Summary

Gross efficiency in cyclic sports: the underlying assumptions investigated
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In order to improve performance, the mechanical power output (PO) produced by the athlete needs to be increased or the power necessary to overcome frictional forces reduced. When the power dissipation side is neglected, improvements in performance can be realized by increasing the amount of metabolic energy produced (anaerobically and aerobically) or the efficiency by which these energetic resources are converted to forward propulsion (i.e. the gross efficiency (GE)). As it seems that humans are approaching the limits of metabolic energy production, recent attention focuses on GE.

To allow simulations of athletic performances in cyclic sports, an energy flow model has been developed. In this model it is assumed that 1) GE determined during submaximal exercise is constant during the day; 2) GE is independent of the altitude above sea level at which exercise is performed; 3) GE determined at submaximal exercise intensities is representative of GE at maximal and supramaximal exercise intensities; and 4) that GE remains constant during fatiguing exercise. The goal of this thesis was to try to test these assumptions regarding GE, which underlie the current version of the energy flow model and, if necessary, to improve the model.

Chapter 2 presents a study in which the effect of: 1) stage duration, 2) relative exercise intensity, 3) work capacity, and 4) a prior maximal incremental exercise test on GE was evaluated. It was shown that stage duration influenced GE, a significantly higher GE was found during 1 min stages (21.1 ± 2.7%), compared to 3 min and 6 min stages (19.7 ± 2.8% and 19.3 ± 2.0%). When studying the effect of relative exercise intensity, an increase in GE was found up to an intensity of ~50% peak PO or ~100% of the PO at the ventilatory threshold, after which GE remained stable up to the limits of the ability to measure GE. Subjects with the highest peak POs did not show the highest GE values, which suggests that there is no relationship between work capacity and GE. Finally, lower GE values were found during a submaximal exercise test when this test is preceded by a maximal incremental exercise test, so there is a small effect of prior maximal exercise.

The results described in Chapter 2 are used to construct a research protocol to determine GE robustly. The reliability of the GE measurements, using this research protocol, has been established in the study described in Chapter 3. GE can be determined reliably so long as steady state exercise is performed and the respiratory exchange ratio (RER) at or below 1.0 is. Besides studying the reliability of measuring GE, the variation in GE within the day was assessed. Although a circadian rhythm in body temperature and
resting oxygen uptake (\(\dot{V}O_2\)) was found, this did not influence GE. As GE remained relatively constant during the day, the first assumption seems to be valid. Multiplying metabolic aerobic energy production with GE, results in the amount of mechanical power output aerobically produced (\(P_{\text{aer}}\)). By subtracting \(P_{\text{aer}}\) from the total PO delivered, the amount of mechanical power anaerobically produced (\(P_{\text{an}}\)) can be calculated (GE method). However, it is also possible to determine the total anaerobic work delivered with the maximal accumulated oxygen deficit (MAOD) method, which is the most widely used method. Chapter 4A reviews the available literature on the MAOD method and finally suggests the use of 10 × 4 min submaximal exercise bouts and the use of a fixed value of the y-intercept for the construction of the linear relationship between PO and \(\dot{V}O_2\) (4+Y MAOD procedure). The anaerobic capacity can then be determined during a supramaximal exercise protocol, which needs to be specific for the athlete’s event. If these suggested adaptations to the original methodology indeed result in a more robust PO-\(\dot{V}O_2\) relationship and therefore in more precise estimations of the anaerobic capacity is investigated in the study described in Chapter 4B. In Chapter 4B the anaerobic capacity and the corresponding 95% confidence interval determined with different MAOD procedures (10-Y, 4-Y, and 4+Y) and the GE method is compared. The results of this study showed that the different procedures did not result in significantly different anaerobic capacities, but the 95% confidence interval of the anaerobic capacity was significantly smaller for the 4+Y MAOD procedure and the GE method. So, the most precise estimates of the anaerobic capacity can be obtained with the 4+Y MAOD procedure and the GE method. However, as individual differences in anaerobic capacity exist, these methods cannot be used interchangeably. Therefore, the use of the GE method is suggested, as this method is less time consuming.

The validity of the second assumption, i.e. GE is independent of the altitude above sea level at which exercise is performed, is investigated in Chapter 5. A significantly lower GE was found, during exercise at an altitude-matched similar relative exercise intensity, when subjects ascended to a simulated altitude of 1,500 m (20.7 ± 1.1%) than at sea level (21.4 ± 0.8%). The exact cause of the lower GE at altitude, when determined at a similar relative exercise intensity, remains to be established, as only an absolute decrease of about 0.2% in GE can be explained by the significantly higher RER under hypoxic conditions. A study in which exercise is performed at a similar relative exercise intensity at sea level and altitude, but also at a similar absolute exercise intensity, might provide more insight in GE at low to moderate altitude and in the underlying processes.
GE can only be determined validly during exercise performed at an intensity below the ventilatory threshold, as otherwise $\dot{V}O_2$ shows a late secondary increase ($\dot{V}O_2$ slow component) and RER exceeds 1.0. Chapter 6A describes a new approach to estimating GE during high intensity exercise. GE is determined during submaximal exercise performed before and after a high intensity exercise bout, based on which GE can be estimated, using back-extrapolation, immediately after high intensity exercise. Using this approach it was shown that GE is lower after a high intensity constant PO bout. The effect of a declining GE on the relative contribution of $P_{aer}$ and $P_{an}$ was illustrated by computing the aerobic and anaerobic contribution to total PO, based on a constant GE and a variable GE. The results showed that a declining GE results in a much larger anaerobic capacity, as determined with the GE method.

