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Energy Cost of Running Related to Running Intensity and Peak Oxygen Uptake

Energieverbrauch beim Laufen in Abhängigkeit von Laufintensität und Peak-Sauerstoffaufnahme

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Summary

› **The hypotheses** that a) a positive correlation between running oxygen uptake ($\dot{V}O_{2run}$) and peak oxygen uptake ($\dot{V}O_{2peak}$) is caused by a higher caloric equivalent and/or more reliance on anaerobic metabolic energy in subjects with lower $\dot{V}O_{2peak}$ and that b) the energy cost per meter increases with relative intensity related to $\dot{V}O_{2peak}$ were tested.

› **Twenty-nine males** (mean±SD age: 24.4±2.7yrs; height: 179.0±5.6cm; body mass: 74.5±6.8kg; $\dot{V}O_{2peak}$: 51.5±5.2ml kg^{-1}min^{-1}) ran at 2.6 and 3.0m s^{-1}. $\dot{V}O_{2run}$, oxygen uptake per meter distance (C_{VO2}), energy cost per meter distance based on respiratory measures and indirect calorimetry (C_{AER}), and net increase in blood lactate concentration (C_{ANAER}), as well as total C ($C_{TOT}=C_{AER}+C_{ANAER}$) were analyzed. Ad a) $\dot{V}O_{2run}$ and C_{VO2} were positively, and C_{ANAER} negatively interrelated with $\dot{V}O_{2peak}$ (all p<0.05). C_{TOT} was independent of $\dot{V}O_{2peak}$. Ad b) C_{VO2} was independent of relative intensity related to $\dot{V}O_{2peak}$, whilst C_{AER}, C_{ANAER} and C_{TOT} increased with relative intensity (all p<0.05).

› **The frequently observed** positive interrelationship between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ reflects less aerobic carbohydrate combustion and less reliance on anaerobic glycolysis in fitter subjects with higher $\dot{V}O_{2peak}$. Additionally, running economy decreases with increasing relative intensity.

Zusammenfassung

› **Die Hypothesen,** dass a) eine positive Korrelation zwischen Sauerstoffaufnahme beim Laufen ($\dot{V}O_{2run}$) und der Peak-Sauerstoffaufnahme ($\dot{V}O_{2peak}$) durch ein höheres kalorisches Äquivalent und/oder eine größere Abhängigkeit von anaerober metabolischer Energie bei Personen mit niedriger $\dot{V}O_{2peak}$ verursacht wird und b) der Energieverbrauch pro Meter Laufstrecke mit relativer Intensität bezogen auf die $\dot{V}O_{2peak}$ ansteigt, wurden getestet.

› **Neunundzwanzig Männer** (Mittelwert±SD Alter: 24,4±2,7Jahre; Größe: 179,0±5,6cm; Körpermasse: 74,5±6,8kg; $\dot{V}O_{2peak}$: 51,5±5,2ml kg^{-1} min^{-1}) liefen mit Geschwindigkeiten von 2,6 und 3,0m s^{-1}. $\dot{V}O_{2run}$, der Sauerstoffverbrauch pro Meter (C_{VO2}), der Energieverbrauch pro Meter basierend auf respiratorischen Messgrößen und indirekter Kalorimetrie (C_{AER}), und Nettoanstieg der Blutlaktatkonzentration (C_{ANAER}) sowie der Gesamtenergieverbrauch ($C_{TOT}=C_{AER}+C_{ANAER}$) wurden analysiert. Zu Hypothese a) $\dot{V}O_{2run}$ und C_{VO2} hingen positiv und C_{ANAER} negativ mit der $\dot{V}O_{2peak}$ zusammen (alle p<0.05). C_{TOT} war unabhängig von der $\dot{V}O_{2peak}$. Zu Hypothese b) C_{VO2} war unabhängig von der relativen Intensität bezogen auf die $\dot{V}O_{2peak}$, wohingegen C_{AER}, C_{ANAER} und C_{TOT} mit relativer Intensität zunahmen (alle p<0.05).

