The physiology of rowing

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Abstract

Rowing competitions for males are performed over a distance of 2000 m and last 5.8–7.4 min. This time is being improved by 0.01 min per year. Races are most often carried out with an initial spurt in order to increase the total aerobic metabolism. Large individuals have an advantage partly because of a larger anaerobic metabolism, but also because the almost constant weight of the boat, oars and coxswain becomes relatively less for oarsmen with larger body dimensions. Oxygen uptake during rowing increases with velocity to the power 2.4. It is estimated that the metabolic cost of rowing at racing speed corresponds to $6.4 \times 10^3$ min$^{-1}$. The most successful oarsmen have a weight of $93 \pm 2.6$ kg (± s.e.) and a maximal oxygen uptake of $5.9 \pm 0.08$ l min$^{-1}$ (± s.e.). A direct relationship is demonstrated between the average maximal oxygen uptake of the crew ($y$) and their placing ($x$) in an international regatta, $y = 6.15 - 0.08x$ ($r = 0.87$). In contrast, measures of muscle strength do not separate the good from less qualified oarsmen except that the best oarsmen can develop a larger force in a simulated rowing position (2000 N). Maximal oxygen uptake is greater during rowing than during running or bicycling, probably because of the intensive involvement of a larger muscle mass. The capacity of the oxygen transporting system is shown to be dependent on the local (muscle) blood flow. Thus metabolic, circulatory and strength measurements indicate that training for rowing should simulate rowing in the boat as much as possible.

Keywords: Aerobic metabolism, anaerobic metabolism, body dimensional influence on work capacity, limiting factors for performance, muscle strength, rowing physiology.

Introduction

A first attempt to describe the physiology of rowing was carried out when Liljestrand and Lindhard (1920) measured oxygen uptake, heart rate and cardiac output during rowing of an ‘ordinary’ boat. Henderson and Haggard (1925) estimated the energy expended in rowing an eight-oared racing shell by the determination of (a) the pull when the boat was towed by a motor boat; (b) the work performed during rowing a machine; and (c) the volume of oxygen consumed from the air by the oarsmen’s breathing. At very low velocities Ewig (see Törner, 1959) determined oxygen uptake during rowing a racing shell.

Since then experiments have focused mainly on the determination of the maximal oxygen
uptake of oarsmen (Mellerowicz and Hansen, 1965; Saltin and Åstrand, 1967; Nowacki et al., 1969, 1971; de Pauw and Vrijens, 1971; Bloomfield and Roberts, 1972; Secher et al., 1974, 1982a,e; Asami et al., 1978), and a comparison has been made with values obtained during other types of exercise (Strydom et al., 1967; Carey et al., 1974; Jackson and Secher, 1976; Cunningham et al., 1975; Strømme et al., 1977; Larsson and Forsberg, 1980). Of special interest for oarsmen is the importance of arm work in the maximal oxygen uptake of the subject (Åstrand, 1952; Taylor et al., 1955; Åstrand and Saltin, 1961a; Andersen et al., 1961; Stenberg et al., 1967; Kamon and Pandolf, 1972; Hermansen, 1973; Gleser et al., 1974; Secher et al., 1974, 1977; Reybrouck et al., 1975; Secher and Oddershede, 1975; Bergh et al., 1976; Strømme et al., 1977).

Oxygen deficit and debt of oarsmen have also been measured (Asami et al., 1978; Hagerman et al., 1978, 1979; Secher et al., 1982a), as has their strength (Yamakawa and Ishiko, 1966; Bloomfield and Roberts, 1972; Hagerman et al., 1972; Secher, 1975; Larsson and Forsberg, 1980), and values have been presented for muscle histochemistry (Bonde-Petersen et al., 1975; Larsson and Forsberg, 1980; Secher et al., 1981), vital capacity (Yamakawa and Ishiko, 1966), heart volume (Mellerowicz and Hansen, 1965), and echocardiographic measurements of ventricular volume and wall thickness (Howald et al., 1977; Keul et al., 1982). These variables have been followed during training for competitive rowing (Schausen, 1965; Larsson and Forsberg, 1980; Secher et al., 1982a) and have been related to rowing performance (Yamakawa and Ishiko, 1966; Hagerman et al., 1972, 1975; Bloomfield and Roberts, 1972; Asami et al., 1978; Larsson and Forsberg, 1980; Secher et al., 1982c).

Representative racing results in international championship regattas arranged by the Fédération Internationale des Sociétés d’Aviron (FISA) have been calculated (Secher, 1973) and the force applied on the oar has been determined (Ishiko, 1968; Hagerman and Lee, 1971; Schnedier et al., 1978; Asami et al., 1978) allowing a calculation of the minimum work performed by the oarsmen at various rowing speeds (Celentano et al., 1974). The investigations have also involved an estimate of the metabolic cost of rowing (di Prampero et al., 1971; Jackson and Secher, 1976). The studies have most often involved male heavyweight rowers. Thus few values exist for women and lightweight rowers (Hagerman et al., 1979; Secher et al., 1982a).

Some biomechanical (Nigg, 1977) and physiological (Törner, 1959; Åstrand and Rodahl, 1977; Reilly, 1981) aspects of rowing have been reviewed in textbooks, and a monograph on biomechanical aspects of rowing has appeared (Schneider, 1980).

The measured variables are most often large, for example, maximal oxygen uptake in excess of 6 l min⁻¹ (STPD), and can be difficult to evaluate as most physiological measures are dependent upon body dimensions (Asmussen and Heebøll-Nielsen, 1955; Åstrand and Rodahl, 1977; Asmussen et al., 1981) and oarsmen are usually large individuals (Hirata, 1979). Another problem has been to explain why heavyweight oarsmen row faster than lightweight ones row (McMahon, 1971).

Rowing is different from most other types of human exercise owing to the fact that the body is supported by a seat, and also because of the involvement of both arms and legs, the two legs working in the same phase. This contrasts with running, for example, during which one leg is predominantly performing work at a time.

This paper describes some aspects of rowing physiology with special reference to the influence of body size on rowing performance and on the measured variables, and to the metabolic cost of...
Rowing competitions

Rowing competitions are performed over a distance of 2000 m for men and 1000 m for women. Races are held for boats in which each rower uses two sculls and in boats where each oarsman handles one larger oar. Fours and pairs may or may not include a coxswain while the single scull is rowed without one. The eights do have a coxswain. Men's events are held separately for German lightweights. They may also compete in an open class. The lightweights are allowed a maximum weight of 72.5 kg and an average weight of 70 kg.

Open-class international rowing championships (European, one North American in 1967, world and Olympic) have been arranged by FISA since 1893. Olympic regattas were introduced in 1900. For women, FISA championships have taken place since 1954 and women have participated in the Olympic Games since 1976. 'Unofficial' lightweight championships were held for the first time in 1974.

