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Oxygen uptake and ventilation during rowing and running in females and males

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This study evaluated if the ventilatory response to exercise is impaired by the cramp position of rowing. Maximal oxygen uptake ($\dot{V}O_{2max}$), maximal expiratory volume ($\dot{V}_{Emax}$), and maximal heart rate (HR_{max}) during rowing and running were compared in 55 males (age, mean ± SD, 21 ± 3 years; height 176 ± 5 cm; body mass 72 ± 6 kg) and 18 females (age 20 ± 2 years; height 164 ± 5 cm; body mass 61 ± 4 kg). $\dot{V}_{Emax}$ was larger during rowing than during running (males, 157 ± 16 vs. 147 ± 13 L min^{-1}; 114 ± 9 vs. 105 ± 11 L min^{-1}, $P < 0.01$). Also $\dot{V}O_{2max}$ was larger during rowing than during running (males, 4.5 ± 0.5 vs. 4.3 ± 0.4 L min^{-1}; females, 3.3 ± 0.4 vs. 3.2 ± 0.4 L min^{-1}, $P < 0.01$). However, HR_{max} was lower during rowing than during running (males, 194 ± 8 vs. 198 ± 11 beats min^{-1}; females, 192 ± 6 vs. 196 ± 8 beats min^{-1}, $P < 0.05$). $\dot{V}_{Emax}$ was correlated to body mass and fat-free mass, as was $\dot{V}O_{2max}$. Thus, the oxygen pulse ($\dot{V}O_{2max}/HR_{max}$) was larger during rowing than during running, while the ventilatory equivalent for oxygen ($\dot{V}_{Emax}/\dot{V}O_{2max}$) was similar. We showed that bending the body during rowing does not seem to impair ventilation either in males or in females. The results indicate that $\dot{V}_{Emax}$ and $\dot{V}O_{2max}$ relate to body size and fat-free mass for both females and males. The findings indicate that the involvement of more muscles, the entrainment, and the body position during rowing facilitates ventilation and venous return and lowers maximal heart rate.

Periodic contraction of muscles and movement during rowing elevates pleural pressure (Rosiello et al., 1987; Siegmund et al., 1999). An increased pleural pressure reduces venous return, end-diastolic volume, and the stroke volume of the heart (Cunningham et al., 1975; Rosiello et al., 1987; Wilmore & Costill, 1999). Also the increased intra-abdomen pressure impairs ventilation at stroke catch (Cunningham et al., 1975) or stroke finish (Siegmund et al., 1999). These physiological changes are considered to impair the expiratory volume ($\dot{V}_E$) and oxygen uptake ($\dot{V}O_2$) at maximal rowing effort (Cunningham et al., 1975; Rosiello et al., 1987).

On the other hand, during the drive phase the knee and hips extend and ventilation is assisted (Siegmund et al., 1999). During rowing a high ventilatory response is elicited (Szal & Schoene, 1989) and ventilatorylocomotion coupling appears to lead adequate ventilation (Siegmund et al., 1999). Rowing involves both upper- and lower-body exercise, while running mainly involves the legs (Secher, 1983; Clifford et al., 1994). $\dot{V}O_2$ increases as the muscle mass involved increases (Secher et al., 1974; Secher et al., 1977). We hypothesized that ventilation and oxygen consumption during rowing are larger than during running.

Specifically, $\dot{V}_E$ is reported to be limited during rowing in females (Mahler et al., 1987). As both the maximal expiratory volume ($\dot{V}_{Emax}$) and maximal oxygen uptake ($\dot{V}O_{2max}$) depend on body size (Secher et al., 1983; Rodgers et al., 1995; Jensen et al., 2001), the low $\dot{V}_E$ of females was considered to reflect their small body size rather than the position used during rowing.