› **Der häufig beobachtete** positive Zusammenhang zwischen $\dot{V}O_{2run}$ und $\dot{V}O_{2peak}$ spiegelt eine geringere aerobe Kohlenhydratverwertung und eine geringere Abhängigkeit von anaerober Glykolyse bei fitteren Personen mit höherer $\dot{V}O_{2peak}$ wider. Zusätzlich nimmt die Laufökonomie mit zunehmender relativer Intensität ab.

KEY WORDS:
Terrestrial Locomotion, Human, Speed, Aerobic, Anaerobic

SCHLÜSSELWÖRTER:
Terrestrische Fortbewegung, Mensch, Geschwindigkeit, Aerob, Anaerob

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Introduction

Running performance of top class endurance athletes but also of recreational and non-specifically trained physically active individuals depends on the maximum aerobic metabolic rate and the energy cost of a unit of running distance (1, 5, 6, 7, 11, 12, 16, 29). There is evidence that elite runners have better running economy (RE) than good and less capable runners (13, 26), and that in untrained individuals RE improves if they take on running exercises (2). However, some other studies reported that RE is essentially the same in sedentary and athletic subjects (9, 11, 31) and independent of running velocity if air resistance can be neglected such as during running on the treadmill (11, 14, 18, 20, 21, 27). In contrast, other studies reported an increase in oxygen uptake (C_{VO2}) or aerobic energy expenditure (C_{AER}) per unit of running distance with increasing relative intensity (8, 13).

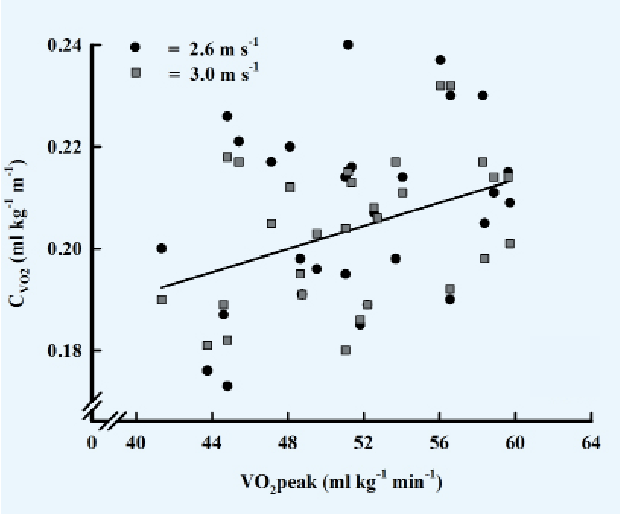

Figure 1

Linear increase in C_{VO2} with VO_{2peak} at 3.0m s^{-1} (black solid line: r=0.41, p<0.05, y=0.001x+0.145).

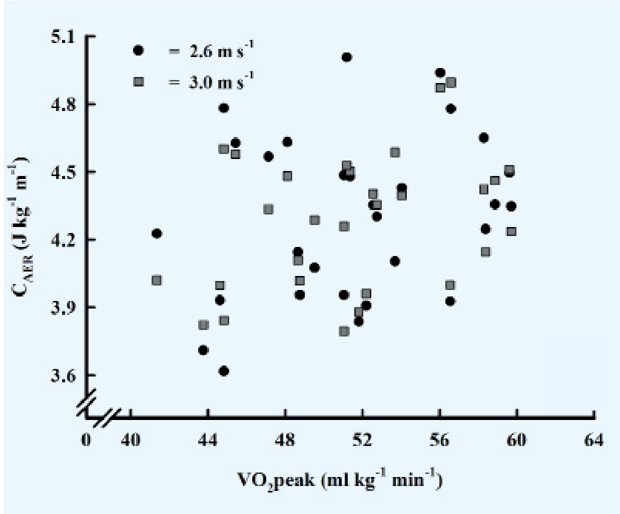

Figure 2

No interrelationship between C_{AER} and VO_{2peak}.