Since the first regatta took place the mean results in the men's open class have improved by about 0.01 min per year (Fig. 1, Table 1, Secher, 1973), while differences in lane and wind circumstances do not allow yet for the detection of significant improvement in results obtained by women and lightweight rowers.

The median of the results obtained in FISA regattas from 1974 to 1982 indicates a race duration in the men's open class of 6.6 min, while the median rowing time for women is 3.4 min, and 6.6 min for lightweights (Table 2). The values presented in Table 2 indicate a difference in

![Diagram](image_url)

Fig. 1. Results obtained by FISA regatta winning eight-oared crews over 2000 m 1893 to 1971. The regression line and its 95% confidence limits are shown. This figure is published with the kind permission of the American College of Sports Medicine.
Table 1. Regression lines between winning results in FISA regattas and the year of the regatta (1979 is the last year included in the calculations). Boat type indicated with the number of oarsmen, plus or minus a coxswain, an x indicates a sculler. The year of the first regatta and the correlation coefficient ($r$) are also shown.

<table>
<thead>
<tr>
<th>Boat type</th>
<th>First regatta</th>
<th>Regression line*</th>
<th>$r$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4+</td>
<td>1893</td>
<td>$Y = -0.0129X + 7.538$</td>
<td>0.69</td>
<td>b</td>
</tr>
<tr>
<td>2-</td>
<td>1920</td>
<td>$Y = -0.0140X + 8.106$</td>
<td>0.54</td>
<td>b</td>
</tr>
<tr>
<td>1x</td>
<td>1893</td>
<td>$Y = -0.0113X + 8.140$</td>
<td>0.57</td>
<td>b</td>
</tr>
<tr>
<td>2+</td>
<td>1893</td>
<td>$Y = -0.0124X + 8.460$</td>
<td>0.60</td>
<td>b</td>
</tr>
<tr>
<td>4-</td>
<td>1924</td>
<td>$Y = -0.0097X + 7.148$</td>
<td>0.49</td>
<td>b</td>
</tr>
<tr>
<td>2x</td>
<td>1898</td>
<td>$Y = -0.0109X + 7.524$</td>
<td>0.65</td>
<td>b</td>
</tr>
<tr>
<td>8+</td>
<td>1893</td>
<td>$Y = -0.0092X + 6.622$</td>
<td>0.57</td>
<td>b</td>
</tr>
</tbody>
</table>

* The year 1900 was chosen as the starting point, $Y =$ winning time in min, $X =$ year of regatta, i.e. 70 for 1970.
* Indicate $P < 0.001$.

results obtained by heavyweights and lightweights of 2.5% in comparable events, supporting the impression that a large body weight is an advantage.

The influence of body dimensions on rowing performance*

According to Hill (1927) the total energy expenditure ($E$) during an exhausting athletic event may be expressed as

$$E = S + ARt$$

where $S$ represents an expendable energy store, $AR$ is the maximal possible increase in metabolic rate above the resting value, and $t$ is the duration of the event.

The energy store corresponds to the sum of energy that can be transformed by hydrolysis of adenosine triphosphate and creatine phosphate (CP), by oxidation using a large part of the oxygen bound to haemoglobin and myoglobin, and by anaerobic splitting of glycogen to give lactate. Thus $S$ may represent the 'oxygen deficit' developed during the event.

The variables making up $S$ are all volume dependent and must therefore be expected to increase in proportion to the power three of a characteristic linear dimension ($p$) of the subject. Total myoglobin, glycogen, CP etc. are proportional to muscle mass, which again is proportional to $p^3$. As the distribution volume for lactate also is proportional to $p^3$ it follows that, for example, blood lactate concentration after maximal exercise should be equal in large and small individuals (Fig. 2, Secher et al., 1983).

$AR$ represents aerobic power, i.e. the energetic ('caloric') value of the volume of oxygen used

* Secher and Vaage, unpublished work.
The physiology of rowing

Table 2. Observed results in rowing (median of winning times in FISA championships 1974-82). Also given are the calculated racing results based on Equations 7 and 9 using the constants developed and matched to the results obtained in the single scull and coxed fours in order to obtain a mechanical efficiency (m) for the equations. Boat velocity and time equivalent of one boat length are also given.

<table>
<thead>
<tr>
<th>Event</th>
<th>Boat type</th>
<th>Observed</th>
<th>Calculated</th>
<th>Velocity</th>
<th>s × (boat length)⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>1x</td>
<td>7.10</td>
<td>6.36</td>
<td>4.65</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>2x</td>
<td>6.36</td>
<td>6.36</td>
<td>5.05</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>4x</td>
<td>5.57</td>
<td>6.04</td>
<td>5.60</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>2-</td>
<td>7.01</td>
<td>6.55</td>
<td>4.75</td>
<td>2.21</td>
</tr>
<tr>
<td></td>
<td>2+</td>
<td>7.22</td>
<td>7.14</td>
<td>4.52</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>4-</td>
<td>6.17</td>
<td>6.22</td>
<td>5.31</td>
<td>2.45</td>
</tr>
<tr>
<td></td>
<td>4+</td>
<td>6.30</td>
<td>5.13</td>
<td>5.13</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td>8+</td>
<td>5.45</td>
<td>5.55</td>
<td>5.80</td>
<td>3.19</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>6.36</td>
<td></td>
<td>5.05</td>
<td>2.38</td>
</tr>
<tr>
<td>Women</td>
<td>1x</td>
<td>3.47</td>
<td></td>
<td>4.40</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>2x</td>
<td>3.24</td>
<td>3.28</td>
<td>4.90</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td>4x</td>
<td>3.20</td>
<td>3.15</td>
<td>5.00</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>2-</td>
<td>3.43</td>
<td>3.35</td>
<td>4.48</td>
<td>2.45</td>
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<tr>
<td></td>
<td>4+</td>
<td>3.21</td>
<td></td>
<td>4.98</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>8+</td>
<td>3.05</td>
<td>3.02</td>
<td>5.41</td>
<td>3.42</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>3.23</td>
<td></td>
<td>4.94</td>
<td>2.80</td>
</tr>
<tr>
<td>Leightweights</td>
<td>1x</td>
<td>7.20</td>
<td>7.21</td>
<td>4.54</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>2x</td>
<td>6.39</td>
<td>6.46</td>
<td>5.01</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>4-</td>
<td>6.30</td>
<td>6.32</td>
<td>5.13</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>8+</td>
<td>5.57</td>
<td>6.05</td>
<td>5.60</td>
<td>3.30</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>6.35</td>
<td></td>
<td>5.07</td>
<td>2.32</td>
</tr>
</tbody>
</table>

* For symbols, see Table 1.

