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Running and cycling economy in athletes; determining factors, training interventions and testing

Thesis for the degree of Doctor Philosophiae

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Norwegian University of Science and Technology
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Løps- og sykkeløkonomi hos idrettsutøvere; bestemmende faktorer, treningsintervensjoner og testing

Arbeidet som denne doktorgradsavhandlingen er basert på ble utført ved Norges teknisk-naturvitenskapelige universitet og Høgskolen i Telemark. Det består av en rekke på fem eksperimentelle studier som har undersøkt bestemmende faktorer for løps- og sykkeløkonomi, treningsintervensjoner og testmetoder.
De viktigste målemetodene i dette doktorgradsarbeidet var målinger av oksygenopptak under submaksimale og maksimale arbeidsbelastninger, under løp på tredemølle og sykling på testergometersykkel. Videre er det blant annet gjennomført laktatmålinger, målinger av maksimalstyrke og effekt i strekkapparat i underekstremitetene, kraftmålinger under løp og antropometriske målinger av idrettsutøverne.

Det først studiet undersøkte effekten av melkesyre på oksygenkostnaden (C_R) ved løp på laktatterskel. C_R ble signifikant forverret når blodlaktatkonsentrasjonen ble økt fra 3 til 5 mm·L^{-1}.

Studie to undersøkte i hvilken grad en vanlig benyttet inkrementell protokoll for måling av oksygenopptak og C_R påvirker reliabiliteten på disse målingene. Hastighet og relativ intensitet ble funnet å ikke påvirke C_R på intensiteter mellom 60 og 90 % av maksimalt oksygenopptak.

I studie tre og fem ble det undersøkt om maksimal styrketrening (knebøy) bedrer løps- og sykkeløkonomi og tid til umattelse ved maksimal aerob hastighet. Både løps- og sykkeløkonomi ble signifikant forbedret etter 8 ukers maksimal styrketrening som et supplement til den vanlige utholdenhetstreningen. Disse forbedringene førte til signifikant lenger tid til utmattelse på maksimal aerob hastighet. Verken maksimalt oksygenopptak eller kroppsvekt ble forandret.

Studie fire undersøkte sammenhenger mellom løps-karakteristika, maksimal styrke, antropometri og C_R. Det ble funnet en signifikant negativ korrelasjon mellom summen av peak kraft, eksentrisk og konsentrisk, i hvert løpesteg og C_R.

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Abbreviations used in this thesis

APF	average peak force
APF_{total}	sum of more than one average peak force
A-V O_2-difference	arteriovenous oxygen difference
BW	body weight
C	oxygen cost of work (work economy)
C_C	oxygen cost of cycling
CE	cycling economy
C_R	oxygen cost of running (running economy)
CT	contact time
CV	coefficient of variance
DLO_2	pulmonary diffusion capacity
DLO_2	muscle diffusion capacity
E	potentional kinetic and gravitational energy
equ	equation
F	force
f	cyclus frequency in running or cycling
FEO_2	fraction of expired oxygen
FIO_2	fraction of inspired oxygen
h	hour
[Hb]	hemoglobin concentration
Hf	heart frequency
Hf_{max}	maximum heart frequency
Hf_{peak}	peak heart frequency
kg	kilogram
km	kilometer
L	liter
$[La^-]_b$	lactate concentration in blood
LT	lactate threshold
m	meter
MAP	maximum aerobic power
MAS	maximum aerobic speed
min	minute

$mmol \cdot L^{-1}$	millimole per liter
MST	maximal strength training
N	Newton
$N \cdot s^{-1}$	Newton per second
$N \cdot m \cdot s^{-1}$	Newton meter per second
η	muscular efficiency
O_2	oxygen
p	p-value
P_R	pedaling resistance
Q	cardiac output
r	correlation coefficient
R	respiratory quotient
RFD	rate of force development
RM	repetition maximum
RPM	rounds per minute
s	seconds
SF	stride frequency
SL	stride length
SD	standard deviation
SV	stroke volume
TPF	time to peak force
VE	minute ventilation
VO_2	oxygen uptake (per minute)
VO_{2max}	maximum oxygen uptake (per minute)
VO_{2peak}	peak oxygen uptake (per minute)
W	watt
WE	work efficiency

List of included papers

This thesis is based upon an introduction to the field, a summary of the thesis and the following papers:

Paper I: Hoff J, Støren Ø, Finstad A, Wang E, Helgerud J
High blood lactate levels deteriorates running economy in elite endurance athletes

Paper II: Helgerud J, Støren Ø, Hoff J
Are there differences in running economy at different velocities?

Paper III: Støren Ø, Hoff J, Støa EM, Helgerud J
Maximal strength training improves running economy in distance runners

Paper IV: Støren Ø, Helgerud J, Hoff J
Running stride peak forces inversely determines running economy in elite runners

Paper V: Sunde A, Støren Ø, Bjerkaas M, Larsen MH, Hoff J, Helgerud J
Strength training improves cycling economy

Summary

Paper I investigated the effect of lactic acid on oxygen cost of running (C_R) in elite athletes. 7 elite endurance athletes (4 orienteers and 3 cross country skiers) participated in this study. The athletes were first tested for C_R at 10 km·h^{-1} and for lactate threshold (LT) on a treadmill with 1.5% inclination, and for maximum oxygen uptake (VO_{2max}) at 5.0% inclination. They were then tested for C_R at their LT velocity with a pre concentration of blood lactate $[La^-]_b$ of either 3 mmol·L^{-1} or 5 mmol·L^{-1} followed by a crossover. C_R deteriorated significantly (5.5 %) when pre $[La^-]_b$ was raised from 3 mmol·L^{-1} to 5 mmol·L^{-1}.

Paper II investigated to what extent a commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities affects the reliability of these measurements. 15 moderately to well trained (9 male and 6 female) endurance athletes participated in this study. C_R, heart rate (Hf) and $[La^-]_b$ during 5 minute runs at velocities ranging from 8.0 to 17 km·h^{-1}, representing intensities ranging from 60% to 90% of VO_{2max} was measured on two different days in random order. The athletes were also tested for LT, VO_{2max}, maximum aerobic speed (MAS) and time to exhaustion at MAS ($_t$MAS). No significant differences in C_R between the different relative velocities or the different set velocities were found for neither the male or for the female athletes, up to 90% of VO_{2max}. The incremental protocol for measuring VO_2 at different velocities was found not to affect the reliability of these measurements. All athletes reached their VO_{2max} while running to exhaustion at MAS. The females showed significantly lower VO_{2max} but significantly better C_R than the males. At velocities representing intensities between 60% and 90% of VO_{2max}, no differences in C_R were found. This means that C_R measured at sub maximal velocities are representative for C_R at race velocity for distances above 10 000 metres for most runners.