Peak oxygen uptake ($\dot{V}O_{2peak}$) and oxygen uptake at given running velocities ($\dot{V}O_{2run}$) are generally accepted measures of maximum aerobic metabolic rate and economy of exercise. Frequent reports that $\dot{V}O_{2run}$ is positively correlated with $\dot{V}O_{2peak}$ (13, 15, 19, 23, 25, 30) are at odds with the supposedly logical conclusion that the combination of high maximum aerobic metabolic rate and high RE is the best concept for best endurance running performance (2, 3, 11, 26, 28, 31, 33). Suggestions that among athletes with similar race performances a negative correlation between $\dot{V}O_{2peak}$ and RE always reflects compensation of lower aerobic power by lower energy cost of a given task, is not fully convincing. Being the best athlete more likely combines high economy with high $\dot{V}O_{2peak}$. Attempts to explain the positive interrelationship between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ based on muscle fiber type and mitochondrial factors remained inconclusive (15, 25).

In previous studies analyzing the $\dot{V}O_{2run}$ to $\dot{V}O_{2peak}$ relationship in subjects with highly different $\dot{V}O_{2peak}$, the applied velocities in walking and running tests reflected substantially different relative intensities in the magnitude of between approximately 20 and above 90% of $\dot{V}O_{2peak}$ (13, 25, 30). A consistent pattern of the $\dot{V}O_{2run}$ to $\dot{V}O_{2peak}$ interrelationship is that the correlation and regression coefficients become higher at velocities which reflect higher relative intensities (13, 30). Partly this may mirror differences in the respiratory exchange ratio (RER) between subjects with different $\dot{V}O_{2peak}$, which may vary the caloric equivalent and thus the metabolic energy per ml O_2 in favor of the less fit subjects (13). Additionally, the relative intensity at which anaerobic energy is required to perform, as indicated by an increase in the blood lactate concentration (BLC), is highly variable between subjects and independent of the absolute metabolic rate. Consequently, the higher correlation and regression coefficients of the $\dot{V}O_{2run}$ to $\dot{V}O_{2peak}$ relationship at the higher velocities may indicate that the less fit subjects had to rely on a higher fraction of carbohydrate combustion than the fitter subjects. Additionally, less fit subjects may rely to some extent on anaerobic energy shifting the metabolic demand from aerobic to partly anaerobic metabolism. These factors may result in utilizing less oxygen at a given metabolic cost of locomotion in less fitter subjects.

Therefore, we tested the hypotheses that a) the positive correlation between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ is caused by a higher reliance on carbohydrate utilization and/or anaerobic metabolic energy in subjects with lower $\dot{V}O_{2peak}$ and b) that RE in terms of the energy cost of a unit of running distance decreases with relative intensity if intensity related effects on carbohydrate and fat combustion, and anaerobic energy are considered.

Methods

Twenty-nine male subjects (mean±SD age: 24.4±2.7yrs; height: 179.0±5.6cm; body mass: 74.5±6.8kg; $\dot{V}O_{2peak}$: 51.5±5.2ml kg^{-1} min^{-1}) signed informed consent conforming to internationally accepted policy statements on the use of human subjects as approved by the local ethics committee. All participants were healthy and physically active but not specifically trained.

They performed an incremental running test on an electronically driven treadmill (Ergo XELG2, Woodway, Germany) in an air-conditioned room (21°C, 60% humidity). The test started with a 3min resting reference phase. The initial running velocity was set 2.2m s^{-1}. The speed was increased stepwise by 0.4m s^{-1} every 3min until exhaustion occurred. After each stage the running was interrupted for 30s for capillary blood sampling.

