Treff G[1], Winkert K[1], Steinacker JM[1]

Olympic Rowing – Maximum Capacity over 2000 Meters

Olympisches Rudern – das Maximum über 2000 Meter

REVIEW

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1. ULM UNIVERSITY HOSPITAL, *Division of Sports and Rehabilitation Medicine, Ulm, Germany*

Summary

› **Olympic rowing** in its current form is a high-intensity boat race covering a distance of 2000 m with fastest race times ranging ~5.5-7.5 min, depending on boat class, sex, and environmental factors. To realize such race times, rowers need strength and endurance, which is physiologically evident in an oxidative adaption of the skeletal muscles, a high aerobic capacity, and the ability to contribute and sustain a relatively high percentage of anaerobic energy for several minutes. Anthropometrically, male and female rowers are characterized by relatively large body measurements.

› **Biomechanics & Physiology:** The sitting position of the rower, the involvement of a large muscle mass and the structure of the rowing cycle, consisting of drive and recovery phase where the rower slides back and forth on a sliding seat, affect the cardiovascular and the respiratory system in a unique manner. In addition to these physiological and anthropometric characteristics, this brief review outlines the extreme metabolic implications of the sport during racing and training and mentions rarely-discussed topics such as established testing procedures, summarizes data on training intensity distribution in elite rowing and includes a short section on heat stress during training and racing in hot and humid conditions expected for the Olympic Games 2021 in Tokyo.

Zusammenfassung

› **Das olympische Rudern** in seiner aktuellen Form ist ein hochintensives Bootsrennen über eine Strecke von 2000 m. Die schnellsten Rennzeiten liegen zwischen ~5.5 und 7.5 min, abhängig von Bootsklasse, Geschlecht und Umweltfaktoren. Um solche Rennzeiten zu realisieren, benötigen Ruderer Kraft und Ausdauer, was sich physiologisch in einer oxidativ adaptierten Skelettmuskulatur zeigt, in einer hohen aeroben Kapazität und der Fähigkeit, einen relativ hohen Anteil anaerober Energiebereitstellung über mehrere Minuten aufrechtzuerhalten. Anthropometrisch zeichnen sich männliche und weibliche Ruderer durch relativ große Körpermaße aus.

› **Biomechanik & Physiologie:** Die Sitzposition des Ruderers, die aktive Nutzung einer großen Muskelmasse und die Struktur des Ruderzyklus, bestehend aus Zug- und Vorrollphase, in der der Ruderer mit seinem Sitz im Boot zurück- bzw. vorrollt, beeinflussen das Herz-Kreislauf- und das Atmungssystem auf einzigartige Weise. Zusätzlich zu diesen physiologischen und anthropometrischen Merkmalen skizziert dieser kurze Überblick die extremen metabolischen Auswirkungen des Sports während des Rennens und des Trainings und erwähnt selten diskutierte Themen wie etablierte Testverfahren, fasst Daten zur Trainingsintensitätsverteilung im Elite-Rudern zusammen und geht in einem kurzen Abschnitt auf den Hitzestress während des Trainings und der Rennen unter heißen und feuchten Bedingungen ein, wie sie bei den Olympischen Spielen 2021in Tokio zu erwarten sind.

KEY WORDS:
Training Intensity Distribution, Aerobic, Anaerobic, Tokyo, Olympic Games

SCHLÜSSELWÖRTER:
Trainingsintensitätsverteilung, Aerob, Anaerob, Tokio, Olympische Spiele

CORRESPONDING ADDRESS:
PD Dr. Gunnar Treff
Ulm University Hospital, Ulm, Germany
Division of Sports and Rehabilitation Medicine
Leimgrubenweg 14, D-89075 Ulm
: gunnar.treff@uni-ulm.de

What is Olympic Rowing?