In both males and females we examined $\dot{V}_{Emax}$, $\dot{V}O_{2max}$, and the maximal heart rate (HR_{max}) during ergometer rowing and treadmill running. Also, the maximal oxygen pulse ($\dot{V}O_{2max}/HR_{max}$) was calculated as an index of stroke volume of the heart (Heath et al., 1981). We also hypothesized that the cardiorespiratory response to exercise is similar between males and females, but that body size affects the response.

Methods

We studied 55 males (age mean ± SD, 21 ± 3 years; height 176 ± 5 cm; body mass 72 ± 6 kg, percentage body fat 11 ± 3%)

and 18 females (age 20 ± 2 years; height 164 ± 5 cm; body mass 61 ± 4 kg; percentage body fat $22 \pm 4\%$). The subjects were informed of the design and risks of the study and provided written informed consent. This study was as approved by the Ethical Committee of the National Institute of Health and Nutrition, and provided written informed consent.

All subjects completed two bouts of exercise: progressive running on a treadmill and rowing on an ergometer (Concept II model C, Morrisville, VT, USA). All subjects are regularly running on a treadmill and rowing on an ergometer and were familiar with both type of exercise. During treadmill running, the initial speed was $160\,\mathrm{m\,min^{-1}}$ for the males and $140\,\mathrm{m\,min^{-1}}$ for the females, and it was increased by $20\,\mathrm{m\,min^{-1}}$ every 2 min with a 3.0% incline of the treadmill. Exercise was terminated when the subjects could not complete a given running speed. During ergometer rowing, the initial load was 150 W for the males and 125 W for the females, and it was increased by 50 W for males and by 25 W for females every 2 min. Exercise was terminated when the subjects were no longer able to maintain the required intensity. It was required that each subject met each of the following criteria to ensure that $\dot{V}O_{2max}$ was reached: (1) a plateau in $\dot{V}O_2$ against exercise intensity; (2) a respiratory exchange ratio exceeding 1.15; (3) blood lactate concentration exceeding 8–9 $\mathrm{mmol\,L^{-1}}$; (4) achievement of age-predicted HR_{max}; and (5) the rating of perceived exertion of 19 or 20 (Bassett & Howley, 2000).

The expired gas was collected in Douglas bags during the last 1 min of each stage, and the volume was measured using a dry gas meter and the concentrations of oxygen and carbon dioxide were determined (Respiromonitor RM-300i, Minato Medical Science Co., Tokyo, Japan). The HR was determined electrocardiographically (Nihon Kohden Co., Tokyo, Japan). The rating of perceived exertion was expressed every 2 min (Borg, 1982). Blood samples were taken using heparinized glass capillaries from the fingertip at the termination of exercise. Blood lactate concentration was analyzed by an enzymatic membrane method using a 1500 Analyzer (Yellow Springs, OH, USA).

Percentage body fat was derived according to the Brozek equation (Brozek et al., 1963) using body density determined by the BOD POD air displacement system (Life Measurement Instruments, Concord, CA, USA; Dempster & Aitkens, 1995).

Data are reported as mean ± standard deviations (SD). The ventilatory equivalent for oxygen ($\dot{V}_{Emax}/\dot{V}O_{2max}$) was calculated (Wilmore & Costill, 1999). Student's *t*-test was performed for comparison of data obtained in males and females between rowing and running. Linear regression analysis was used to evaluate the relationship of each variable between rowing and running. The level of significance was set at $P < 0.05$.

Results

The rating of perceived exertion during rowing was similar to during running (19.5 ± 1.2 vs. 19.4 ± 1.3). $\dot{V}_{Emax}$ was larger during ergometer rowing than during treadmill running (males, 157 ± 16 vs. $147 \pm 13\,\mathrm{L\,min^{-1}}$; females, 114 ± 9 vs. $105 \pm 11\,\mathrm{L\,min^{-1}}$, $P < 0.05$). Also $\dot{V}O_{2max}$ was larger during rowing compared to during running (males, 4.5 ± 0.5 vs. $4.3 \pm 0.4\,\mathrm{L\,min^{-1}}$; females, 3.3 ± 0.4 vs. $3.2 \pm 0.4\,\mathrm{L\,min^{-1}}$, $P < 0.05$).

