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Optimal and freely chosen paddling rate during moderate kayak ergometry

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ABSTRACT: Moderate paddling, as in long distance kayaking, constitutes an endurance activity, which shares energetic aspects with activities such as long distance running and road cycling. The aim of the present study was to investigate whether in moderate paddling there is a U-shaped relationship between oxygen uptake and stroke rate, and also whether elite kayakers apply a freely chosen stroke rate, which is energetically optimal. Eleven young male elite kayakers performed moderate kayak ergometry at preset target stroke rates of 65, 75, and 90 strokes min^{-1}, and at a freely chosen stroke rate, while physiological responses including oxygen uptake were measured. The results showed that considering average values calculated across all participants, there was an approximately U-shaped relationship between oxygen uptake and target stroke rate with a minimum at 75 strokes min^{-1}. The freely chosen stroke rate was 67.0 ± 6.1 strokes min^{-1}. Thus, the freely chosen stroke rate, for the group in total, appeared to be lower and require higher oxygen uptake as compared to the energetically optimal preset target stroke rate. Eight out of 11 participants had a higher oxygen uptake (5.1% ± 6.7%, $p = 0.028$, across all participants) at their freely chosen stroke rate than at the preset target stroke rate, which resulted in the lowest oxygen uptake. In conclusion, an approximately U-shaped relationship between oxygen uptake and stroke rate for young elite kayakers during moderate ergometer kayaking was found. Additionally, the freely chosen stroke rate was systematically lower and, consequently, required higher oxygen uptake than the preset stroke rate, which resulted in the lowest oxygen uptake.

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INTRODUCTION

During prolonged exercise at submaximal intensity, power output is important for performance. The reason is that power output is a determinant of velocity, as described in a previous review article [1]. To generate power output, energy turnover is required. At a set submaximal velocity, or power output, a low energy turnover will in general be associated with high performance. The reason is that energy stores, for example in the form of glycogen depots, last longer at low energy turnover. In other words, glycogen depots deplete during prolonged exercise [2], which eventually impairs performance [3]. Examples of endurance sports are long distance running, road cycling, and long distance kayaking. The focus of the present article is on the latter. Marathon kayaking has been reported to last around 3 h and 25 min [4].

An approximately U-shaped relationship between rate of energy turnover, or its reflective variable rate of oxygen uptake, and stride rate in running [5, 6] and pedalling rate in cycling [7, 8] has been reported repeatedly. In other words, the movement rate affects the rate of energy turnover. Further, there is a particular energetically optimal movement rate, which results in a minimal rate of oxygen uptake, or energy turnover, and corresponds to maximal economy or efficiency. As a consequence, the choice of movement rate is relevant for performance. During submaximal running, the freely chosen stride rate has been reported to be consistent with the energetically optimal stride rate [6]. In submaximal cycling, however, the freely chosen pedalling rate is generally higher than the energetically optimal pedalling rate [9, 10]. In other words, during prolonged cycling, individuals spend more energy than they have to. Further, this appears to compromise endurance performance [10, 11].

Despite some previous research in kayaking focusing on for example sprint [12, 13] as well as on anthropometric and physiological factors accounting for the variability of performance [4, 14–16], submaximal kayaking, as in marathon kayaking (i.e. 42 km), is relatively unexplored in terms of research. As an example, it has not been reported whether there is a U-shaped relationship between rate of oxygen uptake and stroke rate during submaximal kayaking. Moreover, the freely chosen stroke rate has not been reported in the research literature. Consequently, it is currently unknown whether elite athletes during submaximal paddling, as in long distance kayaking, have an energetically optimal rhythmic movement behaviour. Therefore, the aim of the present study was to investigate these aspects. More specifically, it was investigated whether there was an approximately U-shaped relationship between oxygen uptake and stroke rate during submaximal ergometer kayaking. In addition, it was investigated where the freely chosen stroke rate occurred with respect to the mentioned relationship. The novel information from the study could turn out to be useful for kayakers and their coaches in their ongoing work to improve the design of training programmes as well as the competition strategies in long distance kayaking.