Respiratory gas exchange measures were taken continuously during the entire protocol (Oxycon Gamma, Mijnhard, Netherlands). The metabolic cart was calibrated using gases of known concentration and a syringe prior to each test. The breath-by-breath oxygen uptake data were reduced to stationary averages of the final 30s of each stage. Immediately before the start of a test, during each 30s break and after test-termination 20µl capillary blood was drawn from the hyperemic earlobe (Finalgon®, Thomae, Boehringer, Ingelheim, Germany) for the analysis of the BLC (Ebio plus, Eppendorf, Hamburg, Germany). The net lactate concentration (ΔBLC) was calculated as the difference between pre- and post-run at each running velocity.

RE at 2.6 and 3.0m s^{-1} were analyzed in terms of: $\dot{V}O_{2run}$, $C_{\dot{V}O2}$, C_{AER}, total energy cost above rest (C_{TOT}) calculated via C_{AER} plus anaerobic glycolytic energy per meter running distance (C_{ANAER}). Resting $\dot{V}O_2$ can hardly be measured correctly pre-testing which never fulfills conditions of true rest. These are defined as measurements in the morning, fasting and at indifferent temperature. Pre-testing conditions always include pre-test activities and excitement. Therefore, resting was defined as standing still and set as a $\dot{V}O_2$ of 4.5ml kg^{-1} min^{-1}, which reflects standing still in males (4).

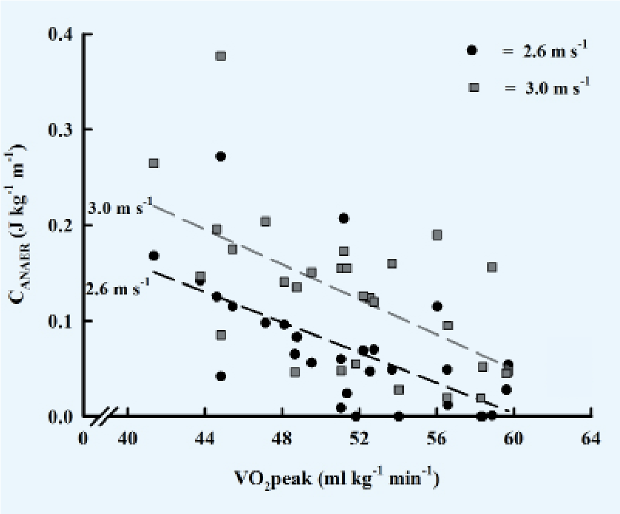

Figure 3

Linear decrease in C_{ANAER} with VO_{2peak} at 2.6m s^{-1} (black dashed line: r=0.62, p<0.001, y=-0.008x+0.48) and at 3.0m s^{-1} (dark gray dashed line: r=0.60, p<0.001, y=-0.009x+0.60).

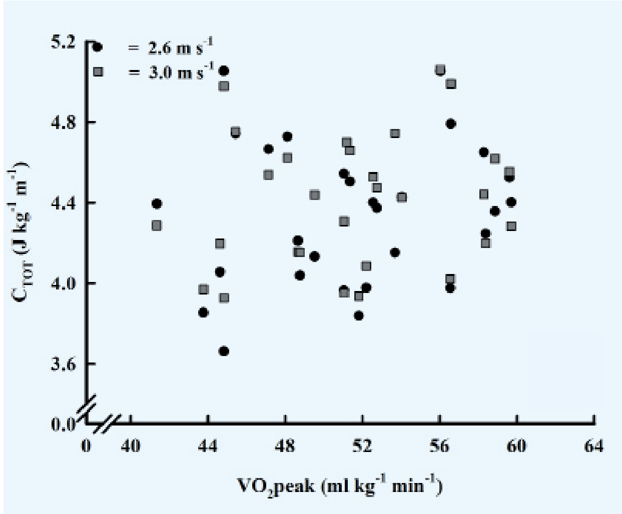

Figure 4

No interrelationship between CTOT and VO_{2peak}.