Paper III investigated if maximal strength training (MST) improves C_R and $_t$MAS among well trained long distance runners on a level treadmill. 17 well trained (9 male and 8 female) runners were randomly assigned into either a maximal strength intervention or a control group. The intervention group (4 males and 4 females) performed half-squats, 4 sets of 4 repetitions maximum (RM), three times per week for 8 weeks, as a supplement to their normal endurance training. The control group continued their normal endurance training during the same period. The intervention manifested significant improvements in 1RM (33.2 %), rate of force development (RFD) (26.0 %), C_R (5.0 %), and $_t$MAS (21.3 %). The control

group showed no changes from pre to post values in any of the parameters. Neither the intervention group nor the control group changed VO_{2max} or body weight (BW).

The relationship between running characteristics and force measures and C_R, as well as the relationship between anthropometric factors, maximal strength in lower extremities and C_R was investigated in paper IV. 11 elite endurance athletes participated in this study. 1RM in half-squat leg press, VO_{2max}, C_R, vertical and horizontal external forces while running, BW, height, leg length, calf circumference, hip width, and body fat, were examined. 3000m best performance times obtained during the last season were recorded. The athletes wore contact soles, and the treadmill was placed with the front on a force platform while the rear end was hanging in a special device constructed for this purpose. Ergospirometric variables were measured while the athletes were running at the same treadmill at the same speed as for the force measurements. The sum of eccentric and concentric peak forces (APFtotal) revealed a significant inverse correlation ($p<0.05$) both with 3000m performance ($R=0.71$) and C_R ($R=0.66$). Moderate inverse correlations were found ($p<0.05$) between C_R and body height ($R=0.61$) and between C_R and body fat percentage ($R=0.62$).

Paper V investigated if MST improves cost of cycling (C_C), work efficiency (WE) and time to exhaustion at maximal aerobic power (${}_t$MAP) among competitive road cyclist in line with the running improvements in paper III. 16 competitive road cyclists (12 male and 4 female) were randomly assigned into either an intervention or a control group. The intervention group (7 males and 1 female) performed half-squats, 4 sets of 4 RM, three times per week for 8 weeks, as a supplement to their regular endurance training. The control group continued their normal endurance training during the same period. The intervention resulted in significant improvements in 1RM (14.2%), RFD (16.7%), C_C (4.8%), WE (4.7%) and ${}_t$MAP (16.1%). No changes were observed in VO_{2max}, BW or cadence. The control group improved WE by 1.4%, but this improvement was significantly lower than in the intervention group.

Running performance times were recorded from the subjects in two of the studies (study III, and study IV). In study III, seasonal best times in 5 km running were collected from each athlete. C_R accounted for 5% of the difference in 5 km performance between these subjects. In study IV, seasonal best times in 3 km running were collected from each athlete. C_R accounted for 13% of the difference in 3 km performance between these subjects. The athletes in study IV were more homogenous regarding VO_{2max} than the athletes in study III.

Since some of the variables measured in two or more of the studies on C_R were tested in identical protocols, results from different studies could be combined in this thesis to gain a stronger statistical power. Such a combination was used to further investigate possible gender differences in C_R as observed in study II. When combining C_R results from study II and study III, and dividing into gender, there is a significantly ($p<0.01$) better C_R for the female subjects (0.663 ± 0.039 $ml \cdot kg^{-0.75} \cdot m^{-1}$) compared to the male subjects (0.724 ± 0.057 $ml \cdot kg^{-0.75} \cdot m^{-1}$). When C_R results from all the four studies on running are combined independent of gender, mean C_R was 0.701 ± 0.051 $ml \cdot kg^{-0.75} \cdot m^{-1}$, showing an inter-individual variation of 7.3%.

Introduction

The energetics of long distance running and cycling

Endurance Performance

Endurance performance, as in long distance running and cycling imposes great demands on both the cardiovascular system and the muscle system. Although Coyle (1999) defines performance in endurance events as: *The power or velocity that can be maintained for durations of 30 minutes to four hours,* long distance running races are commonly regarded as races over distances from 3000 m to 42.2 km, while road cycling distances typically range from approximately 5 km (short prologues) to approximately 250 km (long road races). This gives racing times ranging from approximately 7.30 minutes to approximately 2.30 hours at high performance running, and racing times ranging from approximately 10 minutes to approximately 6 hours in high performance cycling. Medbø and Tabata (1989) have demonstrated a 50 – 50% aerobic / anaerobic energy release already after one minute of maximal bicycle ergometer work. As the duration of a work increases, the higher the energy release from aerobic processes, reaching approximately 99% for a marathon race (42.2 km) (Åstrand and Rodahl 1986). In short time trials, professional road cyclists work at mean heart rates between 80% and 90% of maximum heart rate (Hf_{max})(Padilla et al 2000), which is slightly above the cyclists lactate thresholds (LT). In longer road races, the mean intensity seems to be slightly below LT (Vogt et al 2006).

In distance running and cycling, anaerobic capacity is thus of minor importance compared to the aerobic energy production. An efficient oxygen transport system is thus vital. Endurance sports are apparently demanding in terms of aerobic capacity, but performance over more than a few minutes is also influenced by somatic factors (e.g. gender, age and body dimensions), psychological factors (e.g. attitude, motivation), environment (altitude, heat) and probably most of all training adaptations (Maughan et al. 1969, Åstrand and Rodahl 1986).

Physiological determinants of cardio vascular endurance

Pate and Kriska (1984) have described a model that incorporates the three major factors accounting for inter-individual variance in aerobic endurance performance, namely VO_{2max}, LT and work economy (C). Numerous published studies support this model (Pollock 1977, Farrell et al. 1979, Conley and Krahenbuhl 1980, Di Prampero et al. 1986, Bunc and Heller

1989, Hoff et al 2002). Thus, the model should serve as a useful framework for comprehensive examination of C and the relevance on endurance performance.