Olympic rowing in its current form – at least until Paris 2024 – is a boat race covering a distance of 2000 m. In sweep rowing, two, four or eight male or female rowers use one oar either on backboard or starboard. In sculling boats, one, two, or four male or female rowers generate propulsion with two sculls (“oars”) each. In this category there is also the only remaining boat class for lightweight rowers, the lightweight double sculls, in which no male or female rower may be heavier than 72.5 kg or 59.0 kg, respectively. Depending on boat class and sex, the world best times for the 2000 m distance vary between 5:18 in the men’s eight and 7:07 in the women’s single. Race times for a given boat class in world elite A-finals vary by approximately 0.9-1.1% for crewed boats or single sculls (70), but duration and › variation are substantially influenced by environmental conditions, which are mainly race direction relative to wind, magnitude of wind and waves, occasionally the current of the water, as well as water temperature and, of course, altitude.

To realize such race times, rowers have to accelerate a mass of approximately 15 kg per person for the boat plus the rower's mass at the start. After the start, which is followed by a transition phase, rowers usually change to a race pace. Race tactics in the middle of the race often include sprints, where stroke rate is increased and rowers aim to build a gap to their opponents. In the final 500 m of the rowing race, speed is often boosted and the race usually ends with a spurt. This pacing results in a parabolic racing profile, which is more pronounced in winners of Olympic races than in their opponents (48). However, pacing strategies differ and some very successful boats during the Olympic cycles 2012-16 and 2016-20 rowed with more homogenous 500 m. This takes advantage of the fact that a steady pace requires less peak power than a non-steady one, because the resistance of the water increases with speed by the second power, while the energy required increases by 2.4th to 3rd power (11, 81). Model calculations assume that even the variations in boat speed within each rowing cycle (caused by the boat's inconstant propulsion), increase the 2000 m-race duration by about 5 s, compared to a boat hypothetically moving at constant speed (23). The average mechanical power output of male rowers within a race ranges 450-550 W (30), requiring a considerable amount of energy to generate forces of ~ 480 N. This profile of rowing as a strength dependent, mid-term endurance sport determines the demands for successful competitive rowing.

Metabolism

During racing, the amount of energy provided by multiple energetic pathways for several minutes is outstanding. This warrants a brief summary of the metabolic aspects to understand the sport: The energetic pathways during exercise are (i) anaerobic or non-oxidative pathways (i.e., substrate-level phosphorylation with and without lactate production) and (ii) aerobic or oxidative pathways (i.e., oxidative phosphorylation). Oxidative Phosphorylation depends on oxygen delivery to the working muscle and sufficient supply of reducing equivalents from carbohydrates and fat. During the race, contributions of the pathways change considerably, which has already been demonstrated experimentally – and theoretically – in the 80's of the last century (39, 59) (Figure1).

The schematic rowing race outlined before nicely illustrates the complex combination of, in simplified terms, those three main energy-generating pathways and their changing percentages. At the start, a lot of energy is required to accelerate the boat. This is mainly enabled through directly available adenosine tri phosphate (ATP) stored in the muscle and creatine phosphate (PCr) allowing for anaerobic ATP synthesis without lactate appearance. Even though the PCr stores within the muscle are approximately 10-fold higher than those of ATP, the directly available PCr stored in the muscle is consumed within seconds. However, it is difficult to specify exactly how long the stored PCr will last, because the ratio of PCr-breakdown and -resynthesis largely depends on duration, intensity, and type (20, 61). Immediately after the start, the anaerobic-lactic (or glycolytic) pathway gains importance, where glucose is broken down to generate ATP while lactate is produced. This pathway will relevantly contribute energy throughout the whole race.

Nevertheless, it is the relatively slow responding, aerobic system that dominates energy contribution with approximately 67-88%, delivering the main proportions in the 2nd to 4th 500 m race-splits (58, 59). The importance of the aerobic system for successful rowing performance is manifold. It is efficient, because it allows the synthesis 36 units of ATP per unit glucose. This exceeds by far the ratio from non-oxidative pathways, which deliver only 2-3 units – but notably with a much higher flow rate. Furthermore, the aerobic metabolism does not only have the ability to deliver energy without production of lactate, thereby limiting lactate accumulation during the race, it even allows the oxidation of relevant proportions of the lactate that is produced in the muscle via the anaerobic metabolism (8, 42). Hence, it is the aerobic metabolism that keeps lactate concentration and acidosis within tolerable limits during the main part of the rowing race. On the other hand, the anaerobic lactic metabolism is indispensable for high-intensity exercise in the severe domain of ~80–100% $\dot{V}O_2$max, because it compensates for the longer reaction time and limited energy flow rate of the aerobic system for the extreme energy demand during the race.