MATERIALS AND METHODS

Participants

Eleven male kayakers from a Danish elite-kayaking centre volunteered to participate in the study. Six of the kayakers were medallists at U18 and U23 European and World Championships in marathon kayaking. Four of the kayakers were medallists at U18 and U23 European and World Championships in sprint kayaking. The athletes were characterized by an average ± SD age of 19 ± 3 years, body mass of 80 ± 9 kg, body height of 1.83 ± 0.05 m. All included athletes had trained at least 12 times per week for the preceding two years. The study conformed to the standards set by the Declaration of Helsinki. The present study was carried out in accordance with the recommendations of the North Denmark Region Committee on Health Research Ethics. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science [17]. Prior to the study, all participants were informed about the risks associated with the study and all provided written consent.

Protocol

The present study was an acute intervention study performed in a laboratory. The participants performed two types of tests on an air braked kayak ergometer (Dansprint ApS, Hvidovre, Denmark) on two separate days, 24 h apart. One of the tests was a maximal test to determine VO_{2peak}. The other test was a submaximal test for determination of responses to paddling at various stroke rates. Prior to testing, the participants were instructed to avoid exhaustive exercise and abstain from tobacco and alcohol for 24 h before testing.

The incremental maximal test protocol had earlier been applied on world class paddlers [18]. Briefly, five min warm-up at a target speed of 9 km h^{-1} was performed first. Subsequently, the incremental part began by paddling at a target speed of 11.5 km h^{-1} for one min. Then, the speed was increased by a target of 0.5 km h^{-1} every minute, until exhaustion. Each participant was allowed to freely adjust his stroke rate during the maximal test as long as the target speed was maintained. The participant was verbally encouraged to continue paddling, as long as possible. The test was terminated when the participant stopped paddling or was unable to maintain the target speed. The VO_{2peak} was calculated as an average of the highest six consecutive 5-s VO_2 values attained during the test. In addition, maximal values of pulmonary ventilation, heart rate, and respiratory exchange ratio were calculated. For the maximal test, the drag factor of the ergometer was set at 35, in agreement with a previously reported procedure [19]. Raw data from the Dansprint ergometer were analysed using MATLAB 2018a (MathWorks, Natick, MA, USA).

For the submaximal test, the participant was allowed to choose a preferred drag factor between 25 and 35. The chosen drag factor was applied throughout all submaximal testing. The submaximal test protocol consisted of four 7-min bouts at different stroke rates. The stroke rates were 65, 75, and 90 strokes min^{-1}, as well as freely chosen. These strokes rates were performed in a random order at a constant preset target power output corresponding to 60% of the power output at VO_{2peak}. This submaximal power output is considered moderate. A deviation of 5 W and 5 strokes min^{-1} was accepted during the kayak ergometer paddling. The freely chosen stroke rate was blinded for the participant. Data were recorded during the last two min of each bout and calculated as an average across that period. Rest periods of 5 min separated the bouts. A metronome was used to guide the participant on his stroke rate during bouts at 65, 75, and 90 strokes min^{-1}.

The pulmonary gas exchange was measured breath-by-breath, throughout the paddling, using a portable automated online gas analysis system (Oxycon Mobile, Vyaire Medical GmbH, Höchberg, Germany) including a Hans Rudolph mask. Prior to each test, the gas analysers were calibrated using known gas concentrations. The flow volume sensor was calibrated using a 3-l syringe. Heart rate (HR) was recorded every 5th s with a Polar T31 (Electro Oy, Kempele, Finland). The data were processed with PC software (JLAB, CareFusion, Hoechberg, Germany) on a system-dedicated PC.

Gross efficiency was calculated as the ratio of accomplished mechanical work during the last two min divided by the metabolic energy turnover during the same period, in line with previously applied procedures for ergometer cycling, which take into account values of respiratory exchange ratio [20].

Statistical analysis

All statistical analyses were performed using IBM SPSS for Mac (Version 24.0, SPSS Inc., Chicago, IL, USA). Prior to all analyses, the data were tested for normal distribution and sphericity using the Shapiro-Wilk test and Mauchly's test, respectively. If the assumption of sphericity was violated, a Greenhouse-Geisser correction was made. A repeated measures ANOVA was performed to test for an effect of stroke rate. In case of a significant effect of stroke rate, paired samples t-tests were performed as post hoc testing, applying Bonferroni-adjusted p-values. Data are presented as average ± SD, unless otherwise stated. $p < 0.05$ was considered statistically significant.