Maximal oxygen uptake

VO_{2max} is probably the single most important factor determining success in an aerobic endurance sport (Åstrand and Rodal 1986, Saltin 1990). However, within the same person VO_{2max} is specific to a given type of activity. Therefore, in order to obtain relevant values, emphasis is placed on testing in sport-specific or working specific activities (Strømme et al. 1977). Wagner (1993, 1996) has devised a numerical analysis interactively linking the lungs, circulation and muscles designed to compare the influences of each conductance component on VO_{2max}. The four conductances in question are alveolar ventilation (VE), cardiac output (Q), pulmonary diffusion capacity (DLO_2) and muscle diffusing capacity (DMO_2). Two other independent transport variables considered are haemoglobin concentration ([Hb]) and the fraction of inspired O_2 (FIO_2). At maximal exercise, the majority of evidence points to a VO_{2max} that is limited by O_2 supply, and Q is just as influential as [Hb], DLO_2 and DMO_2 together (Powers et al. 1989, Wagner 1991, Roca et al. 1992, Knight et al. 1993, Wagner 1996, Richardson et al. 1999). Andersen and Saltin (1985) have shown that skeletal muscle has an ability to consume O_2 that vastly exceeds the circulatory systems ability to supply O_2. This is supported by training interventions aiming to increase Q. Helgerud et al. (2007) have shown that aerobic high-intensity intervals improve VO_{2max} and Q more than moderate training. For several groups of patients however, mainly where the disease affects work capacity, a demand limitation is proposed (Wang et al 2008).

Lactate threshold

The LT was defined by Davis (1985) as the intensity of work or VO_2 where the blood lactate concentration gradually starts to increase during continuous exercise. The $[la^-]_b$ represents a balance between lactate production and removal, and there are individual patterns in this kinetics (Brooks 1986). Lactate is not wasted. Without any loss of energy, the process of pyruvate transformation to lactate can be reversed. Pyruvate can thus be oxidized or to a lesser extent be a substrate for synthesis of glucose and glycogen. Both the resting and sub maximally working skeletal muscle, as well as heart muscle and kidney cortex can use lactate as a substrate (Åstrand and Rodal 1986). The relationship between LT expressed as percentage of VO_{2max} and aerobic performance capacity is, however debated. It is argued that for durations of work up to approximately 30 minutes a person's ability to utilize a high percentage of VO_{2max} over an extended period of time is first and foremost a function of time

(Leger 1986, Coetzer et al. 1993). If one person shows better fractional utilization than another person, it is because he covers a given distance in a shorter time, and can therefore work at a higher relative intensity. When some authors try to express LT as work load (Yoshida et al. 1987, Nicholson and Sleivert 2001), it correlates well with performance. Performance at LT depends on both VO_{2max} and C. A correct expression of LT is a % of VO_{2max}, and then the adaptability seems to be minor (Bangsbo 1994, Helgerud et al 2001, Helgerud et al 2007).

Work economy and work efficiency

C is referred to as the oxygen cost of a standardised aerobic workload. C_R or C_C is commonly defined as the steady state VO_2 in $ml \cdot kg^{-1} \cdot min^{-1}$ at a standard velocity or brake power (Conley and Krahenbuhl 1980, Costill et al. 1973, Foss and Hallen 2004). C_R is also commonly defined as energy cost of running per metre ($ml \cdot kg^{-1} \cdot m^{-1}$), (Di Prampero et al. 1986, Helgerud 1994, Helgerud et al. 2001). Conley and Krahenbuhl (1980) and Helgerud (1994) have shown inter-individual variations in C_R at a standard running velocity.

WE is typically defined as the relationship between mechanical work performed and the chemical energy spent in performing it (McMahon 1984, Pate and Kriska 1984, Kent 1994), which is the ratio between work output and C (Åstrand and Rodahl 1986, Hoff et al 2005). According to Margaria (1976), the maximum efficiency with which a muscle may transfer chemical energy into mechanical work during walking or running, is about 25%. To accurately measure the total work output during walking or running is, however a difficult task (Pate and Kriska 1984), at least on level ground. If mechanical work in walking or running is calculated from the product of BW and the net change of the centre of mass per step cycle divided by the time spent in completing this cycle, on level ground the mechanical work should be zero (McMahon 1984) and thus not useful to measure. When mechanical work in walking or running is calculated by use of the equation for kinetic energy $Work = \frac{1}{2} mv^2$ (equ. 1), where m is the body mass, and v is the velocity at which the runner or walker moves, and corrected for the gyration of the limbs around its centre of mass, Cavagna and Kaneko (1977) have found WE to increase steadily with increased running speed. Maximal muscular efficiency values well above the 25% described by Margaria (1976) are shown by Cavagna and Kaneko (1977). They suggest that this is due to passive recoil of muscle elastic elements. Because of the complexity of calculating mechanical work in walking and running (Pate and Kriska 1984), it is thus more common to measure C in these activities. In cycling, however the force applied in the braking of the flywheel, the circumference of the wheel, and the velocity with which the wheel is turning, makes it easy to compute the external power output.

WE is thus easily calculated on cycle ergometer (Mogensen et al 2006):

$$WE = \frac{WorkRate}{EnergyExpenditure - BasalEnergyMetabolism} \text{ (equ. 2).}$$

Factors influencing running and cycling economy

Walking or running mammals, such as humans are very inefficient with regards to the energetic cost of moving (Tucker 1975, Margaria 1976). During walking and running, a recruited muscle both shortens and lengthens in cycles. As it shortens, it does mechanical work, but as it lengthens, mechanical work is done on it (Tucker 1975). According to Tucker (1975) there are two main reasons why human locomotion is inefficient. First, as a muscle is stretched, it consumes extra metabolic energy at the same time as it is absorbing work. Second, as pointed out in Cavanagh et al (1964) about half of the work done by stretching a muscle is converted into heat, while the rest is stored in elastic elements.

C_R could thus be represented by the equation presented in Alexander (1984):

$C_R = \frac{0.5 fE}{\eta}$ (equ. 3) where 0.5 is the approximate amount of energy from braking forces that is not stored in elastic elements, f is the step frequency, E is the potential kinetic and gravitational energy at each step, and η is the efficiency of muscle action, approximately 0.2, as suggested by Alexander (1980). There will be three major ways to improve C_R. One is by decreasing the braking forces that causes stretching of muscle-tendon units i.e. by decreasing vertical movement of the center of mass. All braking forces can, however, not be prevented in running. Because of gravity, the center of mass must to some extent be sent upwards (as a result of a stem) as it will gradually fall down when it is not supported by the legs. To minimize vertical movement of the center of mass will therefore lead to an increase in step frequency (f). A second way to improve C_R is to increase the amount of energy from the braking forces that can be stored in elastic elements in muscle-tendon units i.e. elastic recoil. A third way in which C_R may be improved is by increasing muscular efficiency.