The new approach introduced in Chapter 6A, was applied to a more sport specific protocol, namely time trials of different lengths in Chapter 6B. It was shown that GE is significantly lower after the time trials, varying in length between 500 m and 40,000 m, compared to before. The decrement in GE was larger for relatively shorter time trials (500-4,000 m) and the rate of the decline in GE is in these time trials relatively constant. However, the final decrement in GE is almost attained at 50% of the final time of the 40,000 m.

Based on the results of the studies presented in Chapter 6 it can be concluded that GE determined at submaximal exercise intensities is not representative of GE at (supra)maximal exercise intensities. However, at this moment the exact magnitude of GE during high intensity whole-body exercise remains uncertain, as it has been suggested in the literature that muscle efficiency is higher during high intensity exercise (mainly anaerobic energy production) than during steady state submaximal exercise. In addition, Chapter 6 illustrated that the fourth assumption, i.e. GE remains constant during fatiguing exercise, is invalid.

The same assumptions regarding GE underlie the energy flow model for cycling and the energy flow model for speed skating. The studies described in Chapters 2-6 all made use of cycling exercise, as PO can be easily determined. Thus far, it is impossible to directly measure PO during speed skating exercise, which makes it difficult to determine GE. However, it has been assumed that kinematic characteristics of the speed skating posture/technique reflect skating GE. Studying the effectiveness of the push-off ($e$) in speed skating is expected to provide us more insight in GE during speed skating races. Therefore, the final studies described in Chapter 7, evaluated the change ($\Delta$) in kinematic characteristics and skating velocity ($v$) during World Cup races. Chapter 7A shows that the
increase in $e$ was significantly associated with the decrease in $v$ during the race. No significant association was found between the change in knee and trunk angle and $\Delta v$. These results suggest that the decrease in $v$ over the race is most likely not due to increases in power losses to air friction, but can be partly ascribed to the increase in $e$ (i.e. a less effective push-off), which reflects a decrease in the amount of mechanical power produced. In addition, Chapter 7B addresses the influence of skating event, sex, and performance level on the association between changes in kinematic characteristics and $\Delta v$. Skating event significantly influenced the association between $\Delta e$ and $\Delta v$, which resulted in a significant association between $\Delta e$ and $\Delta v$ for the 5,000 m, without a significant association between $\Delta e$ and $\Delta v$ for the 1,500 m. Sex and performance level did not substantially influence the association between $\Delta e$ and $\Delta v$ and between the change in knee and trunk angle and $\Delta v$. Both studies presented in Chapter 7 suggest that skating efficiency decreases during fatiguing races.

In Chapter 8 the results of the different studies are interpreted in relation to the four assumptions regarding GE, which underlie the current version of the energy flow model for cycling and speed skating. Besides that, suggestions are given to improve the energy flow model. Instead of a constant GE, a declining GE, represented by an exponential function, needs to be used. In addition, the declining GE will result in a lower relative contribution of $P_{\text{net}}$ and a resultant larger relative contribution $P_{\text{an}}$ to total PO. The amount of total anaerobic work available for performance, as has been calculated by assuming a constant GE in Chapter 4B, therefore needs to be adapted.

In addition, directions for future research are provided in Chapter 8; mainly more research is necessary to improve our knowledge about the second and third assumption. Besides that, investigating the relation between the effectiveness of the push-off and skating GE would be valuable. Finally, the practical applications of the presented studies are summarized. 1) It seems that athletes do not have to change their circadian rhythm before important sporting events, as GE remains relatively constant during the day. 2) Coaches, but also scientists, are advised to use the 4+Y MAOD method or GE method to determine the anaerobic capacity of their athletes or subjects. By using the GE method, the effect of the declining GE on the relative contribution of $P_{\text{an}}$ to total PO, can be taken into account, which probably results in an even better representation of the anaerobic capacity. 3) When athletes have to perform at low to moderate altitude, attention should be paid to the lower GE at an altitude-matched similar relative exercise intensity. It might be that altitude acclimatization diminishes the negative effect of acute altitude on GE. 4) It has been shown that cycling GE and the effectiveness of the push-off during speed skating
worsen during high intensity exercise. Training adaptations to pacing strategy and technique may influence the decrement in GE over the race. 5) Coaches and athletes should pay attention to skating with a small and constant $e$. The 2-D movement registration method described in Chapter 7 can be used for this purpose.