C_{AER}, C_{ANAER} and C_{TOT} were calculated by Eq.1, 2 and 3:

Eq.1: C_{AER} [J kg^{-1} m^{-1}]=($\dot{V}O_{2run}$-resting $\dot{V}O_2$) [ml s^{-1}] caloric equivalent [J ml^{-1}] body $mass^{-1}$ [kg^{-1}] $speed^{-1}$[s m^{-1}],

where the caloric equivalent was adjusted to the RER (32). A RER above 1.0, which clearly indicate respiratory compensation of a metabolic acidosis, was set 1.0 (2).

Eq.2: C_{ANAER} [J kg^{-1} m^{-1}] = ΔBLC [mmol l^{-1}] O_2-lactate equivalent [ml $mmol^{-1}$ l kg^{-1}] 21.131 [J ml^{-1}] running $time^{-1}$ [s^{-1}] $speed^{-1}$[s m^{-1}],

where an O_2-lactate equivalent of 3.0ml $mmol^{-1}$ l kg^{-1} was used, which is compatible to a distribution space of lactate of approximately 45% of the body mass (2, 10); the factor 21.131 reflects the caloric equivalent of carbohydrate oxidation (2).

Eq.3: C_{TOT} [J kg^{-1} m^{-1}] = C_{AER} [J kg^{-1} m^{-1}] + C_{ANAER} [J kg^{-1} m^{-1}].

All results are described as mean±SD. Differences between running velocities were tested via repeated measure ANOVA and Bonferroni post hoc test and effect sizes, in the form of partial eta squared (η^2), were calculated. Linear and non-linear regression models were used to identify significant interrelationships between measures of running economy at given running velocities and $\dot{V}O_{2peak}$ or relative intensity. The goodness of fits of different regression models were compared using the F-test (24). For all statistics the significance was set at P<0.05.

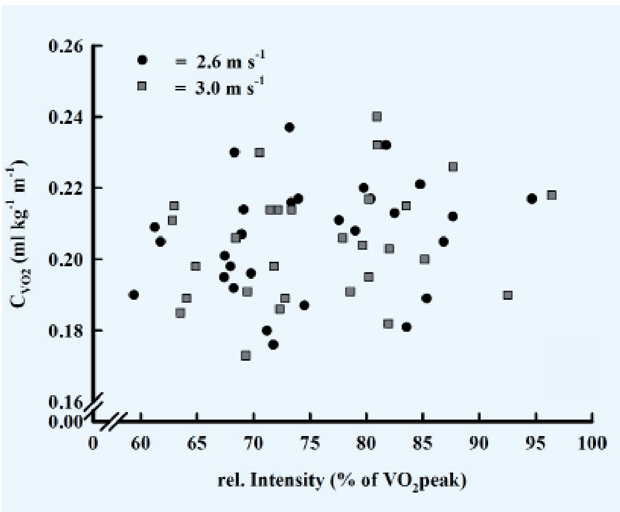

Figure 5

No interrelationship between C_{VO2} and relative intensity.

Results

The $\dot{V}O_{2run}$ at 2.6 and 3.0m s^{-1} running reflected 71±8% and 80±8% of the $\dot{V}O_{2peak}$, respectively. There were significant main effects and medium to large effect sizes for running velocity in $\dot{V}O_{2run}$, BLC, RER, C_{VO2}, C_{AER}, C_{ANAER} and C_{TOT}. Significant pair differences were confirmed in $\dot{V}O_{2run}$, BLC, RER and C_{ANAER} in terms of increases from 2.6 to 3.0m s^{-1}. Furthermore, $\dot{V}O_{2run}$, BLC, RER and C_{ANAER} were lower at 2.6 and 3.0m s^{-1} than at peak velocity whilst $C_{\dot{V}O2}$ was lower at peak velocity than at 2.6 and 3.0m s^{-1} (p<0.05; Tab.1).