Fat metabolism is virtually not relevant during racing, but essential during training. At moderate intensities, ß-oxidation of fat resynthesizes a huge amount of 130 ATP per unit substrate and facilitates rowing for 1 h or more, albeit at much lower intensity than during racing. For further reading we refer the reader to reviews (20, 61).

Aerobic Capacity and Adaptions of the Cardio Pulmonary System

As outlined before, aerobic metabolism is essential for racing. Unsurprisingly, maximum oxygen consumption ($\dot{V}O_2$max), which is the standard measure of aerobic capacity, is very high in rowers, ranging between 6-7 L/min and above 4 L/min in male (44, 51, 75) and female elite rowers (4). $\dot{V}O_2$max is positively correlated to performance on the ergometer both in male (25) and female (4) rowers and also related to on water performance (65, 85). $\dot{V}O_2$max, being the gross criterion of the cardiopulmonary system, is the product of cardiac output and arterio-venous oxygen difference (Fick's principle). Since peak arterio-venous oxygen difference differs not very much between athletes and non-athletes, cardiac output is the major contributor of a high $\dot{V}O_2$max (36). A $\dot{V}O_2$max of 7 L/min requires a cardiac output of approximately 40 L/min (81). Even in male lightweight rowers (i.e., body mass before competition ≤72.5 kg) at a $\dot{V}O_2$max of "only" 5.0 L/min, cardiac output has been measured as high as 30 L/min (50).

Such high cardiac output is only achievable through structural and functional adaptions. In rowers, an increase in left ventricular wall thickness and mass as well as atrial and ventricular enlargement have been reported (1). Notably, cardiac ultrasound-derived bi-atrial strain assessment indicates normal resting function of structurally enlarged atria in rowers (62) and maintained or even improved left ventricular diastolic relaxation velocity despite eccentric left ventricular hypertrophy (82). It is worth mentioning that hemodynamics are largely influenced by the rowing position and the cyclic movement: Due to the seated position, the large muscles of both legs work synchronously and are relatively near to the heart, thereby facilitating venous return to the right heart, which optimizes cardiac stroke volume via the Frank-Starling mechanism (28). On the other hand, the structure of the rowing stroke cycle imposes Valsalva like maneuvers, because especially at the begin of the drive phase (i.e., when the rower applies force to sculls or oar and moves backward relative to the boat) rowers hold their breath to stabilize the core, which means an increase in intrathoracic pressure and high isometric cardiac stress by a transient increase in LV afterload. In the second part of the rowing cycle, the recovery phase (i.e., when the rower slides forward and does not apply forces to the handle), the pressure is released. The pattern creates considerable variations in mean arterial pressure and alterations of the cardiac stroke volume with a decrease of 25% at the begin of the drive phase and a similar increase during recovery (9, 68). The hemodynamic changes during the rowing cycle and specifically the high isometric cardiac stress might also be relevant for some of the differences in cardiac remodeling in comparison with endurance sports disciplines with low isometric stress such as long distance running. Compared to runners, enlargement of the LV in rowers is accompanied by thicker left ventricular walls and higher left ventricular mass (82). Furthermore, the magnitude of hemodynamic changes differs between well-trained and elite-rowers (1), possibly because the magnitude of intrathoracic compression increases with mechanical power output.