$\dot{V}_{Emax}$ during rowing was correlated to $\dot{V}_{Emax}$ during running ($r = 0.74$, $P < 0.001$; Fig. 1). $\dot{V}_{Emax}$ during rowing was correlated to body mass ($r = 0.78$, $P < 0.001$; Fig. 2) and fat-free mass ($r = 0.84$, $P < 0.001$; Fig. 3). Also $\dot{V}_{Emax}$ during running was correlated to body mass ($r = 0.67$, $P < 0.001$) and fat-free mass ($r = 0.77$, $P < 0.001$).

$\dot{V}O_{2max}$ during ergometer rowing was correlated to $\dot{V}O_{2max}$ during treadmill running ($r = 0.96$, $P < 0.001$). $\dot{V}O_{2max}$ during rowing was related to body mass ($r = 0.82$, $P < 0.001$) and fat-free mass ($r = 0.86$, $P < 0.001$). Also $\dot{V}O_{2max}$ during running was related to body mass ($r = 0.80$, $P < 0.001$) and fat-free mass ($r = 0.89$, $P < 0.001$).

The ventilatory equivalent for oxygen during rowing was similar to that derived during running (males, 34.9 ± 1.6 vs. 33.8 ± 2.1; females, 34.1 ± 2.2 vs. 32.6 ± 3.7), and there was no significant gender difference. Also, the ventilatory equivalent for oxygen during rowing was correlated to that obtained during running ($r = 0.47$, $P < 0.001$; Fig. 1).

HR_{max} was lower during ergometer rowing than during treadmill running (males, 194 ± 8 vs. 198 ± 11 $\mathrm{beats\,min^{-1}}$; females, 192 ± 6 vs. 196 ± 8 beats $\mathrm{min^{-1}}$, all $P < 0.05$), and there was no gender difference. HR_{max} during rowing was correlated to that obtained during running ($r = 0.67$, $P < 0.001$; Fig. 1).

Oxygen pulse was larger during rowing than during running (males, 23.2 ± 2.9 vs. $22.0 \pm 2.8\,\mathrm{mL \cdot beat^{-1}}$; females, 17.4 ± 1.8 vs. $16.7 \pm 1.9\,\mathrm{mL \cdot beat^{-1}}$, $P < 0.05$). The oxygen pulse during rowing was correlated to that achieved during running ($r = 0.95$, $P < 0.001$; Fig. 1). Oxygen pulse during rowing was correlated to body mass ($r = 0.78$, $P < 0.001$; Fig. 2) and fat-free mass ($r = 0.86$, $P < 0.001$; Fig. 2). Also oxygen pulse during running was correlated to body mass ($r = 0.76$, $P < 0.001$) and fat-free mass ($r = 0.83$, $P < 0.001$).

Discussion

It has been suggested that the cramp position of rowing might impede the contraction of the diaphragm, attenuate the decrease in lung pressure during inspiration, and thereby also decrease preload of the heart, resulting in not only impaired breathing but also a reduced cardiac output (Cunningham et al., 1975; Rosiello et al., 1987). Also, during rowing the Valsalva-like maneuver used to stabilize the upper body while both legs are extended (Clifford et al., 1994) could diminish the ventricular preload during rowing (Cunningham et al., 1975; Rosiello et al., 1987). However, the findings of a higher $\dot{V}_{Emax}$ and $\dot{V}O_{2max}$ during rowing than running irrespective of sex do not support these suggestions.