RESULTS

The VO_{2peak} attained in the maximal test was 4538 ± 620 ml min^{-1}. Maximal values of power output, pulmonary ventilation, heart rate, and respiratory exchange ratio were 163 ± 25 W, 156.7 ± 29.3 l min^{-1}, 197 ± 7 beats min^{-1}, and 1.16 ± 0.06, respectively.

The measured stroke rate at the target stroke rates of 65, 75, and 90 strokes min^{-1} during the submaximal test was 63.7 ± 0.7, 73.0 ± 0.4, and 87.0 ± 0.7, respectively. The freely chosen stroke rate was 67.0 ± 6.1 strokes min^{-1} with an inter-individual range of 58 to 79 strokes min^{-1}.

Power output at the target stroke rates of 65, 75, and 90 strokes min^{-1}, as well as at the freely chosen stroke rate, was the same in the different conditions, namely 98 ± 15 W.

The rate of oxygen uptake during the submaximal kayak ergometer paddling is presented in figure 1. Supplementary data, including values of relative rate of oxygen uptake, pulmonary ventilation, RER, heart rate, and gross efficiency, are presented in Table 1. Considering the average values of rate of oxygen uptake calculated across all participants, there was an approximately U-shaped relationship between rate of oxygen uptake and preset target stroke rate (Figure 1). The rate of oxygen uptake at 75 strokes min^{-1} was significantly ($p = 0.026$) different from the value at 65 strokes min^{-1}. The freely chosen stroke rate was located near the left upward leg of the relationship, again when considering the average value calculated across all participants (Figure 1). In other words, for the group in total, it appeared that the freely chosen stroke rate tended to be lower and require a higher rate of oxygen uptake as compared to the preset target stroke rate of 75 strokes min^{-1}. When comparing the rate of oxygen uptake across the preset target stroke rates for each

TABLE 1. Responses to paddling in a kayak ergometer. n = 11. Data are presented as average ± SD.

	$\%VO_{2peak}$ (%)	Pulmonary ventilation (l min^{-1})	RER	Heart rate (beats min^{-1})	Gross efficiency (%)
Target of 65 strokes min^{-1}	64.9 ± 3.7	78.2 ± 10.8	0.90 ± 0.04	149 ± 12	9.7 ± 0.7
Target of 75 strokes min^{-1}	61.0 ± 3.2[b]	78.2 ± 9.6	0.92 ± 0.03	148 ± 13	10.3 ± 0.8
Target of 90 strokes min^{-1}	63.0 ± 5.5	83.0 ± 11.0[a]	0.91 ± 0.03	150 ± 11[c]	9.9 ± 0.9
Freely chosen stroke rate	63.0 ± 2.7	75.3 ± 9.3	0.90 ± 0.05	147 ± 11	10.0 ± 0.9

[a]Different from target stroke rate of 75 strokes min^{-1} ($p = 0.030$) and freely chosen stroke rate ($p = 0.020$). [b]Different from target stroke rate of 65 strokes min^{-1} ($p < 0.001$). [c]Different from target stroke rate of 75 strokes min^{-1} ($p = 0.048$) and freely chosen stroke rate ($p = 0.011$). RER, respiratory exchange ratio.

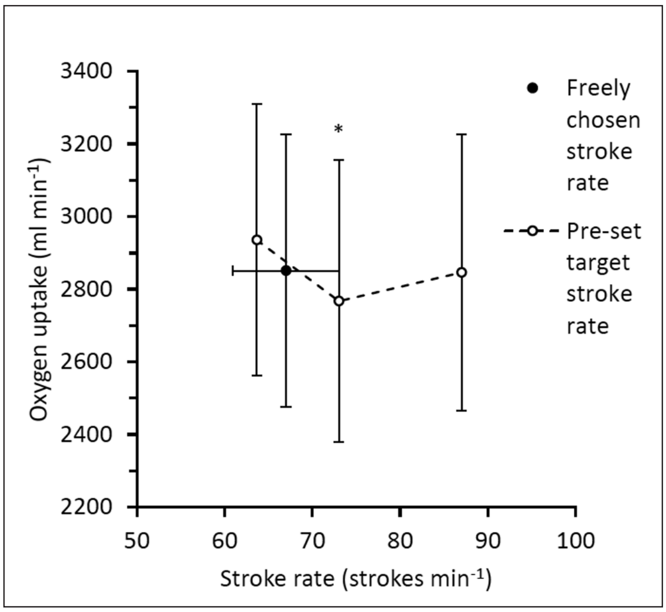

FIG. 1. Rate of oxygen uptake (average values with SD bars) as a function of stroke rate during paddling in a kayak ergometer. n = 11. *Different from target of 65 strokes min^{-1} ($p = 0.026$).