*b First regatta 1977.

per unit of time. Maximal aerobic power is equal in both large and small well-trained athletes when related to body weight to the power 2/3 (Vaage and Hermansen, 1977; Secher et al., 1983; Table 3). This result is expected since, in physiological events, time can be shown to correspond to a linear body dimension (Asmussen et al., 1981). Aerobic power, therefore, must be expected to increase in proportion to \( p^{3/2} = p^{2/3} \). The influence of body dimensions on \( E \) may be expressed accordingly as

\[
E = k_1 p^3 + k_2 p^2 t
\]  

(2)

or

\[
E = k_1 w + k_2 w^{2/3} t
\]  

(3)

where \( w \), the body mass is assumed to be proportional to \( p^3 \), and the \( k \) values are constants.
Fig. 2. Blood lactate concentrations after maximal bicycle or treadmill exercise plotted against body weight.

Fig. 3. Relationship between the calculated duration of rowing over 2000 m for men and the weight of the oarsman. The thick line represents results calculated using the approximate weight (wb) per oarsman of coxless boats.

The mean boat resistance to progression (BR) increases in proportion to the velocity of the boat (v) to the power 1.95 (Celentano et al., 1974). BR is also dependent on the total load carried by the boat, wb, i.e. the weight of the rower and the weight of the boat, rigging and oars. This dependency can be calculated for the single scull from the data of Balukow (1964) to be proportional to (w + wb) to the power 0.56 at racing speed and within the range of displacements measured, 80–120 kg. Thus

\[ BR = k_1 v^{1.95} (w + wb)^{0.56} \]  

(4)

At constant boat velocity the work (W) performed by the oarsman is BR times the distance rowed (d), that is, \( W = BR \times d \) and \( E \) is balanced by \( W \) through the mechanical efficiency (me):

\[ E \times me = BR \times d \]  

(5)

for which an 'allometric' expression (Huxley and Teissier, 1936, see Asmussen et al., 1981) according to the above is

\[ (k_1 w + k_2 w^{2/3}) me = k_3 e^{1.95} (w + wb)^{0.56} d \]  

(6)
Table 3. Average values ± s.e. for age, height, weight, per cent fat and maximal values of heart rate ($HR_{max}$), oxygen uptake ($VO_2_{max}$), oxygen pulse and ventilation ($VE_{max}$) in winners of international rowing competitions and their less successful counterparts.

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Fat (%)</th>
<th>$HR_{max}$ (min⁻¹)</th>
<th>$VO_2_{max}$ (l min⁻¹)</th>
<th>$VCO_2_{max}$ (l min⁻¹)</th>
<th>$VO_2_{max}$ (ml kg⁻¹ min⁻¹)</th>
<th>Maximum oxygen pulse $VE_{max}$ (l min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Winners of international rowing championships (n = 14)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25.6</td>
<td>192</td>
<td>93</td>
<td>6.5</td>
<td>185</td>
<td>5.89</td>
<td>288</td>
<td>63</td>
<td>32</td>
</tr>
<tr>
<td>± s.e.</td>
<td>0.58</td>
<td>1.5</td>
<td>2.6</td>
<td>0.54</td>
<td>2.5</td>
<td>0.076</td>
<td>4.9</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Internationally competing oarsmen (n = 13)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25.1</td>
<td>189</td>
<td>84</td>
<td>8.3</td>
<td>190</td>
<td>5.58</td>
<td>291</td>
<td>67</td>
<td>29</td>
</tr>
<tr>
<td>± s.e.</td>
<td>0.47</td>
<td>1.1</td>
<td>1.8</td>
<td>0.43</td>
<td>3.0</td>
<td>0.064</td>
<td>4.7</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>t values</td>
<td>0.6685</td>
<td>1.3007</td>
<td>2.7281b</td>
<td>2.3097*</td>
<td>1.2997</td>
<td>3.0847b</td>
<td>0.4418</td>
<td>1.6885</td>
<td>2.6575b</td>
</tr>
</tbody>
</table>

*P < 0.05.

b P < 0.02.

* P < 0.005.
and as, at constant boat velocity, \( v = \frac{dt}{C_1} \)

\[ t^{1.95} (k_1 w + k_2 w^{2/3} t) me = k_3 (w + wb)^{0.56} d^{2.95}. \]  

Equation 6 can be modified to include the number of rowers \( n \) in the boat. Thus the energy expenditure will increase with the number of oarsmen, and so will the resistance:

\[ n (k_1 w + k_2 w^{2/3} t) me = k_3 v^{1.95} [n (w + WB)]^{0.56} d \]

where \( WB \) is taken to mean the weight of the boat, rigging and coxswain per oarsman, and it is assumed that boat resistance increases with an increase in displacement as for the single scull. Equation 8 may be written as:

\[ n^{0.44} t^{1.95} (k_1 w + k_2 w^{2/3} t) me = k_3 n^{0.56} d^{2.95} \]  

or

\[ n^{0.44} (k_1 w + k_2 w^{2/3} t) me = k_3 v^{1.95} (w + WB)^{0.56} d. \]

Accepting McMahon’s (1971) assumption that the boat weight per oarsman and the body weight per oarsman are constant, and disregarding the anaerobic metabolism, Equation 10 can (since \( dt^{-1} = v \)) be reduced to the formula derived by McMahon (1971)

\[ v = k_4 v^{0.15} \]

in which \( k_2, k_3, w^{2/3}, (W + Wb)^{0.56} \) and \( me \) make up the new constant \( k_4 \). Thus for boats of similar construction and with their weight (including a cox) proportional to the number of oarsmen, the boats containing many oarsmen should go faster than those containing fewer oarsmen. Taking as an example the results for the eights and the pairs (Table 2), the difference in time at the finishing line amounts to \( 22\% \) [16\% from the regression lines (for 1979), and 6\% for women] while the prediction from Equation 11 would be \( 23\% \).

For the application of Equations 7 and 9, the constants \( k_1 \) and \( k_2 \) can be calculated from the energy equivalents of the measured oxygen deficit \( E(OD) \) and total oxygen uptake \( E(VO_2) \) during ‘all-out’ exercise on a rowing ergometer

\[ E(OD) = k_1 w \]

and

\[ E(VO_2) = k_2 w^{2/3} t. \]

In seven male oarsmen (Secher et al., 1982a) with an average weight of 82 kg, the mean value of \( OD \) was 4.8 l \( O_2 \) and the mean value of \( VO_2 \) was 30.2 l during a row of 6 min on a Gjessing ergometer. These values give a \( k_1 \) value of about 1200 J kg\(^{-1}\) and a \( k_2 \) value of about 91 J kg\(^{-2/3}\) s\(^{-1}\).

In four female rowers with an average weight of 66 kg, \( OD \) was 4.2 l \( O_2 \) and \( VO_2 \) was 14.0 l for 4 min of maximal rowing (Secher et al., 1982a). Thus, \( k_1 \) was found to be about 1340 J kg\(^{-1}\) and \( k_2 \) to be about 73 J kg\(^{-2/3}\) s\(^{-1}\).