At 3.0m s^{-1}, $\dot{V}O_{2run}$ (r=0.41, p<0.05, y=0.21x+30.0) as well as $C_{\dot{V}O2}$ were positively interrelated with $\dot{V}O_{2peak}$ (Fig. 1). Irrespective of running speed, C_{AER} was independent of $\dot{V}O_{2peak}$ (Fig. 2). C_{ANAER} was negatively interrelated with $\dot{V}O_{2peak}$ at both given velocities (Fig. 3). C_{TOT} was independent of $\dot{V}O_{2peak}$ (Fig. 4).

$C_{\dot{V}O2}$ was independent of relative intensity related to $\dot{V}O_{2peak}$ (Fig. 5). A quadratic function best described (p<0.01) the positive interrelationship between C_{AER} and C_{ANAER}, and relative intensity which flattens in C_{AER} and increases progressively in C_{ANAER} (Fig. 6 and 7). The latter results in an interrelation between C_{TOT} and relative intensity which was best described by a linear fit (Fig. 8).

Discussion

The main findings of the present study were a) that below peak running velocity, C_{TOT} is independent of $\dot{V}O_{2peak}$ and b) that C_{TOT} increases with relative intensity related to $\dot{V}O_{2peak}$. Consequently the results support the hypothesis a) that the positive correlation between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ at given speeds is caused by the higher reliance on carbohydrate oxidation plus anaerobic me-

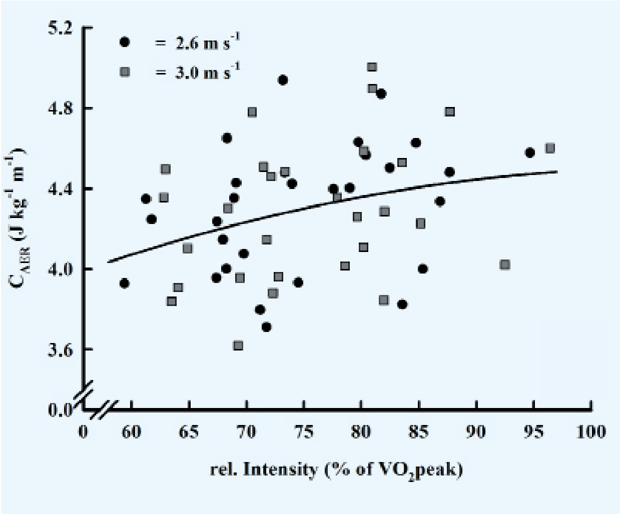

Figure 6

Non-linear increase in C_{AER} with relative intensity ($r=0.32$, $p<0.05$, $y=1.9\ 10^{-4}x^2-4.05\ 10^{-2}x+2.3$).

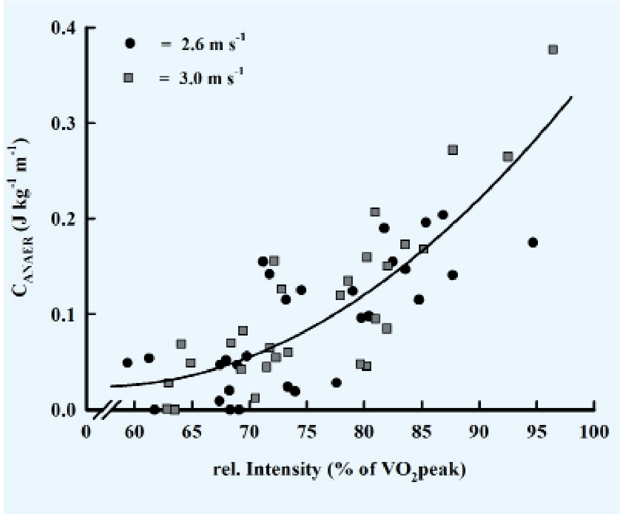

Figure 7

Non-linear increase in C_{ANAER} with relative intensity ($r=0.67$, $p<0.001$, $y=1.8\ 10^{-4}x^2-2.010^{-2}x+0.6$).

tabolic energy in subjects with lower $\dot{V}O_{2peak}$. They also support the hypothesis b) that RE decreases with increasing relative intensity.