During rowing, locomotion drives ventilation and this phenomenon is called entrainment (Siegmund

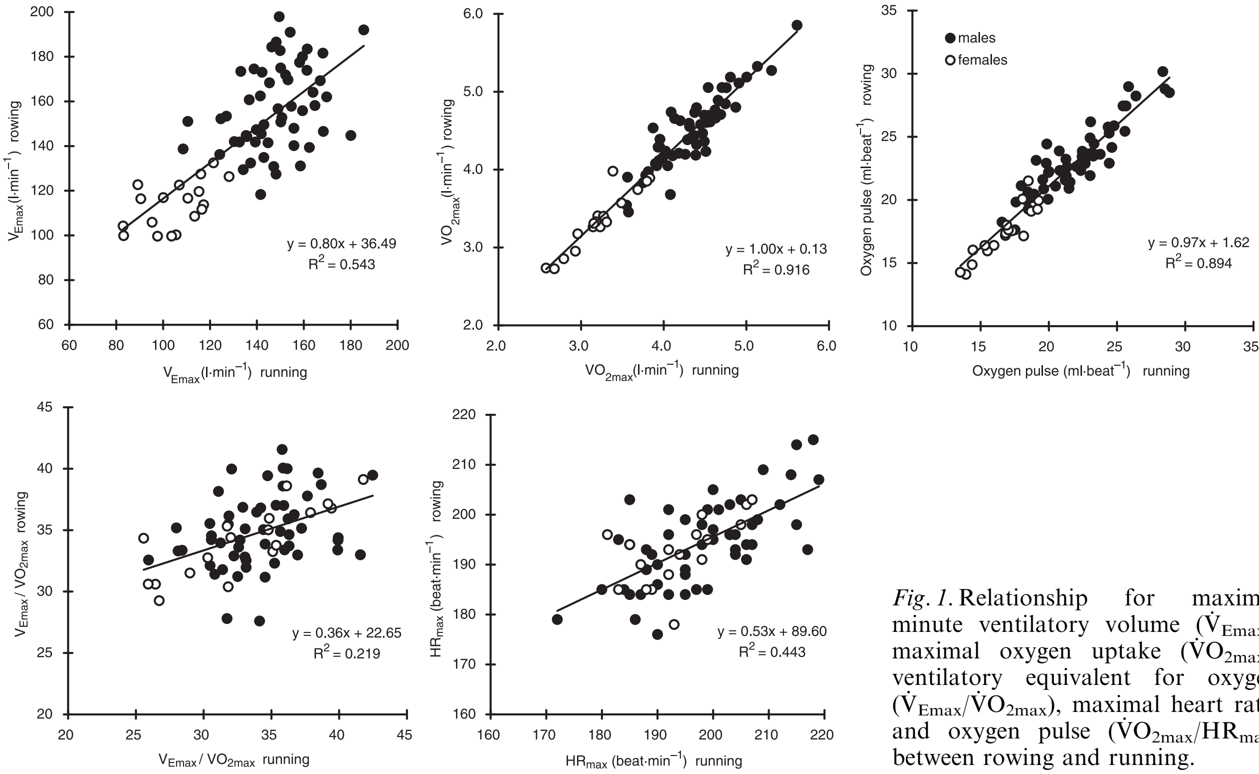

Fig. 1. Relationship for maximal minute ventilatory volume ($\dot{V}_{Emax}$), maximal oxygen uptake ($\dot{V}O_{2max}$), ventilatory equivalent for oxygen ($\dot{V}_{Emax}/\dot{V}O_{2max}$), maximal heart rate, and oxygen pulse ($\dot{V}O_{2max}/HR_{max}$) between rowing and running.

et al., 1999). Rowing leads to a high ventilatory response that is a product of a lower tidal volume and a high respiratory frequency, resulting in a high $\dot{V}_E$ (Szal & Schoene, 1989). The position during rowing increases in central respiratory drive (Szal & Schoene, 1989). The entrainment as well as the position used during rowing causes hyperventilation (Szal & Schoene, 1989; Siegmund et al., 1999).