\( k_3 \) may be calculated from the data of Balukow (1964) for the single scull to be 0.263 N kg\(^{-0.56}\) v\(^{-1.95}\).
The physiology of rowing

\[ \text{wh and } \text{WB are found from the minimum boat weight including rigging allowed by FISA, the} \]
\[ \text{weight of the oars, and the weight of the coxswain (50 kg for men and 40 kg for women).} \]
\[ \text{The mechanical efficiency during rowing is not known but may be expected to be low, because} \]
\[ \text{22\% or more of the energy is used in a direction transverse to the direction of the boat} \]
\[ \text{(Celentano et al., 1974). Equation 7 will fit the results obtained in FISA regattas for the single} \]
\[ \text{scull if a mechanical efficiency of 15.92\% is assumed (Fig. 3, Table 2).} \]
\[ \text{Taking as an example an increase in body weight of a male rower of 10 kg, the use of the} \]
\[ \text{allometric expression for rowing, Equation 7, indicates a 1.1\% per 10 kg time advantage for the} \]
\[ \text{heavier rower. The calculated value for body weights of 70 and 93 kg indicates an advantage for} \]
\[ \text{heavyweights of 2.6\% over a rowing distance of 2000 m (Fig. 4, wh = 20 kg).} \]
\[ \text{The calculated average disadvantage of carrying an extra boat weight of 10 kg per oarsman,} \]
\[ \text{for example, due to a difference in boat construction and rigging, or due to a coxswain, amounts} \]
\[ \text{to 1.6\% (Fig. 3). The observed value on average is also 1.6\% per 10 kg per oarsman when the} \]
\[ \text{results of coxed and coxless pairs and fours (Table 2) are compared.} \]
\[ \text{The calculations may have significant implications. Females row fours and quad scull boats} \]
\[ \text{with a coxswain rather than a coxless boat. Therefore they move a boat weight per rower of} \]
\[ \text{28 kg instead of 18 kg. Using Equation 9 with the constants developed for females it is} \]
\[ \text{calculated that if women row coxless boats, the advantage of a 70 kg over a 60 kg female would} \]
\[ \text{be reduced from 2.1 to 1.8\%. Furthermore if women were to row 2000 m as men do, the} \]
\[ \text{advantage of the 10 kg heavier athlete would be reduced to 1.5\%.} \]
\[ \text{In conclusion, the larger anaerobic capacity (oxygen deficit) of heavyweights provide them} \]

\[ \text{Fig. 4. Calculated time differences between rowing results of heavyweight (average} \]
\[ \text{weight 93 kg) and lightweight (average weight 70 kg) oarsmen and the distance rowed. The} \]
\[ \text{calculations are based on Equation 7 assuming that } k_1 \text{ and } k_2 \text{ are independent of} \]
\[ \text{the duration of the event. The thick line is the same as in Fig. 3.} \]

\[ \text{Fig. 5. Experimental set up for collecting expired air during rowing. This figure is published with the} \]
\[ \text{kind permission of the American College of Sports Medicine.} \]
with an advantage during rowing which is accentuated because any given weight of a boat, oars, rigging and coxswain is relatively less for an athlete with larger body dimensions.

The metabolic cost of rowing†

The relationship between heart rate and oxygen uptake during rowing in a tank has been used to estimate the metabolic cost of rowing by the determination of the heart rate during rowing (di Prampero et al., 1971). A more direct approach is to measure the oxygen uptake during rowing using Douglas bags (Fig. 5, Jackson and Secher, 1976; Strømme et al., 1977).

Using the Douglas bag method, values were determined during steady-state rowing on a canal on days with calm water for two experienced oarsmen with weights of 79 and 92 kg, respectively. In the single scull, velocities between 2.1 and 4.9 m s\(^{-1}\) were used, in the double sculls the velocities were between 2.4 and 4.9 m s\(^{-1}\), and in the coxless pairs the velocities were between 2.4 and 5.1 m s\(^{-1}\) (Figs. 6–8).

Oxygen uptake ranged between 1.21 and 4.87 l min\(^{-1}\) for one oarsman and between 1.53 and 6.45 l min\(^{-1}\) for the other. The resting value was 0.28 l min\(^{-1}\). The results obtained for the two subjects were treated as one sample. In order to reduce the influence of the anaerobic metabolism on the results at the greatest speeds ('flattening' out of the curves), only oxygen uptake values which were lower than 95% of the highest recorded value were used for the calculations (Figs. 6–8).

![Fig. 6. Oxygen uptake during rowing a single scull in two subjects. Values indicated with open symbols were not used in the regression.](image)

† Some of these results have been presented in another form by Jackson and Secher (1976) and Åstrand and Rodahl (1977).
The physiology of rowing

For the coxed pairs, boat resistance to progression is found to follow the equation

$$ BR = av^b $$

where $a$ has a value of $4.7 \text{ kg m}^{-0.95}\text{s}^{-0.05}$ and $b$ has a value of 1.95 (Celentano et al., 1974; cf. Equation 4).

The relationship between oxygen uptake and rowing velocity is also expected to be a power function, but the rate of oxygen uptake, being a measure of power, or force $\times$ velocity, is...
according to Equations 4 and 5 expected to increase with velocity to the power 2.95. Expressing oxygen uptake as a power function of \( v \), then

\[
\dot{V}O_2 = a'v^{b'} + c
\]  

(15)

where \( c \) is the rate of oxygen uptake at rest. Subtracting \( c \) on both sides allows for the logarithmic expression

\[
\log(\dot{V}O_2 - c) = \log a' + b' \log v
\]

(16)

which is a straight line with a slope \( b' \) and intercept \( \log a' \). Thus the constants \( a' \) and \( b' \) may be determined experimentally from measured oxygen uptake at various rowing velocities.

For the three boat types studied the following equations were developed (Figs. 6–8)

- **Single scull:**
  \[
  \dot{V}O_2 = 0.194v^{2.21} + 0.28 \quad r = 0.98
  \]  

(17)

- **Double sculls:**
  \[
  \dot{V}O_2 = 0.172v^{2.24} + 0.28 \quad r = 0.98
  \]  

(18)

- **Pairs:**
  \[
  \dot{V}O_2 = 0.103v^{3.64} + 0.28 \quad r = 0.98
  \]  

(19)

where \( r \) is the correlation coefficient. Oxygen uptake is measured in \( 1 \text{ min}^{-1} \) and boat velocity in \( \text{m s}^{-1} \).

Oxygen uptake was also determined during 'no-load' tank rowing using a frequency of 20, 30 and 40 strokes per minute (Fig. 9). This was done in order to separate the oxygen uptake used for boat progression from the total oxygen uptake by subtracting the oxygen uptake found during no-load rowing at the applied number of strokes per minute (Fig. 10). Accordingly, the oxygen uptake used for boat progression was found to be

- **Single scull:**
  \[
  \dot{V}O_2 = 0.060v^{2.60} \quad r = 0.93
  \]  

(20)

- **Double sculls:**
  \[
  \dot{V}O_2 = 0.030v^{3.14} \quad r = 0.95
  \]  

(21)

- **Pairs:**
  \[
  \dot{V}O_2 = 0.013v^{3.57} \quad r = 0.97
  \]  

(22)

On average the total rate of oxygen uptake increased with the velocity to the power 2.4 (Equations 17–19) while the estimated oxygen uptake used for boat progression (Equations 20–22) increased with a mean boat velocity to the power 3.1, i.e. close to the expected value of 2.95.