The present results clearly support but also extent recent suggestions that measuring RE in terms of C_{AER} or C_{TOT} is more appropriate than expressing RE as $\dot{V}O_{2run}$ or $C_{\dot{V}O2}$ (13). They also indicate that previous reports that $\dot{V}O_{2run}$ was positively correlated with $\dot{V}O_{2peak}$, which becomes more obvious at higher running velocities and/or mechanical power and thus relative intensity (13, 15, 23, 25, 30), do not contradict the conclusion that a combination of high maximum aerobic metabolic rate and high RE is the best concept for a most successful endurance running performance (2, 3, 11, 26, 28, 31). However, they challenge suggestions that among athletes with similar race performances a positive correlation between $\dot{V}O_{2peak}$ and $\dot{V}O_{2run}$ always reflects compensation of lower aerobic power by less energy cost of a given task. The previously reported higher $\dot{V}O_{2run}$ in athletes with higher $\dot{V}O_{2peak}$ does not necessarily reflect lower RE. Alternatively it may indicate lower reliance on carbohydrate utilization and/or anaerobic energy. The positive interrelationship between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ does not require specific muscle fiber compositions or mitochondrial factors (15, 25). However, differences in the metabolic profile of slow- and fast-twitch muscle fibers may strongly contribute to a higher $\dot{V}O_{2peak}$ in athletes with extremely high fractions of slow-twitch fibers. This allows less reliance on carbohydrate combustion and anaerobic energy including a reduced maximum glycolytic rate. These factors increase $\dot{V}O_{2run}$ and $C_{\dot{V}O2}$ (Fig. 1). No corresponding interrelation between C_{AER} and $\dot{V}O_{2peak}$ may reflect that higher $\dot{V}O_{2run}$ and $C_{\dot{V}O2}$ indicate either a higher lipid oxidation rate at a given C_{AER} (identical RE) or even lower C_{AER} (higher RE) and/or an increased C_{AER} (lower RE). Irrespective of RE the combination of higher $\dot{V}O_{2peak}$ and reduced maximum glycolytic rate results in a lower C_{ANAER} (Fig. 3). On aggregate, C_{TOT}, the combination of all above effects, is independent of $\dot{V}O_{2peak}$ and highly variable between individual subjects (Fig. 4).

Whilst considering for effects of aerobic substrate utilization, a potential contribution of anaerobic energy remains undetected when calculating C_{AER} based on respiratory data only. The present findings clearly demonstrate that within the given range of the RER the aerobic fitness related effect on relative reliance of carbohydrate does not fully compensate for the underestimation of the energy cost of running based on $\dot{V}O_{2run}$ and $C_{\dot{V}O2}$ related to $\dot{V}O_{2peak}$ in less fit subjects (Fig. 1). The effect of changes of the caloric equivalent on C_{TOT} was less than half the magnitude of that of C_{ANAER}.

No interrelationship between $C_{\dot{V}O2}$ and relative intensity (Fig. 5) was highly confirmatory of previous findings (11, 14, 18, 20, 21, 22, 27). However, in conjunction with growing evidence of an interrelationship between both C_{AER} and C_{TOT} and relative intensity (2, 9, 13; Fig. 6, 7 and 8) the independence between $C_{\dot{V}O2}$ and relative intensity also indicates that purely $\dot{V}O_{2run}$ based estimations of the energy cost of running may substantially underestimate the real metabolic cost at higher exercise intensities (Fig. 8).