In cycling, vertical movement of the center of mass is minimal, unless riding uphill. The braking forces are first and foremost represented by the resistance to the cyclist and bicycle moving forward, and transferred to the pedals. The resistance to the cyclist moving forward is represented by the resistance to the rolling tyres, air resistance and gravitational energy if riding up hill. On an ergometer, the resistance is represented by the artificial braking of the flywheel and transferred to the pedals. A modified version of the equation for C_R presented in Alexander (1984), and applied to C_C can thus be $C_C=\frac{fP_R}{\eta}$ (equ.4) where f is the pedaling frequency (cadence), P_R is pedaling resistance at each round, and η is the efficiency of muscle action, still approximately 0.2, as suggested by Alexander (1980). According to Faria (1992), air resistance is by far the greatest retarding force affecting cycling. Consequently, the aerodynamics should be a major factor influencing C_C. At speeds above 30 $km \cdot h^{-1}$, air resistance account for more than 90% of the total resistance the cyclist encounter. However, air resistance will not contribute to pedaling resistance on an ergometer cycle in a laboratory. At a given power, pedaling resistance will then be directly influenced by the pedaling frequency. One way to improve C_C on an ergometer cycle is thus to choose the optimal cadence related to the power output. A second way is by increasing muscular efficiency.

Muscular efficiency

Strength, Power and Rate of Force Development

Strength is defined as the maximal force a muscle or muscle group can generate (Komi, 1992). Power is work (which is the product of force and work distance) divided by time. Power is thus the rate of doing work, and is measured in watts (Åstrand and Rodahl, 1986). RFD is closely related to power. It is defined as *the rate at which a force is developed* (Kent 1994). If the force itself and the time to reach this force, or the time in which this force is acting is measured, RFD is measured as Ns^{-1}. If, in a dynamic action, the distance of a movement in which force is measured is taken in to account, RFD can be measured as Nms^{-1}. The latter is the same as watts, and in this case RFD is the same as power.

The importance of strength and power in long distance running or cycling would intuitively seem small. Each step would in average only account for a small percentage of the maximum force production possible in the involved muscle groups. In the final sprint toward the finish line, high power production may be of some importance, as is shown in shorter running distances and in soccer. Wisløff et al (2004) demonstrated a strong positive correlation between 1RM half-squat strength and sprinting and running performance among soccer players. No studies have shown correlation between maximal strength and C, but several studies have shown strong correlations between *training induced improvements* in maximal strength and C (Johnston et al. 1997, Paavolainen et al. 1999, Hoff et al 1999, Hoff et al 2002, Millet et al. 2002, Østerås et al., 2002, Hoff and Helgerud 2003, McMillan et al 2005, Hoff et al 2005, Loveless et al 2005).

Running or cycling velocity

In 1963, Margaria et al. reported that when energy expenditure is given as functions of running speed, the functions appear to be straight lines given net aerobic conditions. They argue that since the extrapolations of these lines cross the ordinate very close to the rest metabolism, the net energy consumption per distance covered is independent of speed. Helgerud (1994) and Slavin et al (1993) reports no change in C_R with increasing running velocities, whereas Hoff and Helgerud (2003) and Harris et al. (2003) reports slightly decreasing C_R with increasing running velocities, as is reported by Loveless et al (2005) in C_C with increasing work intensity. Theoretically, if the intensity of work is high enough and at least above LT, measures over a relative short amount of time (i.e. 5 minutes) could show an improvement in C_R with increasing speed. This is because the relative amount of energy released aerobically decreases while the relative amount of energy released anaerobically increases. On the other hand, a deterioration of C_R with increasing speed is observed. Hunter and Smith (2007) found deterioration in C_R (approximately 3%) at the end of a one hour running session at a speed close to maximal effort among 16 experienced distance runners. Also, Collins et al (2000) have found deteriorated C_R (approximately 5%) after an intense interval session and Thomas et al (1995) report of deterioration in C_R (approximately 5%) during a submaximal but intense 5-km running session.

Ventilatory demands

VO_2 is measured as a product of the difference between inspired O_2 (FIO_2) and expired O_2 (FEO_2) and the total pulmonary ventilation (VE) (Åstrand and Rodahl 1986). As the difference $FIO_2 – FEO_2$ represents the arterio-venous oxygen difference (A-V O_2-difference) (Åstrand and Rodahl 1986), a lower VE at a standard work or velocity should thus be a result of either one or two of the following causes: One; the total aerobic demand for performing the work has been lowered, Two; an increase in the A-V O_2-difference. Improvements in any variable that may improve C will lower C_R and thus also VE, since VO_2 is a product of the difference between FIO_2 and FEO_2 and VE. Arterial blood flow to exercising muscle occurs almost exclusively between muscle contractions (Shoemaker et al 1994). Mean transit time is found to positively correlate with A-V O_2-difference (Saltin, 1985). If, as a result of a decrease in skeletal muscle contraction time, the A-V O_2-difference increases, both C_R and VE may theoretically decrease simultaneously. A high VE is energy demanding in itself. According to Aaron et al (1992) the relative oxygen cost of breathing increases from rest up to approximately 10% at an intensity corresponding to VO_{2max}.

Franch et al (1998) found that VE decreased on average 11 $L \cdot min^{-1}$ following intense interval training among male recreational runners. Since individual decrements in VE correlated with improvements in C_R, Franch et al (1998) suggest that these improvements may account for 25-70% of the improved C_R. It may however, be argued the opposite; that the improvement in C_R leads to the lower VE. Saunders et al (2004) found no such relation between VE and C_R. In the study by Saunders et al (2004), elite distance runners improved their C_R by 3.3% after 20 days of simulated moderate altitude exposure, but with no detectable changes in VE

Muscle fiber type distribution

Both Coyle et al (1992) and Mogensen et al (2006) have reported a close relationship between muscle fibre type I and cycling efficiency. Coyle et al (1992) found that the percentage of type I fibres in m.vastus lateralis, correlated positively with cycling efficiency.

Contact time

Nummela et al. (2007) have shown a strong negative correlation between contact time (CT) and C_R among young runners. Further, in a study by Paavolainen et al. (1999), it is indicated that better performance in a 10 km time trial is related to higher pre-activation of the working muscles accompanied with shorter CTs during the run. However, both Williams and Cavanagh (1987) and Kyrolainen et al (2001) have found no correlation between CT and C_R.

Braking forces

Vertical and horizontal forces in running

Heglund and Taylor (1988) have found C_R among different sized animals to be determined primarily by the cost of activating muscles and of generating a unit of force for a unit of time. It is hypothesized by Taylor (1985) that RFD during locomotion, rather than the mechanical work that the muscles perform determines C_R. Farley and McMahon (1992) and Kram and Taylor (1990) have found C_R to be proportional to the weight supported, i.e. directly dependent on the vertical forces. However, by increasing and decreasing horizontal resistance during treadmill running, Chang and Kram (1999) have found horizontal forces to constitute more than 33% of the total metabolic cost of horizontal running. When running on track, Kyrolainen et al (2001) actually found that the average horizontal forces in the braking phase of the step could explain over 80% of C_R.