The heart's main function is the transport of blood from the lung to the brain and skeletal muscle in order to deliver oxygen. The oxygen transport capacity itself is determined by the total amount of hemoglobin, which is very high in rowers (75) and directly affects $\dot{V}O_2max$ and performance variables (74). Interestingly, and in contrast to other endurance athletes, where training-induced plasma volume expansion exceeds the increase of hemoglobin mass, hemoglobin concentration in rowers is not lower than in untrained persons (73). This is due to the close correlation between hemoglobin mass and muscle mass (64), the latter also being relatively high in rowers (75). The causality behind this correlation is the oxidative adaption of a rower's musculature, containing approximately 70% to 80% of Type I fibers (33, 37, 60). These Type I fibers have a high oxidative capacity and therefore depend on sufficient oxygen delivery, which is – when rowing in normoxia – principally determined by hemoglobin mass, blood volume, and cardiac output. However, the oxygen demand in competitive rowing may exceed its availability, frequently leading to exercise induced arterial hypoxemia (52), which is an unmissable sign of the severity of exercise. However, this phenomenon is not limited to rowing, as recently reviewed (10).

The aforementioned effects of the rowing cycle are particularly relevant for pulmonary function and breathing mechanics, because the respiratory muscles face a dual demand: they assist in propulsive force generation and are also an effector of ventilatory control. Since stroke and respiratory rate increase in concert, breathing is increasingly entrained. At high work rates with high respiratory frequencies, the time constraints on breathing result in high peak flow of more than 10 L/s, a dynamic compression of the airway occurs during expiration, and tidal volume reaches the flat part of the thoracic compliance curve. The ventilatory response is characterized by restricted tidal volumes and time and flow constraints for breathing (71) (Figure 2). Hence, large airways and lung volumes are important for rowers. Of note, lung capacity has been reported to be as high as 11.68 L (GB elite rower Pete Reed, according to (13)).

Anaerobic Capacity

The severity of rowing is also highlighted by an extreme post-race acidosis, with pH values as low as 6.74 (49), associated with whole blood lactate concentrations of 26 mmol/L (own, unpublished data obtained from routine ergometer testing of national squad rowers) and serum lactate concentrations as high as 32 mmol/L (49). These data indicate a relevant contribution of anaerobic, metabolism during racing, which amounts to approximately 12-33%, based on the inversed data on aerobic contribution mentioned before. However, the magnitude of post-race peak lactate concentration is a poor measure of non-oxidative contribution (38), because it is the result of lactate appearance and removal (for review see (15)). To estimate non-oxidative capacity, the maximal accumulated oxygen deficit (MAOD) (41) is currently the method of choice and also post exercise lactate kinetics may provide a good and minimally invasive measure of anaerobic contribution to rowing (37). A traditional method that for the determination of anaerobic lactic power that has recently been increasingly discussed again is the maximum lactate accumulation rate ($\dot{V}Lamax$) (22).

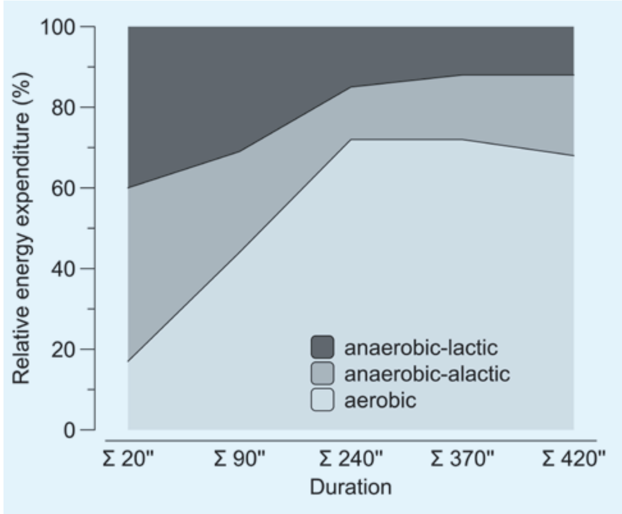

Figure 1

Relative energy expenditure during simulated rowing. Data were obtained in highly trained GDR-rowers during 7-min all-out tests. Tests were terminated after 20, 90, 240, 370, and 420 seconds, where rowers were blinded to the timepoints of termination. Each time point represents the cumulated contribution of each pathway to the respective time point. Adapted from (59).

