimizing cost and risk of complications. Currently, this technology has been validated for use with clinical populations (7,11,13). The authors of the present study are aware of only one attempt to validate this technology during exercise in a healthy population. Elliott et al. (2010) compared CO with bioreactance to CO with inert gas rebreathing and found a systematic underestimation of CO at rest and throughout a range of exercise intensities for bioreactance when compared to rebreathing. The authors did find a strong correlation with VO$_2$ ($r$(10) = .84, P<0.001) that is in agreement with the findings of the present study during both arm ($r$(6) = .67, P<0.001,) and leg ($r$(8) = .84, P<0.001) exercise. Since we found consistent differences between measures of CO throughout a range of VO$_2$ and a strong correlation between CO and VO$_2$, the comparisons between arm and leg exercise using the bioreactance measures are valid.

**CONCLUSIONS**

When comparing larger to smaller muscular individuals during a small muscle mass exercise (arm ergometry), individuals with a greater muscle mass displayed greater COabs. This increased COabs with larger muscular individuals was not seen during large muscle mass exercise (leg ergometry), thus confirming that the CO response cannot keep up with the perfusion demands of large muscle mass as exercise intensity increases.

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**REFERENCES**


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