Elastic storage of energy

C_R is of course a reflection of the runner's technique, which in turn is greatly influenced by biomechanical and neuro-muscular recruitment patterns (McMahon 1984, Williams and Cavanagh 1987). It has been estimated that the achilles tendon can store 35% of the kinetic and potential energy in a step at moderate running speeds, and when the speed increases, elastic storage and reutilization of energy seems to become increasingly important (Ker et al. 1987).

Muscle – tendon stiffness

According to Alexander (1991), one of the most important roles of the muscle is to modulate tendon stiffness to enhance exploitation of elastic energy. A tight muscle-tendon system and consequently a high degree of stiffness may thus be advantageous regarding C_R, as shown in kangaroos by Dawson and Taylor (1973) and in humans after plyometric training (Spurrs et al 2003). This is supported by the findings from Jones (2002) and Craib et al. (1996) that runners who were the least flexible in the lower limbs also had the best C_R. Yoon et al (2007) have found a negative correlation between ankle joint torque at midpoint and CT in rebound jumps. They also found the ankle joint torque to correlate positively with ankle joint stiffness. Arampatzis et al. (2006) investigated the influence of muscle-tendon unit's mechanical and morphological properties on C_R among runners at three different levels of C_R. They found that the patellar tendon among the more economical runners was more compliant at low force levels, and that the triceps surae had higher contractile strength, with greater tendon stiffness. However, Lichtwark and Wilson (2007) have demonstrated a model predicting an optimal degree of muscle-tendon stiffness, suggesting that optimal muscle-tendon stiffness may be gait or task dependent and that the highest degree of stiffness thus does not necessarily lead to better muscle efficiency. Also, Kerdok et al. (2002) have shown changes in both muscle-tendon stiffness and C_R when manipulating the stiffness of running surface. Kerdok et al. (2002) are thus indicating that human runners adjust the level of muscle tendon stiffness towards the most optimal degree, to maintain consistent support mechanics on different surfaces.

Frequency of movement cycle

Step frequency in running and cadence in cycling

Testing different sized animals and scaling for body mass, Heglund and Taylor (1988) have shown that mass specific energetic cost of trotting and galloping is almost directly proportional to the stride frequency used to sustain a constant speed. According to Cavanagh and Williams (1982), most runners naturally choose a stride frequency which minimizes metabolic cost. In a study by Hunter and Smith (2007), the self optimized stride frequency among 16 experienced runners, which was both the self-selected one and the one expressing the best C_R, averaged 87 steps per minute. If most runners naturally choose a stride frequency which minimizes metabolic cost, there should not be a significant relationship between stride frequency and C_R. This is in line with Kyrolainen et al. (2001) who did not find significant correlations between stride frequency and C_R. In cycling, however, it is argued that the self selected cadence may be too high to optimize C_C (Chavarren and Calbet 1999, Foss and Hallen 2004). According to Lucia et al (2001), the preferred cadence among professional cyclists during competitions range from approximately 90 RPM to approximately 105 RPM in relatively flat courses. In contrast, it is reported that optimal cadence with regard to C_C is significantly lower than this, but increasing with increasing workload. Chavarren and Calbet (1999) have found the most economic cadence to be 60 RPM at several different work intensities ranging from 54% to 93% of MAP among competitive road cyclists. Foss and Hallen (2004) found the most economical cadence to be 60 RPM at 50 W and 80 RPM at 275 and 350 W among road cyclists at a national level. Why professional cyclists choose higher cadence than the most economic ones is an open question. Previous laboratory studies measuring C_C had prior to the study by Foss and Hallen (2004) been carried out during short time (3-8 min) submaximal or maximal work stages. Foss and Hallen thus hypotised that elite cyclists would perform best at their most efficient cadence during prolonged time trial cycling (approximately 30 min). They found that the time results at freely chosen cadence (mean 90 RPM) were similar to those attained at the most efficient cadence (80 RPM). Marsh and Martin (1997) have compared highly trained cyclists and runners and less-trained non-cyclists regarding power output on preferred and most economical cycling cadences. They concluded that cycling experience and minimization of aerobic demand were not critical determinants of preferred cadence. This finding was supported by the results from Hansen and Ohnstad (2008), that freely chosen cadence was unaffected by increased loading on the cardiopulmonary system and was steady and individual over a 12 weeks period. Hansen and Ohnstad (2008) concluded that freely chosen cadence is primarily a robust innate voluntary motor rhythm, minimally affected by internal and external conditions.

Leg swing in running and cycling

A rather controversial aspect concerning C_R is that of the metabolic cost of leg swing. Modica and Kram (2005) have shown that the cost of initiating and propagating leg swing comprises approximately 20% of net C_R, by using an external swing assist. In cycling, measures of unloaded cycling made by Tokui and Hirakoba (2007) have shown an internal power output ranging from approximately 3 W (at 40 RPM) to approximately 90 W (at 120 RPM). The C_C of unloaded cycling in this study ranged from approximately 0.6 $L \cdot min^{-1}$ (at 40 RPM) to 1.6 $L \cdot min^{-1}$ (at 120 RPM). They also found cycling efficiency to be best at a cadence of 80 RPM, with a marked reduction of efficiency (19%) from 80 to 120 RPM. They speculate that the reduced efficiency at 120 RPM is due to higher levels of internal power output accompanying the higher cadence. Based on the studies by Modica and Kram (2005) and Tokui and Hirakoba (2007), it seems that the movements of limbs alone may contribute to a significant part of the net metabolic cost of running or cycling, and that the higher the frequency, the higher the cost. Is it the limb-moving frequency per se (i.e. activation-relaxation rate) that increases the cost of movement, or is it the muscle shortening velocity that naturally accompanies the frequencies? This problem has been addressed in bicycling by McDaniel et al (2002), whose results suggest that it is the muscle-shortening velocity and not the activation-relaxation rate that significantly contributes to the net metabolic cost.