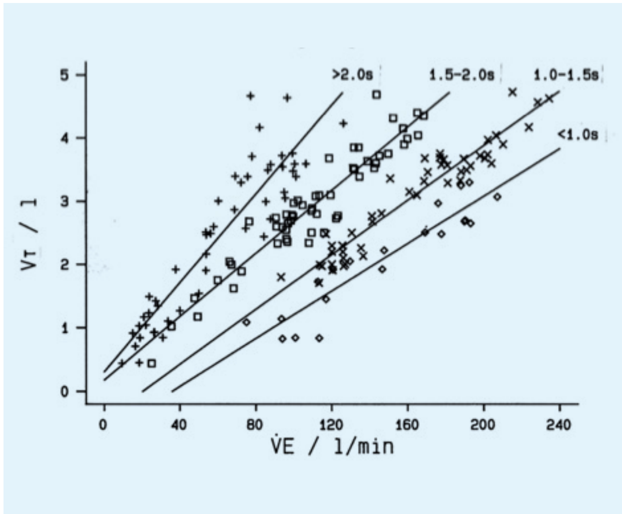

Figure 2

Tidal volume (VT) as a function of minute ventilation (VE) during rowing at different work rates. The breaths of four rowing strokes at each work load are displayed as symbols coded for breath duration, where + represents >2.0 s, ☐ represents 1.5-2.0 s, X represents 1.0-1.5 s, and ◊ represents <1.0 s. Data obtained in four national team rowers. Figure from (71), printed with permission.

Table 1

Mechanical power output, heart rate, blood lactate, oxygen uptake, respiratory ratio, and calculated energy expenditure at first and second lactate threshold in 11 elite rowers during rowing ergometer testing. LT1 and LT2: Lactate threshold 1 and 2 according to (12); [Lac]: blood lactate concentration; VO_2: oxygen consumption; VO_2max: percent of maximum oxygen consumption; RER: respiratory exchange ratio; AEE: activity related energy expenditure; CHO and LIP: percentage of carbohydrates and fat, respectively, contributing to AEE. Data from (83).

VARIABLE	LT1	LT2
Mechanical power output (W)	262±24	356±30
Heart rate (min^{-1})	139±10	166±7
Maximum Heart Rate (%)	71±4	85±3
[Lac] ($mmol \cdot L^{-1}$)	0.8±0.3	2.4±0.3
VO_2 ($L \cdot min^{-1}$)	4.2±0.5	5.5±0.4
VO_2max (%)	65±7	84±6
RER ( )	0.88±0.04	0.95±0.04
AEE ($kJ \cdot min^{-1}$)	89.6±10.0	118.0±9.2
CHO (%)	61.1±1.2	84.3±1.1
LIP (%)	38.9±1.2	15.7±1.1

However, its interpretation is based on several theoretical assumptions and the only data provided for elite rowers is an average recommendation of less than 0.6 $mmol \cdot s^{-1} \cdot kg^{-1}$ (21), but we are not aware of data reporting longitudinal changes. At least partly related to the difficulties in its assessment – the actual adaptability of anaerobic performance in elite endurance rowers and especially its interaction with changes in aerobic performance appears currently unclear and often remains anecdotal.

Anthropometrics

In elite rowers, the aforementioned characteristics are associated with a relatively large physique; in fact, some of these characteristics are directly mediated by body size and high muscle mass (e.g., cardiac output or $\dot{V}O_2max$). Furthermore, from a biomechanical perspective, long leverage is necessary to facilitate high stroke forces and an extended rowing drive phase (5, 65). Hence, elite male and female senior open class rowers exhibit a high body mass of ~94.3 kg and ~76.7 kg and a standing height of ~193.3 cm and ~180.8 cm, respectively (29). Consequently, body mass, standing height and lean body mass are accepted determinants of rowing performance (25, 45). A recent analysis revealed that anthropometric characteristics at junior age already affect long-term career attainment even within elite U19 National Team rowers (84).

Performance Testing

Measures of rowing performance have been reviewed previously (69). They can be assessed on-water, which is specific, or on rowing ergometers, which is semi-specific. On-water performance measurements include GPS data and mechanical sensors that allow to measure forces at the oar, the oarlock (i.e., the axis around which the oar rotates), and/or the foot stretcher. Changes in on-water performance may be due to changes in technical efficiency of the rower, uncontrollable environmental factors, and/or due to changes in physiological performance. That is why on-water testing is often used for the technical training of rowers, but physical performance is generally monitored on rowing ergometers, during controlled laboratory conditions.