This underestimation gets even more evident at peak velocity where $C_{\dot{V}O2}$ suggests a slight but significant increase in RE in the magnitude of 2 to 3% which at RER <1.0 is similar to that in C_{AER}. The latter clearly indicates that analyses of RE do not only require consideration of changes in the caloric equivalent ›

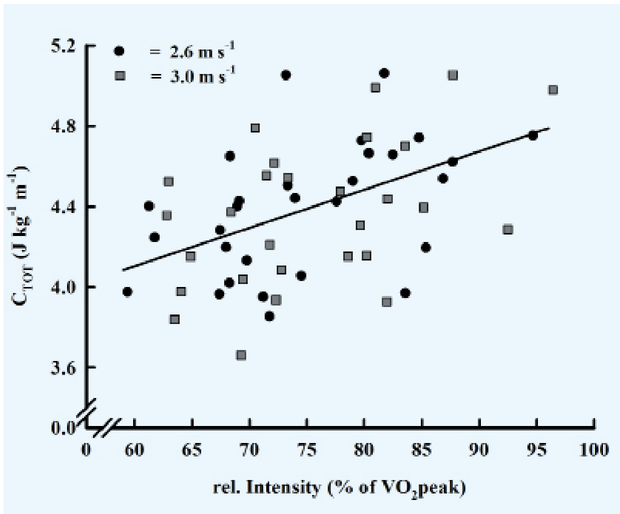

Figure 8

Linear increase in C_{TOT} with relative intensity ($r=0.47$, $p<0.001$, $y=0.019x+3.0$)

Table 1

Metabolic measures and corresponding energy costs per meter running (p-value and partial eta of main effects; a=Significant pair difference with 2.6m s^{-1}, b=Significant pair difference with 3.0m s^{-1}).

	2.6 M S^{-1} (MEAN±SD)	3.0 M S^{-1} (MEAN±SD)	PEAK (MEAN±SD)	SIG.	η^2
VO_{2run} (ml kg^{-1} min^{-1})	36.3±2.7	40.7±2.6a	51.5±5.2a,b	<0.001	0.885
BLC (mmol l^{-1})	2.4±0.9	3.5±1.4a	9.8±2.3a,b	<0.001	0.891
RER	0.94±0.05	0.99±0.06a	1.11±0.04a,b	<0.001	0.856
C_{VO2} (ml kg^{-1} m^{-1})	0.207±0.017	0.204±0.014	0.198±0.014a,b	<0.01	0.251
C_{AER} (J kg^{-1} m^{-1})	4.306±0.364	4.287±0.301	4.189±0.292	<0.05	0.132
C_{ANAER} (J kg^{-1} m^{-1})	0.071±0.066	0.127±0.080a	0.319±0.082a,b	<0.001	0.821
C_{TOT} (J kg^{-1} m^{-1})	4.377±0.387	4.414±0.327	4.507±0.283	<0.05	0.116

but also the potential use of anaerobic energy to prevent potentially substantial overestimations of RE at running velocities causing an increase in the BLC. In the present study at peak velocity the increase of C_{ANAER} is approximately 2 and 2.5 times as high as the above mentioned decreases in $C_{\dot{V}O2}$ and C_{AER} compared to 2.6 and 3.0m s^{-1}, respectively. The latter furthermore stresses that estimations of the anaerobic fraction of energy required for a given performance based on estimations of the accumulated oxygen deficit (17) is likely to result in substantial underestimations of C_{ANAER}.

In conclusion, C_{TOT} including C_{AER} plus C_{ANAER} is independent of $\dot{V}O_{2peak}$. The consistently observed positive interrelationships between $\dot{V}O_{2run}$ and $\dot{V}O_{2peak}$ as well as $C_{\dot{V}O2}$ and $\dot{V}O_{2peak}$ reflect less reliance on aerobic carbohydrate combustion and anaerobic glycolysis in fitter subjects with a higher $\dot{V}O_{2peak}$. Frequent observations of no interrelationship between $C_{\dot{V}O2}$ and relative intensity do not support independence of RE and running velocity. The non-linear increases of C_{AER} and C_{ANAER} with the relative intensity are degressive (Fig. 6) and progressive (Fig. 7), respectively. In combination, these nonlinear increases resulted in a linear intensity related increase of C_{TOT} (Fig. 8).

Conflict of Interest

The authors have no conflict of interest.

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