The Frank–Starling mechanism indicates that enhanced venous return, i.e. enhanced preload, stretches the ventricle and augments stroke volume (Tate et al., 1994; Wilmore & Costill, 1999). The oxygen pulse is an index of stroke volume of the heart (Heath et al., 1981). Therefore, the higher oxygen pulse during rowing than running does not support the suggestion that preload of the heart is lower during rowing than during running (Cunningham et al., 1975; Rosiello et al., 1987).

HR_{max} is reported to be stable during rowing (Secher, 1983). HR_{max} does not seem to be affected by sex (Wilmore & Costill, 1999). In this study there were no significant differences of HR_{max} between females and males during the two types of exercise. HR_{max} does not depend on the type of exercise (Wilmore & Costill, 1999). However, we observed a lower HR_{max} during ergometer rowing than during treadmill running. During rowing the subjects use both the lower and upper body, while during running they use mainly their legs (Secher, 1983). A higher $\dot{V}O_{2max}$ during rowing than during running supports the fact that rowing involved a larger muscle mass than running (Secher et al., 1974; Secher et al., 1977; Savard et al., 1989). During exercise, an increase in active muscle mass enhances venous return and central blood volume because of the muscle pump (Davies & Sargeant, 1974; Klausen et al., 1982; Toner et al., 1983), which enhances stroke volume of the heart (Tate et al., 1994). Also, an elevated central blood volume slows HR with a decrease in sympathetic activity due to the cardiopulmonary reflex (Ray et al., 1993; Van Lieshout et al., 2001).

Body size affects $\dot{V}_E$ and aerobic capacity (Secher et al., 1983; Rodgers et al., 1995; Jensen et al., 2001), and this was observed regardless of sex. In this study $\dot{V}_{Emax}$ and $\dot{V}O_{2max}$ increases as fat-free mass increases. Fat-free mass is related to blood volume and to stroke volume of the heart, indicating that a large fat-free mass is associated with a high aerobic capacity (Hunt et al., 1998). Also, oxygen pulse as an indication of stroke volume of the heart (Heath et al., 1981) was correlated to body mass and fat-free mass independent of sex. The results are consistent with the data from West et al. (1997).

For females their breast has been considered to pressurize air in the lung while bending the body forward during rowing (Cunningham et al., 1975; Mahler et al., 1987). However, females possessed a ventilatory equivalent for oxygen similar to that of the males during both types of exercise, indicating that a mechanical impairment on ventilation is not substantiated.

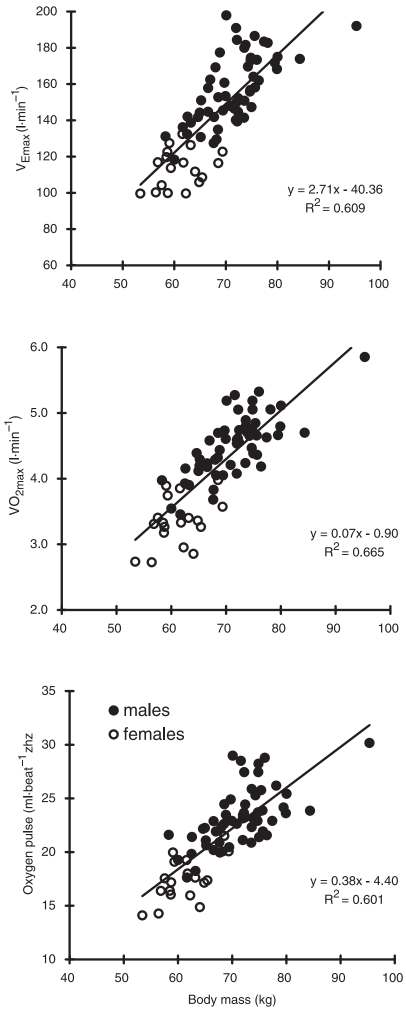

Fig. 2. Maximal minute ventilatory volume ($\dot{V}_{Emax}$), maximal oxygen uptake ($\dot{V}O_{2max}$), and oxygen pulse ($\dot{V}O_{2max}$/HR_{max}) during rowing related to body mass.