Other factors interacting as determinants for running and cycling economy

Anthropometric factors

Anderson (1996) lists a number of anthropometric factors that could have a positive effect on C_R. These includes lower than average height for men, low percentage of body fat, leg morphology which distributes mass closer to the hip joint, and narrow pelvis. An inverse correlation between calf circumference and C_R is shown by Lucia et al (2006). Williams and Cavanagh (1987) have found elite female runners to have narrower pelvis than a female student population of the same age. Steudel-Numbers et al. (2007) have shown an inverse correlation between relative leg length and C_R, and Bunc (2000) reports of worse C_R expressed as $J{\cdot}Kg^{-1}{\cdot}m^{-1}$ with higher percentage body fat among non-trained females.
Little is reported regarding anthropometric factors and C_C. Cyclists at an international level seems to be more heterogeneous in body dimensions than long distance runners at the same performance level. According to Mujika and Padilla (2001), male professional road cyclists represent variable anthropometric values. Although Faria (1992), count air resistance as the greatest retarding force affecting cycling, and thus state that the aerodynamics should be a major factor influencing C_C, anthropometric factors seem to be much less important regarding air resistance than are posture and equipment.

Gender

Helgerud (1994) has reported a better C_R at velocities equal to LT among female intermediate national elite marathon runners than in their performance-matched male counterparts when expressing C_R per kg body weight raised to the power of 0.75 and metre. This is seemingly not in line with results from Daniels and Daniels (1992) who reported male runners to be 6-7% more economical than women of equal VO_{2max} at set velocities, or with the results from Bunc and Heller (1989), who found no significant differences in C_R between the sexes. However, the results from Daniels and Daniels (1992) and Bunc and Heller (1989) are expressed per kg body mass. As females in general differ from the general male in a lower total body mass and a higher percentage of fat (Marieb and Hoehn 2007), it is important to scale for body mass when comparing genders. In cycling, Yasuda et al (2008) reports no gender-specific differences in mechanical efficiency during leg-cycling at intensity relative to ventilatory threshold. But according to Weber and Schneider (2000) there may be a gender specific difference in aerobic and anaerobic efficiency, as they have shown untrained women to have a lower maximal accumulated oxygen deficit than untrained men after all out cycling, even when corrected for active muscle mass. To our knowledge, gender specific difference has not been reported in cycling economy.

Variations in Cost of running, Cost of cycling and efficiency

Inter individual variability in C_R is reported by di Prampero et al. (1986) to be 8%, if C_R is expressed per kg body mass. This is in accordance with results from Margaria et al (1963), who found experienced runners to spend 5-7% less energy (measured as kcal per kg body weight per hour) compared to nonathletes when running at given velocities. When the heterogeneity of a tested variable within a group of subjects increases, so does the inter-individual variability concerning this variable. Thus, Morgan et al (1995) found a within-group variation of 20% in C_R in four different groups of runners, showing that the elite runners had a better C_R than the subelite runners, who in turn had a better C_R than the good runners, and that the good runners had better C_R than the untrained subjects. Although there is reported relatively large inter individual variability among runners regarding C_R, this variability may not be equally apparent in cycling. To compare the variability in running and cycling is somewhat difficult because of the practice of using economy measurements in running and efficiency measurements in cycling. Moseley et al (2004) report no differences in C_C between world-class and recreational cyclists. On the other hand, gross mechanical efficiency has been found to be 1.4% higher in trained cyclists than in untrained cyclists by Hopker et al (2007). This is seemingly a smaller difference than what has been shown in C_R between trained and untrained runners (Margaria et al 1963, Morgan et al 1995). Since the difference in C_C is expressed as a per cent of a per cent (the latter being approximately 22%), the 1.4% difference reported by Hopker et al (2007) is in reality approximately $1.4 \cdot (100/22)$ % = 6.4%, and thus in line with what is reported in running. As C does not increase in the same proportion as body weight, part of the variation in C_R in published experiments will be due to weight differences. Allometric scaling seems to reveal smaller inter-individual differences in C_R. Helgerud (1994) typically show SD's of approximately 5% between marathon runners when expressing C_R as oxygen cost per kg bodyweight raised to the power of 0.75 and metre. The variation in C_R between soccer players are also shown to be relatively small. Hoff et al. (2005) testing 36 professional players showed CV to be less than 5%. This is in line with the results from Helgerud et al. (2001), Helgerud et al. (2003) and Hoff and Helgerud (2003)

Training induced changes in Cost of running and Cost of cycling

Adaptations to endurance training

In a controlled intervention study by Helgerud et al. (2001), an improvement of 6.7% in C_R among junior soccer players after eight weeks of interval running training, is reported. A 3.7% improvement is shown from a similar intervention in a soccer Champions League team where the training mode was treadmill running (Helgerud et al. 2003). Both interventions were followed by an improvement in VO_{2max} of approximately 10%. The C_R improvement is in accordance with results from Billat et al. (2002). They found improved C_R expressed as time to exhaustion at running velocities representing 90% and 95% VO_{2max} after four weeks of interval training at MAS. This may indicate that high intensity interval training may increase race specific C_R among athletes competing at velocities representing approximately the runners VO_{2max} (3000m and 5000m).

As C_R is an expression of running technique it should be an obvious consequence from increasing the volume of running that running technique is improved. This is elegantly shown in McMillan et al. (2005) where soccer players used the same intervention with high intensity aerobic interval training as used by Helgerud et al (2001, 2003), this time only with the difference that the endurance training intervention was running with the soccer ball in a track including changes in direction and pace. The results from this intervention showed the same 10% improvement in VO_{2max}, but no change in running economy measured on the treadmill. For inexperienced runners an improvement in C_R from increased amounts of running or walking should be expected. The same should thus apply to cycling efficiency. This is shown in an intervention study by Hintzy et al (2005) where nine previously sedentary women improved gross efficiency by 11% after 6 weeks of low intensity cycling endurance training. Competitive runners would probably not improve C_R much from increased volume of running, as it already constitutes almost all of their training. However Scrimgeour et al. (1986) found C_R to correlate highly with weekly running distance among marathon and ultra marathon runners. At 13 km $\cdot$ h^{-1} the athletes running more than 100 km per week exhibited more than 15% better C_R than those running less than 60 km per week. Of course as the study by Scrimgeour et al (1986) is not an intervention, one can not conclude that it is the higher amount of km covered per week that leads to the better C_R. It may be that the better C_R leads to the higher weekly training distance. A person with 15% lower cost of running will spend 15% less energy by covering a given distance, and should thus be able to run longer.

Adaptations to strength training

All strength training performed over an extended period of time will lead to some hypertrophy (Kraemer and Ratamess 2004). The amount of hypertrophy will depend on several factors. Two important determining factors seem to be type of strength training and muscle fibre type distribution (Kraemer and Ratamess 2004). Traditional hypertrophy training consisting of 5 - 12 repetitions maximum involves contractile protein damage and connective tissue damage as well as metabolic stress. Studies indicate greatest hypertrophic response when the maximum number of repetitions per set exceeds 5 but are below 12 (Atha 1981, Tesch 1988, Campos 2002). The hypertrophic response is most likely due to an increase in myofibril cross-sectional area (Goldspink 1992).