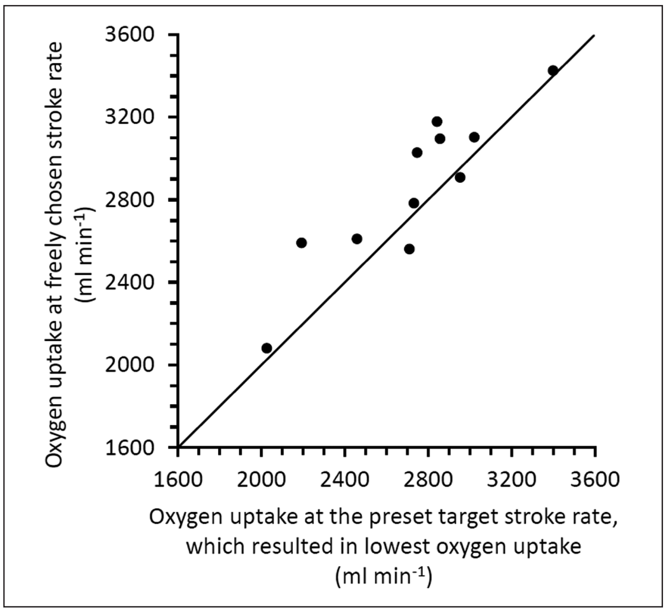

FIG. 2. Rate of oxygen uptake during paddling in a kayak ergometer at freely chosen stroke rate versus the same variable measured at the preset target stroke rate, which showed the lowest value of rate of oxygen uptake. n = 11. The average difference was 5.1% (paired samples t-test, $p = 0.028$). A line of identity is inserted.

individual, it was observed that one individual had his lowest value at the target stroke rate of 65 strokes min^{-1}. Six other participants had their lowest value at the target stroke rate of 75 strokes min^{-1}. Finally, four participants had their lowest value at the target stroke rate of 90 strokes min^{-1}. This additional detailed information on individual data is not visible in Figure 1, since the figure contains average (± SD) data. Figure 2 shows that 8 out of 11 participants had a higher rate of oxygen uptake at their freely chosen stroke rate as compared to the preset target stroke rate, which resulted in the lowest rate of oxygen uptake. In terms of amount, this difference was 5.1% ± 6.7% ($p = 0.028$), across all participants.

DISCUSSION

The kayakers who participated in the present study had a VO_{2peak} of about 57 ml kg^{-1} min^{-1}, on average. This value is somewhat lower than the average value of about 62 ml kg^{-1} min^{-1}, which was reported for a Spanish group of elite kayakers (26.2 ± 2.8 years old) at the beginning of a training period [18]. Of note, the present kayakers were relatively young. In addition, the present testing was performed in October, about four weeks after the last competition of the season. These circumstances might explain the somewhat lower VO_{2peak} of the present kayakers as compared to the Spanish group.

The gross efficiency was calculated to be approximately 10% at 100 W, across the group of participants in the present study. For comparison, a value of approximately 11.5% at 100 W has been reported previously [21]. Minor systematic deviations in calculated values of the metabolic energy turnover or the accomplished mechanical work can explain such a difference. It is also possible that the difference represents a real physiological difference between the two groups of kayakers. A better paddling technique and a larger type 1 muscle fibre proportion in the major active muscles [20, 22, 23] are examples of possible reasons for a higher gross efficiency.