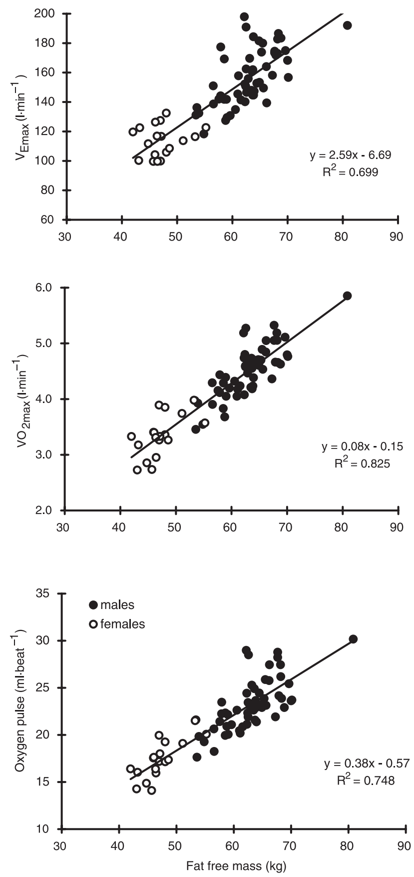

Fig. 3. Maximal minute ventilatory volume ($\dot{V}_{Emax}$), maximal oxygen uptake ($\dot{V}O_{2max}$), and oxygen pulse ($\dot{V}O_{2max}$/HR_{max}) during rowing related to fat-free mass.

We showed that bending the body during rowing does not seem to impair ventilation either in males or in females. The findings suggest that ventilation, oxygen consumption during exercise, and delivery of blood to active muscles relate to body size and fat-free mass rather than to the sex of the subjects. The results of this study showed that the cardiorespiratory response to (seated) ergometer rowing is enhanced compared to (upright) treadmill running. Also ergometer rowing attenuates an increase in maximal heart rate compared to treadmill running. The findings indicate that the involvement of more muscles, the entrainment, and the position during rowing facilitates ventilation and venous return for both females and males.

Perspective

The present study indicates that rowing does not impair the $\dot{V}_{Emax}$, $\dot{V}O_{2max}$, and oxygen pulse at maximal effort. These findings do not support suggestions that the contraction of the diaphragm and abdominal muscles during rowing reduces ventilation and oxygen consumption (Cunningham et al., 1975; Rosiello et al., 1987). Our findings are in part explained by the fact that the locomotion and ventilation coupling elicits high ventilation during rowing (Siegmund et al., 1999). This study also indicates a lower HR_{max} and a higher oxygen pulse during (seated) rowing compared to (upright) running. The findings are not in agreement with the fact that the movement during rowing elevates a pleural pressure and reduces venous return and the stroke volume of the heart (Rosiello et al., 1987). Our results appear to be responsible for the fact that the involvement of more muscles increases venous return as a muscle pump (Klausen et al., 1982), enhances the stroke volume (Tate et al., 1994), and slows HR due to the cardiopulmonary response (Ray et al., 1993; Van Lieshout et al., 2001). The current study also showed that cardiorespiratory response to rowing related to body size irrespective of the sex of subjects.

Key words: rowing, cardiorespiratory responses, heart rate, oxygen pulse, venous return, muscle pump, locomotion and ventilation coupling, body size.

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References

Bassett DR Jr, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 2000: 32: 70–84.

Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982: 14: 377–381.

Brozek J, Grand J, Anderson JT, Key A. Densitometric analysis of body composition: revision of some quantitative assumptions. Ann NY Acad Sci 1963: 110: 113–140.

Clifford PS, Hanel B, Secher NH. Arterial blood pressure response to rowing. Med Sci Sports Exerc 1994: 26: 715–719.

Cunningham DA, Goode PB, Critz JB. Cardiorespiratory response to exercise on a rowing and bicycle ergometer. Med Sci Sports 1975: 7: 37–43.