An accepted ergometer test, probably applied by all elite rowing programs in the world, is the 2000 m test, where the rower aims to cover the virtual distance of 2 km as fast as possible. Race times are approximately ≤ 5:50 min and ≤ 6:50 in male and female elite athletes, respectively. The reliability of the test is good (typical error 1.3% [95%CI 0.9, 2.9] and especially in small boats on elite level, the result is clearly associated with on water performance outcome (47). However, this test is extremely exhaustive and does not allow for differentiated diagnosis of changes, for example, in basic endurance.

Therefore, several world rowing programs (personal observation: G. T.) employ different protocols of incremental step tests on the rowing ergometer, which were developed in the 80's of the last century. Step tests enable the creation of a lactate power curve for the calculation of established variables such as power at 2 or 4 mmol/L blood lactate concentration or individual threshold concepts (25, 46, 79) which have been identified as determinants of 2000 m ergometer performance (4, 25). Also, the maximum power output during a 7 x 2-min incremental step test has recently been shown to be closely related to 2000 m ergometer performance (r = 0.99) and $\dot{V}O_2$ (r = 0.96) (27). Furthermore, incremental step tests enable the scientific staff to define individual intensity zones for endurance training. It is worth mentioning that data obtained on rowing ergometers allow for a sufficient transfer to on-water rowing (80), however they need individual validation.

Incremental step tests can be modified and combined with metabolic analyzers to assess maximum oxygen consumption on rowing ergometers in step- or ramp-wise protocols (26), however several characteristics of the wind-braked rowing ergometers make these tests more difficult compared to cycle ergometer tests and require advanced technology, at least if elite populations are targeted (76).

It is worth mentioning, that the reliability and validity of the frequently used rowing ergometers was not validated in similar quality as is the case with e.g., cycle ergometers. That is surprising, because the few studies published suggest a limited validity (7, 35) and furthermore a high stroke-by-stroke variability in ergometer testing has been observed (77). This gap in knowledge may be due to the lack of appropriate testing devices, but since these have been recently developed (43), it is likely that the international rowing community will soon receive such results.

Training

Training of competitive rowers generally includes rowing (ergometer and boat), non-specific endurance training like cycling or cross-country skiing, resistance training, and additional training like stretching or yoga. The volume of training increased over the decades to 1128 (1104–1200) h/year in Norwegian rowers (16) and we can assume that most elite rowers train around 25 h/week (16, 44). There are two reasons or "justifications" for these high volumes: First, the development of rowing technique and crew efficiency requires sufficient time. Secondly, the attempt to optimize aerobic endurance performance through volume-based training; i.e., adaption of the cardio-respiratory system and in particular of the skeletal muscle via mitochondrial biogenesis (24). Indeed, there is clear evidence that endurance performance increases with training volume in rowers (16), runners (14), and that very high volumes at low intensity can prepare for world records in high intensity exercise