It can merely be speculated upon why there is an approximately U-shaped relationship between rate of oxygen uptake and stroke rate. The lower the stroke rate is, the higher the force needs to be in each stroke, to maintain a set power output. Therefore, it is possible that paddling at a low stroke rate will result in higher recruitment of type 2 muscle fibres. Furthermore, since type 2 muscle fibres appear to be less efficient during work production [20, 22, 23], this could at least partly explain the left upward leg of the approximately U-shaped relationship. It is also possible that there is increased muscle activation for torso stabilization at low stroke rates. This suggestion is based on propositions made in reports of arm cranking studies [24, 25]. As to the right upward leg of the relationship, previous research suggests that internal work, or internal power, can explain it. Internal power has been described as representing the energy changes of moving body segments [26]. It has been estimated to be about 15, 41, and 91 W at 61, 88, and 115 crank revolutions per min, respectively, during pedalling [27].

A limitation to the application of the present results is that paddling on a kayak ergometer obviously deviates from on-water kayaking. One study has shown that there are biomechanical differences between the two types of paddling [28]. Thus, it was reported by Fleming *et al.* [28] that ergometer paddling did not perfectly replicate kinematic and kinetic responses at an intensity corresponding to 85% of VO_{2max}. Another study compared physiological responses during on-water kayaking and kayak ergometry [29]. In that study, it was found that ergometer paddling accurately simulates on-water kayaking with respect to physiological demands. However, it should be noted that the study by van Someren *et al.* [29] applied short-term (4 min) high-intensity kayaking. Thus, as always, thoughtfulness should be exercised when comparing results from laboratory studies to performance in field conditions. This was recently discussed in detail by Winchcombe *et al*. [31]. They also reported data which indicated that stroke rate was higher during ergometer kayaking than during on-water kayaking, at comparable rates of oxygen uptake. However, it should be noted that Winchcombe *et al.* [31] used a KayakPro ergometer while a Dansprint ergometer was used in the present study. It is likely that the type of ergometer plays a role in stroke rate. As an example, inertial load varies between cycle ergometers, and this variable affects the pedalling rate [30]. It thus appears that it might be difficult to compare studies which use different kayak ergometers. Also, the freely chosen stroke rate during on-water kayaking, at a work load resulting in a rate of oxygen uptake of approx. 2700 ml min^{-1}, on average was reported to be 66 [31]. For comparison, the freely chosen stroke rate during ergometer kayaking at a work load resulting in a rate of oxygen uptake of approx. 2800 ml min^{-1}, in the present study, was on average 67. That correspondence perhaps indicates that the Dansprint ergometer, which was used in the present study, closely simulates on-water kayaking.

The applied perspective of the present findings is the following. The present study showed that there is an energetically optimal stroke rate for moderate ergometer kayaking, which results in a minimal rate of oxygen uptake. This is similar to what is known for stride rate during running [5, 6] as well as pedalling rate during cycling [7, 8]. The present study also showed that young elite kayakers in general during ergometer kayaking appear to freely choose a stroke rate that is *lower*, and thereby less optimal, than the energetically optimal stroke rate. This is in contrast to cycling, where a higher pedalling rate than the energetically optimal pedalling rate is generally chosen [9, 10]. During long distance kayaking, where energy depletion constitutes one of the challenges, the natural (i.e. freely chosen) rhythmic movement behaviour might result in impaired performance as compared to a more optimal rhythmic movement behaviour, as it has previously been reported for cycling [10, 11]. Perhaps it requires specific training to be able to paddle at a relatively high stroke rate and exploit the potential advantage that the present study points to. This could be elucidated in future research studies. Further, that particular aspect should be considered by athletes as well as coaches who focus on long distance kayaking. For completeness, it should be mentioned that a marathon kayak race has portages and tactical elements, which result in some interruptions of the prolonged steady paddling.

CONCLUSIONS

In conclusion, the present study revealed that there is an approximately U-shaped relationship between rate of oxygen uptake and stroke rate for young elite kayakers during submaximal paddling on an ergometer. Also, the freely chosen stroke rate was lower and, consequently, required a higher rate of oxygen uptake as compared to the stroke rate that resulted in the lowest rate of oxygen uptake. In other words, it appears that young elite kayakers can optimize their freely chosen rhythmic movement behaviour by increasing their stroke rate slightly during moderate paddling, as performed in long distance kayaking.

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Conflict of interest

The authors decleared no cofilct of interest.

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