Davies CTM, Sargeant AJ. Physiological responses to one- and two-leg exercise breathing air and 45% oxygen. J Appl Physiol 1974: 36: 142–148.

Dempster P, Aitkens S. A new displacement method for the determination of human body composition. Med Sci Sports Exerc 1995: 27: 1692–1697.

Heath GW, Hagberg JM, Ehsani AA, Holloszy JO. A physiological comparison of young and older endurance athletes. J Appl Physiol 1981: 51: 634–640.

Hunt BE, Devy KP, Jones PP, DeSouza CA, VanPelt RE, Tanaka H, Seals DR. Role pf central circulatory factors in the fat-free mass-maximal aerobic capacity relation across age. Am J Physiol 1998: 275: E1178–H1182.

Jensen K, Johansen L, Secher NH. Influence of body mass on maximal oxygen uptake: effect of sample size. Eur J Appl Physiol 2001: 84: 201–205.

Klausen K, Secher NH, Clasusen JP, Harling O, Jensen JT. Central and regional circulatory adaptation to one-leg training. J Appl Physiol 1982: 52: 976–983.

Mahler DA, Andrea BF, Ward JL. Comparison of exercise performance on rowing and cycle ergometers. Res Q Exerc Sports 1987: 58: 41–46.

Ray CA, Rea RF, Clary MP, Mark AL. Muscle sympathetic nerve response to dynamic one-legged exercise: effect of body posture. Am J Physiol 1993: 264: H1–H7.

Rodgers DM, Olson BL, Wilmore JH. Scaling for the $\dot{V}O_2$-to-body size relationship among children and adults. J Appl Physiol 1995: 79: 958–967.

Rosiello RA, Mahler DA, Ward JL. Cardiovascular responses to rowing. Med Sci Sports Exerc 1987: 19: 239–245.

Savard GK, Richter EA, Strange S, Keins B, Christensen NJ, Saltin B. Norepinephrine spillover for skeletal muscle during exercise in humans: role of muscle mass. Am J Physiol 1989: 257: H812–H818.

Secher NH. The physiology of rowing. J Sports Sci 1983: 1: 23–53.

Secher NH, Ruberg-Larsen N, Binkhorst RA, Bonde-Petersen F. Maximal oxygen uptake during arm cranking and combined arm plus leg exercise. J Appl Physiol 1974: 36: 515–518.

Secher NH, Clausen JP, Klausen K, Noer I, Trap-Jensen J. Central and regional circulatory effects of adding arm exercise to leg exercise. Acta Physiol Scand 1977: 100: 288–297.

Secher NH, Vaage O, Jensen K, Jackson RC. Maximal aerobic power in oarsmen. Eur J Appl Physiol 1983: 52: 88–93.

Siegmund GP, Edwards MR, Moore KS, Tiessen DA, Sanderson DJ, McKenzie DC. Ventilation and locomotion coupling in varsity male rowers. J Appl Phyisol 1999: 87: 233–242.

Szal SE, Schoene RB. Ventilatory response to rowing and cycling in elite oarsmen. J Appl Physiol 1989: 67: 264–269.

Tate CA, Hyek MF, Taffet GE. Mechanism for the responses of cardiac muscle to physical activity in old age. Med Sci Sports Exerc 1994: 26: 561–567.

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

Van Lieshout JJ, Pott F, Madsen PL, van Goudoever J, Secher NH. Muscle tensing during standing effects on cerebral tissue oxygenation and cerebral artery blood velocity. Stroke 2001: 32: 1546–1551.

West GB, Brown JH, Enquist BJ. A general model for the origin of allometric scaling laws in biology. Science 1997: 276: 122–126.

Wilmore JH, Costill DL. Respiratory regulation during exercise (pp. 245–273); Cardiovascular control during exercise (pp. 333–380). In: Wilmore JH, Costill DL. Physiology of Sport and Exercise. eds. Illinois: Human Kinetics, 1999.