Using the equations developed for the total oxygen uptake during rowing (Equations 17–19) and the rowing results presented in Table 2, the metabolic cost of rowing at racing speed can be calculated to be an average of 6.38 \( 1 \text{ min}^{-1} \) (for 1979, Table 4). Corresponding values can be calculated for previous years using the equations describing the relationship between rowing results and the year of the regatta (Table 1). It appears (Table 4) that the metabolic cost of rowing at racing speed has increased progressively with a value of 190 \( \text{ml min}^{-1} \) between 1919 and 1929, but 240 \( \text{ml min}^{-1} \) between 1969 and 1979.

Hendersson and Haggard (1925) estimated that the metabolic cost of rowing at racing speed was about 6.11 \( O_2 \text{ min}^{-1} \) (30 kcal \( \text{min}^{-1} \)) in 1924, while the estimate from Table 4 would be 5.21 \( O_2 \text{ min}^{-1} \). However, their greatest measured oxygen uptake was only 4.31 \( \text{min}^{-1} \), and only one subject attained a work output of about 420 W. This, however, was over a period...
limited to 3 min, whereas the duration of a race in the eights would be expected to be 6.4 min in 1924 (Table 1).

According to Equation 14 the power of rowing at racing speed in the coxed pairs (in 1979, Table 1) is 386 W in the direction of the boat, or a total work output of 471 W if 22% (or more) of the work is in a transverse direction (Celemanno et al., 1974). Accepting a metabolic cost of rowing at racing speed of about 6.38 l min⁻¹, the mechanical efficiency of rowing should be 22%.
Table 4. Calculated metabolic cost of rowing at racing speed in FISA championships 1919-79.

<table>
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</thead>
<tbody>
<tr>
<td>Metabolic cost (l O₂ min⁻¹)</td>
<td>5.10</td>
<td>5.29</td>
<td>5.48</td>
<td>5.69</td>
<td>5.91</td>
<td>6.14</td>
<td>6.38</td>
</tr>
</tbody>
</table>

Oxygen uptake during simulated race rowing

The previous considerations were made under the assumption that rowing velocity is close to constant during a race. It appears, however, that rowing velocity is greatest at the beginning of a race and then diminishes gradually during the next 1500 m to increase to near the average velocity for the final 500 m (Schneider, 1980; Secher et al., 1982a, Fig. 11).

The reason for the initial spurt is not known. The most economical way to row the 2000 m would be to keep an average velocity throughout the race. One explanation could be psychological. Oarsmen are sitting with their backs towards the direction of the boat. They therefore have to be in the lead in order to see their competitors. This mechanism, however, does not explain why oarsmen row in a similar pattern when performing all-out exercise on a rowing ergometer (Hagerman et al., 1978; Schneider, 1980; Secher et al., 1982a).

Fig. 11. Relative 500 m racing times calculated for all participants in the finals (1st to 6th place) of the 1974 world championship FISA regatta for men. Values indicated (± s.d.) at the 250 marks. Also shown relative 500 times for the three first boats in each competition. Horizontal line indicates the average relative 500 m racing time.
A physiological explanation for the initial spurt performed could be that the rate of increase in oxygen uptake at the onset of exercise is highest the greater the work load (Hill and Lupton, 1923; Furusawa et al., 1924; Neukirch, 1938; Åstrand and Saltin, 1961b; Linnarsson, 1974). Accordingly, the total oxygen uptake and work output during a given period of exercise is larger when an initial spurt is performed than when one attempts to keep exercise at an average intensity throughout a race (Secher et al., 1982a, Fig. 12). In this respect it is interesting that it appears the initial spurt can be performed without an increase in the total anaerobic metabolism as indicated by the size of the oxygen debt (Fig. 12) and the blood lactate concentration (Secher et al., 1982a).

**Fig. 12.** Oxygen uptake followed during intense bicycle exercise of 6 min duration and for the following 100 min of rest. Values are shown with an intended constant work load procedure and during exercise performed with an initial spurt.

**Contribution of the anaerobic and aerobic metabolism to rowing**

There is no simple way to express the contribution of the anaerobic metabolism to exercise. The existence of an anaerobic metabolism is often assessed by measurement of blood (or muscle) lactate concentrations despite difficulties in determining the distribution volume for lactate (Margaria et al., 1963; Klausen et al., 1974). In oarsmen maximum blood lactate concentration has been found to be 11 mmol l⁻¹ after 'maximal' running on a treadmill, while 15 mmol l⁻¹ was obtained after a national competition, and 17 mmol l⁻¹ after a FISA championship regatta (Vaage, 1977). Thus psychological factors may influence the results. The average value for blood lactate in Fig. 2 is 12.5 ± 0.45 mmol l⁻¹ (S.E.).

Determination of an oxygen debt, i.e. the oxygen uptake above the resting value after
termination of exercise (Fig. 12) is another method of estimating anaerobic metabolism. Values of oxygen debt presented for oarsmen are based on a collection of expired gas over a period of 30 min, but this collection period is arbitrarily chosen. Values are smaller in beginners (9 l) than in well-trained oarsmen (14 l) (Asami et al., 1978; Hagerman et al., 1978, 1979) with a maximum value of 33 l (Secher et al., 1982a). For women and lightweights, values of 10 and 12 l have been presented (Hagerman et al., 1979).

‘Oxygen deficit’ would probably be a more accurate measure of the size of the anaerobic metabolism, but it is based on calculations rather than on direct measurements. For international calibre oarsmen values of 8 l have been published for lightweights and 6 l for women (Hagerman et al., 1979), somewhat larger values than those determined by our group (Secher et al., 1982). The values we determined corresponded to a 14% contribution by the anaerobic metabolism for men during ‘all out’ rowing for 6 min, while the contribution in ‘all out’ rowing in women was 23% for 4 min. These values are somewhat less than those generally expected for other types of ‘all out’ exercise of 4 to 6 min (Åstrand and Rodahl, 1977).