Neural adaptations to strength training includes both selective activation of motor units, increased recruitments of motor units, increase of motor unit discharge rate, motor unit synchronization and co-contraction regulation of antagonists (Behm 1995). These neural adaptations have in common an increased ability of activation and regulation of motor unit signals as a result of external and to some extent internal demands (Kraemer and Ratamess 2004, Gandevia 2001). Based on the classic force-velocity curve of Hill (1938), it has been debated whether or not neural adaptations are subject to velocity specific strength training. While several authors (Coyle et al 1981, Kanehisa and Miyashita 1983, Kaneko et al 1983) have reported high velocity strength training to increase high velocity strength more than low velocity training, Behm and Sale (1993) have demonstrated that *intent* of high velocity in strength training produces almost the same high velocity strength response. As discussed in Hoff (2001), the recruitment pattern, rather than the actual movement velocity seem to be the crucial factor for the neural adaptations associated with strength training. This is also elegantly shown in the study by Hoff and Helgerud (2003). MST with high loads and focus on maximal mobilization in the concentric phase in a group of soccer players showed an increase in RFD of 52.3 %. Strength training has also been reported to increase muscle – tendon stiffness (Kerdok et al. 2002), and tendon cross-sectional area (Kongsgaard et al. 2005). Hypertrophy leading to a significant increase in muscle physiological cross-sectional area will cause an increase in total body weight (Kraemer and Ratamess 2004). This weight gain may prove negative on an athletes running performance, since the athlete has to transport and support his own body weight while running. Also in cycling weight gain may prove negative on performance, at least when climbing hills. When MST is performed with high loads, few repetitions and with focus of maximal concentric mobilization, improvements in maximal strength have been reported without any changes in body weight (Hoff et al., 1999, Hoff et al., 2002, Østerås et al., 2002, Hoff and Helgerud 2003, Hoff et al. 2005, McMillan et al. 2005).

MST performed without concurrent endurance training has previously been reported to impair aerobic endurance performance. According to Tanaka & Swensen (1998), training of MST without concurrent endurance training will reduce relative mitochondrial density, capillary density, oxidative enzyme activity, and intramuscular fatty acid storage. Gettman & Pollock (1981) found that MST performed over eight to nine weeks resulted in a 0.5 to 9.0% decrease in VO_{2max} among their subjects. It is likely that the reduced densities are only relative, due to muscular hypertrophy from MST. The reduced performance could also by large be due to reduced volume of endurance training. On the other hand, intense endurance training without concurrent MST seems to impair the capacity to perform maximal power output. Dudley and Fleck (1987) have shown reduced vertical jump height after an increased amount of endurance training, and also increased vertical jump height when the amount of endurance training is reduced. Performed as a minor part of the total training volume, and when combined with endurance training, MST does not seem to impair the development of VO_{2max}. When comparing three different training groups, one training only MST, one only endurance training, and one a combination of the former two, Dudley & Fleck (1987), found no significant differences in VO_{2max} improvements between the endurance group and the combination group. This is in accordance with results from McCarthy et al. (1995), who performed a similar study. Several studies have reported improved work economy after MST as a supplement to endurance training, especially when employing strength training designed to enhance strength through neuromuscular adaptations rather than hypertrophy (Hoff and Almåsbakk 1995, Hoff et al. 2002). C at a standardised workload in double poling cross-country skiing improved by 10 - 20% after MST using a modified pull-down apparatus in three separate experiments (Hoff et al., 1999, Hoff et al., 2002, Østerås et al., 2002). Hoff et al. (1999) points at the relative reduction in force and high improvement in rate of force development and thus reduced contraction time as a determining factor for improved circulation. Østerås et al. (2002) conclude that the improved exercise economy can be partly explained by a specific change in the force-velocity relationship and the mechanical power output. Regarding running economy Hoff and Helgerud (2003) have demonstrated an improvement in C_R among soccer players by 4.7%, expressed as $ml \cdot kg^{-0.75} \cdot m^{-1}$, after eight weeks of MST. McMillan et al. (2005) using the same intervention have found similar improvements. A strength training intervention using the same intervention with experienced distance runners competing in orienteering and cross-country skiing was carried out by Hoff et al. (2005), and have shown a 5% improvement in C_R when running at 10% inclination and an 8% improvement in C_R when running at 20% inclination, indicating that relative load is an important factor for running economy. Paavolainen et al. (1999) also claim that strength training changes running economy, but both increased body weight, multiple interventions and increased running that also improves VO_{2max} makes it problematic to detect the cause and relationship. In a study by Hansen et al (2007), 14 non-cyclists performed strength training 4 days per week for 12 weeks. They report a 20% improvement in 1 RM squats, accompanied by a decrease in cadence of 8 RPM at a cycling intensity of 37% of VO_{2max}, and a 3% improvement in C_C at the same intensity. Marcinik et al (1991) reported improvements in cycling in LT brake power and time to exhaustion at 75% of MAP after 12 weeks of strength training, indicating an improvement in C_C.

MST as a supplement to endurance training is shown to improve C_R. However, no studies have shown that the subjects with the highest 1RM results have the best C_R. The question thus arise: what are the mechanisms behind the shown improvements in C_R? Theoretically, both an increase in RFD (Hoff and Helgerud, 2003), a more optimal activation of motoneurons and muscle fibers (Gandevia 2001), an optimizing of muscle-tendon stiffness (Kerdok et al, 2002) and pre-activation of working muscles (Paavolainen et al, 1999), a shorter contact time (CT) (Nummela et al. 2007) as a result of MST may improve C_R, possibly together with other factors. Central changes affecting muscle activation may occur both at a supraspinal as well as at a spinal level (Gandevia 2001). Further investigations regarding these variables are needed to gain a more thorough understanding of the effects of MST on C_R.