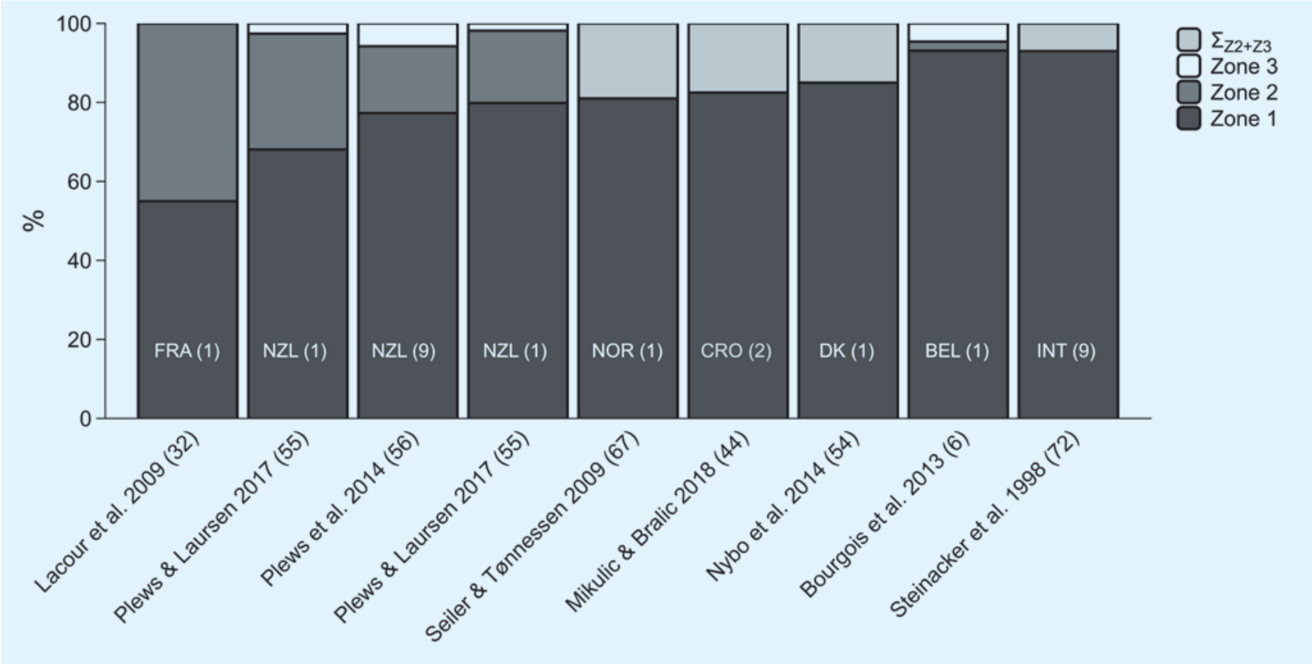

Figure 3

Training intensity distribution in elite rowing according to published studies. France (FRA), New Zealand (NZL), NOR (Norway), CRO (Croatia), DK (Denmark), BEL (Belgium), INT (Various countries); Numbers in brackets represent sample size of the respective publication; zones represent training intensities below first lactate or ventilatory threshold (zone 1), between first and second lactate or ventilatory threshold (zone 2), and above second lactate or ventilatory threshold (zone 3) (66, 78); if no separate data were provided for zones 2 and 3, these are presented together.

like 4000 m track cycling (63). On the other hand, considering the relatively short race duration and high intensity of a rowing race, such high training volume may appear surprising, especially in the light of research indicating that low volume high-intensity training can induce similar performance improvements and metabolic changes in the skeletal muscle as high-volume low intensity training (19), albeit the findings on high intensity training and mitochondrial biogenesis are controversial, as extensively reviewed Bishop et al. (2).

However, according to the literature and personal observations in several high-performance rowing programs, it seems to be consensus that successful elite rowing training necessitates a "certain" volume of ~ 20-25 h/week (even though lower numbers of 12-15 h/wk are reported, too (55)), a dominant proportion of low intensity training, and always a smaller percentage of "higher" intensities. The latter is clearly supported by the literature, indicating that high intensity training in elite athletes is extremely effective, if added on an already high training volume (34). It is therefore not surprising that the training intensity distribution (i.e. the distribution of different training intensities over a given period of time) has received increased attention in recent years. Figure 3 illustrates that leading world rowing programs apply a pyramidal intensity distribution (i.e., the proportion of a particular training intensity zone in the total training decreases with increasing intensity (78)). To the best of our knowledge, there are no data available indicating that a polarized intensity distribution (i.e., highest percentages spent in both low-intensity, followed by considerable amounts of high intensities, exercise but only a small proportion of training at mid intensities (78)) is superior to a pyramidal on the long term in elite rowing. In particular, we have not seen any data suggesting that successful rowers avoid mid or lactate threshold intensities, which is more or less a characteristic of polarized distributions. However, polarized training may be superior in individual athletes (79) and is probably applied by most coaches during certain phases of a competitive season. It is beyond the scope of this review to present the current literature on training volume, intensity distribution, and periodization, but even this brief outline indicates that most elite rowers train "a lot" and that individual variability within the detailed programs is high.