**Ventilation during rowing†**

It has been argued that ‘the cramped position of the body while rowing should constrict the abdominal muscles and limit their ability to aid the expiratory phase of each breathing cycle’ (Cunningham et al., 1975). Ventilation during rowing, however, does not seem to be ‘low’. As during other types of dynamic exercise (Asmussen and Nielsen, 1946; Salin and Åstrand, 1967) ventilation increased linearly with oxygen uptake to approximately 80% of the maximal oxygen uptake (Fig. 13). With a further increase in work intensity ventilation increased exponentially to reach values of 158 and 206 l min⁻¹ (BTPS) at slightly submaximal oxygen uptakes of 4.70 and 6.25 l min⁻¹, respectively (the maximal values were 4.87 and 6.45 l min⁻¹). There appeared to be no difference in ventilation whether the subject rowed the single or double sculls. The subject reaching a ventilation of 206 l min⁻¹ during rowing had a ventilation of 243 l min⁻¹ during exhaustive bicycle exercise.

**Heart rate during rowing†**

Heart rate during rowing competitions has been measured (Ishiko, 1968; Pruett, 1977; Schneider, 1980; Fig. 14). Heart rate measurements have also been obtained during rowing ergometer exercise (Hagerman and Lee, 1971; Secher et al., 1982a). In general these show the same maximal values as during bicycling (Hamley and Thomas, 1969; Cunningham et al., 1975). To make possible a prediction of the metabolic cost of rowing, heart rate was measured at various submaximal intensities (di Prampero et al., 1971). A fixed amount of oxygen consumed per minute, however, does not necessarily result in one and the same heart rate even in the same subject. It is well known that heart rate during submaximal arm exercise is higher than during leg exercise at the same pulmonary oxygen uptake (Christensen, 1931; Asmussen and

† Unpublished work carried out with Roger C. Jackson, University of Calgary, Alberta, Canada.
The physiology of rowing

Fig. 13. Pulmonary ventilation during rowing measured in two oarsmen.

Fig. 14. Heart rate of one subject followed during race rowing in single and double sculls.
Hemmingsen, 1958; Åstrand et al., 1965; Stenberg et al., 1967; Vokac et al., 1975). Also, the maximal heart rate seems to be dependent upon the muscle mass involved in exercise (Stenberg et al., 1967; Klausen et al., 1982) and may vary from one type of exercise to another, especially when repeated maximal bursts of activity are involved (Tørring, personal communication; own experience).

During race rowing heart rate was higher in the single than in the double sculls for an oarsman trained for double sculls rowing (Fig. 14). Even more surprising was the finding of a similar heart rate during bicycling and single scull rowing, but a significantly lower heart rate at a given oxygen uptake during double sculls rowing in the same subject (Fig. 15). These findings could indicate that heart rate during dynamic exercise is dependent upon the specific work situation that applies rather than on the muscle groups involved, especially when specific training is carried to an extreme as in competitive sports. The difference in heart rate response cannot be explained by a difference in the work performed per stroke in the two boat types. During bicycling heart rate is the same at a given oxygen uptake at various pedalling rates (Knuttgen et al., 1971).

Recent work supports the assumption that heart rate during dynamic exercise is dependent upon the specific work procedure applied (Klausen et al., 1982). Six subjects performed submaximal exercise on bicycle ergometers with one leg and two legs before and after eight weeks of one-leg training with each of both legs. During submaximal one-leg exercise heart rate decreased by 11% whereas a nonsignificant decrease of only 2% was seen during two-leg exercise at the same oxygen uptake. No changes were seen in the maximal heart rates which were greatest during two-leg exercise.

Fig. 15. Heart rate during various submaximal and maximal work loads plotted against oxygen uptake during rowing single and double sculls, and during cycling. Same subject as in Fig. 13.
exercise increases heart rate (and blood pressure) when it is attempted to keep work intensity constant. Furthermore, during constant load static exercise, heart rate and blood pressure have been shown to vary with voluntary effort if the contraction is made easier or more difficult by vibration applied to the agonist or antagonist muscle (Goodwin et al., 1972). These findings, including the measurement of heart rate during rowing, can be explained by central nervous mechanisms playing a dominant role in the regulation of cardiovascular adjustments to exercise.

Muscle characteristics in oarsmen

Human skeletal muscle consists of slow and fast twitch fibres. On average the percentage of the two fibre types in the vastus lateralis of the quadriceps and in the deltoideus muscles is generally around 50% (Johnson et al., 1973; Saltin et al., 1977), but the proportion of slow twitch fibres can vary among individuals from 10 to 95%. Elite oarsmen have about 70% slow twitch muscle in m. vastus lateralis as well as in m. deltoideus and only few fast twitch 'b' fibres (Bonde-Petersen et al., 1975; Larsson and Forsberg, 1980; Secher et al., 1981). Thus the muscles of oarsmen exhibit a fibre composition characteristic of endurance athletes (Saltin et al., 1977), but with larger muscle fibre areas especially of the slow twitch fibres in m. vastus lateralis (7300 μm²; Larsson and Forsberg, 1980) than in untrained individuals (3600–4800 μm²; Andersen, 1975; Ingjer, 1979). The capillary network is dense in the muscles of oarsmen with values of around 600 mm⁻² (Larsson and Forsberg, 1980) compared with around 320–350 mm⁻² in controls (Andersen, 1975; Ingjer, 1979).

It seems reasonable that oarsmen do not have many fast twitch fibres. With a cadence at racing speed of about 33 strokes per minute (Fig. 10) each stroke may have a duration of about 0.9 s. This time period allows ample time for force to be developed in the slow twitch muscle fibres, while the fast twitch fibres will have contributed only during the first part of each stroke (Warmolds and Engel, 1972; Secher et al., 1978, 1981). Further, subjects with many slow twitch fibres show little muscle fatigue during repeated dynamic (isokinetic) muscle contractions (Thorstensson, 1976). This may explain why endurance athletes are found among people with many slow twitch fibres. It has been shown that people with a dominance of fast twitch muscle fibre tend to drop out of endurance training programmes (Ingjer and Dahl, 1979).

Muscle strength in oarsmen

At racing speed, Ishiko (1968) measured the force applied to the oar. In the best oarsmen the peak force varied between 700 and 900 N. Smaller values have also been reported but in less qualified oarsmen (Schneider et al., 1978; Asami et al., 1978).

Muscle strength is most often expressed by values recorded during maximal voluntary (isometric) muscle contractions (e.g. Asmussen et al., 1959; Asmussen and Heeboll-Nielsen, 1961). The maximal forces developed during dynamic contractions become progressively smaller with increasing shortening velocity of the muscles involved as expressed by the force–velocity relationship (Hill, 1938; Wilkie, 1950).
In the force–velocity relationship the maximal power, being force times velocity, is developed at a force corresponding to about 35% of the maximal isometric force. In order to develop a dynamic rowing strength of about 800 N, it may be argued that oarsmen need an isometric rowing strength of about 2250 N.

Muscle strength of oarsmen has been measured in hand, trunk and leg muscles. The measurements do not in general separate good from less qualified oarsmen (Hagerman et al., 1972; Larsson and Forsberg, 1980) although oarsmen are stronger than (Danish) controls (Table 5). Secher (1975) found that only the isometric strength measured in a simulated rowing position separates elite (2000 N) from (lighter) national and club oarsmen (1800 and 1600 N).