Rowing training is physically demanding (72), due to the volume, the muscular effort, but also due to the enormous metabolic expense. This is underlined by our own data in Table 1, indicating that already at a low to moderate intensity around lactate threshold 1, male elite rowers spend a considerable amount of energy. Extrapolated to a hard training week including 16-h of rowing, this will result in a metabolic expense of 85,584 kJ/week. If accounting for resting metabolic rate and 8 h of additional training like cycling etc., energy expenditure approximates 110,688 kJ/week (83).

This energy expenditure implicates that rowers depend on sufficient nutrition to avoid relative energy deficiency in sports (31). Furthermore, the metabolic strain also points to an upper limit of training volume, which has principally been calculated already in 1977 by Alois Mader (39). Beyond such ceiling, regression may occur, as underpinned by current data for excessive high-intensity training (17). It is worth noting that the only description to date of an exercise-associated hyponatremia that occurred during a training camp with multiple, but not in itself long training sessions, was also published in the field of rowing where hyponatremia was related to training stress (40).

Heat Stress

The Olympic Games in Tokyo 2021 will be held in hot and humid conditions with expected Wet Bulb Globe Temperatures (WBGT) peaking at 28.6 ± 2.8° C (18). Such conditions are not fully compensable even by pre-acclimatized athletes – although pre-acclimatization is highly › recommended – because in hot and humid conditions, metabolic heat production in endurance events is likely to exceed heat dissipation.

The Olympic rowing regatta itself will be held in the morning hours with expected WBGT ranging 25 < 28° C. Nevertheless, coaches and rowers fear these conditions, and for good reasons, because the unavoidable heat stress reduces both maximum and sub-maximumperformance (53). The good news is: based on established heat stress models (57) – which are of course limited for such special populations as highly trained athletes – the core of an acclimatized rower will probably not reach a critical temperature of 39 ≤ 40° C during a 6-min race, as long as the rower is not "overheated" already at the start. Hence, it is recommended that rowers reduce pre-race heat exposition and apply pre- and per-cooling routines (reviewed by (3)). Notably, we recommend such routines also for daily training in such conditions, because core temperature is a function of environment, metabolic heat (and thus intensity), duration, and heat dissipation.

If dissipation is very low due to hot and humid conditions, a critical increase in core temperature is likely also at moderate intensities, if training duration is long and environmental factors are unfavorable. However, we are not aware of specific medical or scientific reports on heat illness and -stroke in rowing.

Areas of Future Research

Within this brief review some areas for future research were already mentioned: Metabolic expense and consequences for a factual limitation of training volume, the assessment of anaerobic power and capacity and their potential for adaption in elite rowers, its interaction with aerobic training, and practical consequences. We are also awaiting research on quality criteria for rowing ergometers validity, which is crucial for anaerobic power assessment.

There are some – perhaps eternal – questions of rowing that are still not clearly answered, such as the proportions of specific vs. non-specific endurance training, the optimal dosage and timing of strength vs. endurance training in a concurrent sport, or the perfect training intensity distribution for Olympic rowing. Modern technologies of training data acquisition can help us to answer more questions here in the future. In the field of biomechanics, modern motion capture systems increasingly allow measurement of a rower's movement in the boat and will enable researchers to link these data to the established mechanical sensors attached to the boat.

From a physiological perspective, aspects of brain blood flow remain unresolved (as recently highlighted by (81)), probably mainly because it currently cannot be measured during high-intensity rowing due to technical limitations. There are also niche topics left such as the impact of the high hemoglobin mass of elite rowers on the buffering capacity of the blood. A whole field of new questions will arise if „coastal rowing" becomes an Olympic discipline and if the race distance should be cut to 1500 m at the Olympic Games in Los Angeles in 2028. The latter, however, would end the uniqueness of this sport in the form described here.

Conflict of Interest

The authors have no conflict of interest.

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