Table 5. Maximal voluntary strength in élite oarsmen, and in Danish controls of similar age and height.

<table>
<thead>
<tr>
<th>Strength</th>
<th>Elite oarsmen (N)</th>
<th>Per cent of expected valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-leg extension</td>
<td>4022</td>
<td>118</td>
</tr>
<tr>
<td>Two-leg extension</td>
<td>8339</td>
<td>135</td>
</tr>
<tr>
<td>Backward extension of trunk</td>
<td>1099</td>
<td>115</td>
</tr>
<tr>
<td>Forward flexion of trunk</td>
<td>942</td>
<td>134</td>
</tr>
<tr>
<td>Arm strength, pull</td>
<td>638</td>
<td>118</td>
</tr>
<tr>
<td>Hand grip</td>
<td>746</td>
<td>114</td>
</tr>
</tbody>
</table>


Yamakawa and Ishiko (1966) found a correlation between strength measures and rowing performance. This finding could not be confirmed by Bloomfield and Roberts (1972) and may reflect the larger body dimensions of the more successful oarsmen studied by Yamakawa and Ishiko, strength being expected to increase in proportion to $p^2$ (see Åstrand and Rodahl, 1977). In the 40 oarsmen studied by Secher (1975), strength measured in a simulated rowing position showed a positive correlation to hand grip strength only.

During the strength measurements it was noted (Secher, 1975) that when oarsmen extend both legs simultaneously they can develop a strength similar to or exceeding the sum of the strength measured in each of the two legs. In untrained subjects the strength of two legs is about 13–25% less than would be expected from the strength measured in each leg (Secher et al., 1976, 1978). The oarsmen seem to have learned to develop an ‘extra’ strength when using both legs simultaneously. This finding may reflect that during, for example, walking, running, jumping and bicycling, the legs are used alternately while during rowing the legs are used simultaneously in the kick against the stretcher.

To see if the ‘difference’ in strength seen during one-leg and two-leg extension is dependent on muscle fibre involvement the two measures of leg strength were performed during partial neuromuscular blockade (Secher et al., 1978). Two drugs were used. Decamethonium which first blocks fast twitch muscle fibres (Paton and Zaimes, 1951; Zaimes, 1953; Jewell and Zaimes, 1954) causing the contractions to be slow and enduring (Secher et al., 1978, 1981). In contrast,
tubocurarine mainly blocks slow twitch fibres (Secher et al., 1982d) and the contractions are probably therefore relatively fast, and peak force cannot be sustained for more than a few tenths of a second (Secher et al., 1978, 1981). Thus when decamethonium is used it is probable that the contractions are dominated by slow twitch fibres, whereas they are probably dominated by fast twitch fibres when tubocurarine is applied. During neuromuscular blockade caused by decamethonium the force developed by both legs underwent a greater fractional reduction than the force developed by one leg (Fig. 16), while the relative two-leg strength was unaffected or even tended to increase when tubocurarine was used. These findings may suggest that untrained individuals are unable to use the slow twitch muscle fibres as much during maximal two-leg exercise as during maximal one-leg exercise. In contrast trained oarsmen may have learned to mobilize their slow twitch fibres just as much during maximal two-leg extension as during maximal one-leg extension.

Fig. 16. Force maxima from recordings of maximal voluntary contractions before and after a single intravenous injection of decamethonium. At maximum action of the drug, strength is probably developed by slow twitch fibres. At this time two-leg strength is less than the strength developed with one leg only.
Maximal oxygen uptake in oarsmen

An increase in the total aerobic metabolism during maximal exercise of 4 to 6 min duration will be reflected by a similar increase in the maximal oxygen uptake (aerobic power, \( \text{PO}_2 \text{ max} \)) of the subject (Secher et al., 1982a). Thus the use of aerobic power for the assessment of aerobic metabolic capacity seems justified in oarsmen.

Maximal aerobic power measured in young untrained Swedish men is about 3.4 l min\(^{-1}\) (Bergh, 1977). In oarsmen it ranges between 2.3 l min\(^{-1}\) (Strydom et al., 1967) and 6.6 l min\(^{-1}\) (Hagerman et al., 1978). A direct relationship between placing \( x \) in an international championship regatta and the average maximal oxygen uptake of a crew \( y \) has been established, 

\[
y = 6.15 - 0.08x, \quad r = 0.87, \quad n = 10 \quad \text{(Secher et al., 1982e)}
\]

giving a value of 6.1 l min\(^{-1}\) for first place and 5.1 l min\(^{-1}\) for 13th place (Fig. 17) when 15 to 20 crews are competing as in FISA championships. These findings indicate that the maximal aerobic power of the best oarsmen is somewhat less (0.3–0.5 l min\(^{-1}\), Tables 3 and 4) than the estimated metabolic cost of rowing at racing speed (6.38 l min\(^{-1}\)).

One group reported a maximal oxygen uptake of 7.77 l min\(^{-1}\) (Nowacki et al., 1969, 1971). However, their oxygen uptake increased upwards curvilinearly with increasing work intensity. Further, the work applied on the bicycle to obtain this value was 450 W which should elicit an oxygen uptake of about 6.6 l min\(^{-1}\) only when using an efficiency value of 20% for the calculation. Another puzzling finding is a larger average maximal oxygen uptake (5.57 l min\(^{-1}\))
at 2040 m altitude (Silvetta, Austria) than at sea level (5.09 \text{l min}^{-1}) (Ratzeburg, West Germany). Both findings are explainable if the authors’ apparatus overestimated large ventilations.

The large maximal oxygen uptakes of oarsmen are due mainly to their large body dimensions. When the maximal oxygen uptake is expressed per kg body weight or related to body weight to the power 2/3 (Vaage and Hermansen, 1977), the smaller and less successful oarsmen show similar or slightly larger values (Table 3).

In Table 3 oarsmen show an oxygen uptake of about 290 \text{ml min}^{-1} \text{kg}^{-2/3}, while much larger values are seen in, for example, long distance skiers (Vaage and Hermansen, 1977; Bergh, 1977). In a Danish professional bicyclist a value of 366 \text{ml min}^{-1} \text{kg}^{-2/3} can be calculated (Mikkelsen, 1980). Such a value would indicate that oarsmen with a weight of 93 kg should be able to develop oxygen uptakes of about 7.5 \text{l min}^{-1}.

A correlation between rowing performance and vital capacity (Yamakawa and Ishiko, 1966) may reflect the advantage of the larger oarsman (Equation 7), vital capacity being a volume \((p^3)\).

International competitive oarsmen have vital capacities of about 6.8 \text{l} (BTPS) with a largest recorded value of 9.1 \text{l}, but are characterized by their large aerobic power, rather than by their large vital capacity (Fig. 18).†

Hagerman et al. (1979) reported maximal oxygen uptakes of 4.11 \text{l min}^{-1} in women with a body weight of 68 kg, and 5.11 \text{l min}^{-1} in lightweight oarsmen. The corresponding values for

![Fig. 18. Regression lines between maximal oxygen uptake (\(\text{VO}_2\text{max}\)) and vital capacity (\(\text{VC}\)) in experienced (●) and inexperienced (○) oarsmen. Ratio \(\text{VO}_2\text{max} \times \text{VC}^{-1} = 0.77\) (range 0.63–0.93) in the experienced, versus 0.67 (0.49–0.80) in the inexperienced (\(P<0.001\)).

† Unpublished work carried out with Roger C. Jackson, University of Calgary, Alberta, Canada. Some of these results have been presented in another form by Jackson and Secher (1976) and Åstrand and Rodahl (1977).
Danish female rowers are 3.8 l min⁻¹ and 66 kg (Secher et al., 1982a), while untrained Swedish women have values of about 2.1 l min⁻¹ (Bergh, 1977).

It is interesting that training for rowing may increase the thickness of the left ventricular posterior wall of the heart to 12.6 mm compared with 9.4 mm in control samples and 11.1 mm in cross-country skiers and long-distance runners. These on the other hand increase the left ventricular end-diastolic diameter to 6.0 cm in relation to 5.3 cm in oarsmen and 5.0 cm in controls (Howald et al., 1977). These findings suggest that training for rowing mainly leads to a pressure overload, while skiing and running lead to a volume overload of the heart, or that training for rowing increases heart dimension in the same direction as weight lifting (Longhurst et al., 1980). This might be because of the involvement of the arms during rowing, but during combined arm and leg exercise, blood pressure is maintained at the same level as during leg exercise (Stenberg et al., 1967; Secher et al., 1977). A more likely explanation for a pressure load during rowing is the long duration of each stroke. However, blood pressure measurements during rowing have not been performed, and in the study of Keul et al. (1982) the dimensions of oarsmen's hearts fell within the group of endurance athletes, i.e. with a small left ventricular wall thickness in relation to the end-diastolic diameter. The later finding is in agreement with unpublished results by Lund on Danish experienced oarsmen. Thus further (longitudinal) studies of echocardiographic findings in oarsmen are needed.

The role of arm work in maximal oxygen uptake

It is known that skiing induces a larger maximal oxygen uptake than running (Åstrand, 1952; Andersen et al., 1961; Stromme et al., 1977). Also, arm cranking during running (Taylor et al., 1955) or 'ski-walking' (Hermansen, 1973) elicit larger values than running. Laddermill climbing likewise gives larger values than running or bicycling (Kamon and Pandolf, 1972). In contrast, combined arm and leg exercise on bicycles is reported to induce the same maximal oxygen uptake as leg exercise alone (Åstrand and Saltin, 1961a; Stenberg et al., 1967), but this result is probably a result of too small an arm work load (Gleser et al., 1974; Secher et al., 1974; Reybrouck et al., 1975; Bergh et al., 1976). A similar finding is a larger maximal oxygen uptake during combined arm and leg swimming (free style) than during swimming with the legs alone (Secher and Oddershede, 1975).

During rowing well-trained oarsmen obtain larger values than during bicycling (Jackson and Secher, 1976) or running (Stromme et al., 1977) although conflicting reports have appeared (Strydom et al., 1967; Carey et al., 1974; Cunningham et al., 1975; Larsson and Forsberg, 1980). Of special interest was the finding of an increase in maximal oxygen uptake during rowing but not during running in the course of a training period for competitive rowing (Larsson and Forsberg, 1980).

A discussion of the role of muscle mass in maximal oxygen uptake is of importance as it has been used to argue for the role of the heart on the one hand and for 'peripheral' factors on the other as limiting the oxygen uptake (Åstrand and Saltin, 1961a). Obviously some muscles, for example, respiratory, heart and stabilizing muscles, are active during both leg and combined arm and leg exercise. Therefore a 'direct' additional effect of maximal oxygen uptake measured during arm and leg exercise cannot be expected, but it may be expected that the maximal oxygen

\[ \text{Secher} \]
uptake should increase in proportion to the increase in muscle mass if peripheral factors were of importance (Bergh et al., 1976). It has been shown that maximal oxygen uptake during combined exercise is similar to that measured during leg exercise in arm-untrained subjects, but is larger than the leg value in arm-trained athletes (Secher et al., 1974; Secher and Oddershede, 1975; Fig. 19). Thus when two muscle groups are working simultaneously, the maximal oxygen uptake increases in proportion to the state of training of the added muscle group.

Another question is to what extent circulation to one working muscle group interferes with circulation and oxygen uptake in another active muscle group. When severe arm exercise is added to ongoing leg exercise, leg blood flow and leg oxygen uptake decrease (Secher et al., 1977). Leg blood flow and leg oxygen uptake also are smaller when both legs are working simultaneously than when one leg is working alone (Klausen et al., 1982). In both models blood pressure is of a similar magnitude when work is performed with 'one' or several muscle groups. One explanation is that exercise with one muscle group induces a vasoconstriction in another working muscle group stressing the importance of vascular resistance for local oxygen uptake (Clausen, 1976; Secher et al., 1977; Klausen et al., 1982).

Thus it seems as if models involving combined exercise cannot reveal the relative role of the heart or peripheral limitations for maximal oxygen uptake. The question may however be

![Maximal oxygen uptake during combined arm and leg exercise plotted against maximal oxygen uptake during arm exercise. Both values normalized according to the subjects maximal oxygen uptake during leg exercise. Horizontal and vertical lines indicate situations where either maximal oxygen uptake during combined arm and leg exercise or arm exercise alone, are identical with the maximal oxygen uptake during leg exercise. This figure is published with the kind permission of the American Physiological Society.](image-url)
academic. From a practical point of view the important question is whether peripheral factors are of significance. If peripheral factors are not of importance, all types of exercise increasing maximal oxygen uptake, for example, running or bicycling can be used for oarsmen's training. If, on the other hand peripheral factors are of importance, training for rowing should include as much rowing as possible.

It is known that endurance training increases enzyme activities, capillarization (Andersen and Henriksson, 1977; Ingjer, 1979; Klausen et al., 1981) and local blood flow (Klausen et al., 1982). Furthermore, it may be argued that some peripheral changes (in the arms) are needed to explain why untrained subjects have a maximal oxygen uptake during arm exercise which is about 30% less than during leg exercise, while arm-trained subjects may have a maximal aerobic power during arm exercise of up to 17% greater than during leg exercise (Secher et al., 1974; Tesch et al., 1974; Secher and Oddershede, 1975).

In conclusion, strength measurements as well as measurements of the metabolic and circulatory capacity in humans indicate that to a large extent training response is specific to the type of exercise trained for. If oarsmen therefore cannot row, as might happen during the winter, training sessions should be made up to simulate the work in the boat.

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The physiology of rowing


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