Rationale and aims of the experiments

Long distance running and cycling are activities where energy released aerobically is predominantly determining the performance (Åstrand and Rodal 1986; Medbø and Tabata 1989). Running or cycling economy is considered one of the three major factors accounting for inter-individual variance in aerobic endurance performance (Pate and Kriska 1984). The main aim of this thesis is to gain further knowledge about long distance running and cycling economy measured as the oxygen cost of running and cycling (C_R and C_C) by investigating:

- Determining factors for C_R (study IV).
- The reliability of an incremental test protocol for calculating C_R at different velocities and intensity levels (study II).
- The intensity levels to which C_R is reliably calculated (study II).
- The influence of lactic acid concentrations on C_R (study I).
- The effect of maximal strength training on C_R and C_C (studies III and V)

And further, to calculate from the results in the five studies:

- The relative importance of C_R and C_C on aerobic endurance performance
- Possible gender differences in C_R

Paper I:

Lactic acid accumulation is associated with development of muscle fatigue during exercise (Fitts 1994), and is thus considered to be negatively correlated to endurance performance (Åstrand and Rodahl 1986, Pilegaard et al 1999). As C_R deterioration seems to be related both to an increasing intensity and an increasing duration (Sproule 1998), the main aim of study I is to investigate if increased lactate levels influence C_R during endurance running.

Paper II:

C_R is often measured as the oxygen cost per meter of running. Helgerud (1994) and Slavin et al (1993) reports no change in C_R with increasing running velocities, whereas Hoff and Helgerud (2003) and Harris et al. (2003) reports slightly impaired C_R with increasing running velocities. If C_R is to deteriorate with increasing intensity and $[La^-]_b$, there should be an upper limit regarding intensity up to which C_R is a reliable measure of running economy. The main aim of study II is to find this limit, and further to evaluate the reliability of an incremental protocol for assessing C_R. Since Helgerud (1994) has shown that female marathon runners have better C_R than their performance matched male counterparts, a secondary aim in study II is to investigate potential differences between genders in C_R.

Paper III:

In both cross-country skiing (Hoff et al., 1999, Hoff et al., 2002, Østerås et al., 2002), soccer, (Hoff and Helgerud 2003, McMillan et al. 2005), and uphill running (Hoff et al. 2005), MST has been shown to improve C_R. Also in distance running, C_R is improved as a result of MST (Millet et al. 2002, Paavolainen et al. 1999, Johnston et al. 1997). But neither Millet et al. (2002), Johnston et al. (1997) nor Paavolainen et al. (1999) have scaled for body weight when reporting the C_R results. In these three studies several different strength training or ballistic exercises were used, which makes it difficult to identify the cause of improvements. In study III the main aim is to investigate if MST improves C_R for well trained runners when running at 1.5% inclinations. A secondary aim in study III is to investigate if MST has an effect on $_t$MAS.

Paper IV:

Conley and Krahenbuhl (1980) and Helgerud (1994) have shown inter-individual variations in C_R at a standard running velocity. The causes of this variability are not well understood, but it seems likely that anatomical traits, mechanical skill, neuromuscular skill and storage of elastic energy are important factors (Pate and Kriska 1984). Also, MST interventions have improved C_R (Hoff and Helgerud 2003, McMillan et al. 2005, Hoff et al. 2005, Millet et al. 2002, Paavolainen et al. 1999, Johnston et al. 1997). The purpose of study IV is to identify possible causes of inter-individual variations in C_R, and also to possibly identify some of the factors involved when MST affects C_R. Thus, the aim of this study is to detect possible relationships between anthropometrical measures, vertical and horizontal ground reaction forces, stride frequency, maximal strength in lower extremities, CT and C_R among elite endurance athletes.

Paper V:

No studies have shown correlations between maximal strength and C_C, but several studies have shown strong correlations between *training induced improvements* in maximal strength and work economy (C). In cross country skiing (Hoff et al., 1999, Hoff et al., 2002, Østerås et al., 2002), soccer, (Hoff and Helgerud 2003, McMillan et al. 2005), and uphill running (Hoff et al. 2005), MST has been shown to improve C in only eight weeks. Likewise, Millet et al. (2002), Paavolainen et al. (1999) Johnston et al. (1997) have found improvements in C_R after MST interventions. Loveless et al (2005) have shown that maximal strength training improves C_C in previously untrained subjects. The aim of this study is thus to assess to what extent maximal strength training with emphasis on neural adaptations, as a supplement to endurance training, affect C_C and work efficiency (WE) among competitive road cyclists. A secondary aim in study v is to investigate if MST has an effect on $_t$MAP.

Methods

Subjects

Subject characteristics are presented in table 1.

Table 1 Subject characteristics (N = 63)

	Study I	Study II	Study III	Study IV	Study V
N (Interv. + control)	7 (7+0)	15 (15+0)	17 (8+9)	11 (11+0)	13 (8+5)
Level	Elite	Moderately to well trained	Well trained	Elite	Well trained
Age in Years (Mean ± SD)	23.0± 3.0	30.0 ± 9.2	28.6±10.1	21.4±3.9	32.9±9.0
Gender (Males + Females)	7+0	9+6	9+8	11+0	10+3
Sport (N)	Orienteering (4) CC skiing (3)	Dist. running (8) CC-country skiing (4) Triathlon (3)	Dist. running (17)	Dist. running (2) CC skiing (5) Orienteering (2) Biathlon (2)	Road Cycling (13)

N, number of subjects. Interv, intervention group. Control, control group. SD, standard deviation. CC skiing, cross – country skiing. Dist. Running, distance running.

Testing procedures

In studies II, III and V ergo-spiro-metrical data were collected using the metabolic test system, Sensor Medics Vmax Spectra (Sensor Medics 229, Yorba Linda, California, USA). Lactate measurements were performed using an Arcray Lactate Pro LT-1710 analyzer, venous whole blood (Arcray Inc. Kyoto, Japan) and heart rates were measured using Polar s610 heart rate monitors (Kempele, Finland). The treadmill used in studies II and III was a Woodway PPS 55sport (Waukesha, Germany), and the ergometer cycle used in study V was a Lode Corival 906900 (Lode, Groningen, Netherlands) modified at Department of Sport and Outdoor Life Studies, Telemark University College (Bø, Norway) to fit competitive cyclists.

Figure 1 Subject on the ergometer cycle, connected to the metabolic test system

Picture from study V. The subject has approved the use of the picture in this thesis. The ergometer cycle is a modified Lode Corival 906900. The metabolic test system is a Sensor Medics Vmax Spectra.

In studies I and IV ergo-spiro-metrical data were collected using the portable metabolic test system Cortex Metamax II (Cortex, Leipzig, Germany). Heart rate was measured using a Polar S410, (Kempele, Finland). The treadmill used in these two studies was a Technogym RunRace (Gambettola, Italy). Lactate measurements in study I were performed using an YSI 1500 Sports Lactate analyzer (whole blood) (Yellow Springs Instruments CO, USA).

The RFD data in study III and V were collected using the Muscle Lab system (Ergo test Technology, Langesund, Norway). Body fat was measured in study IV with a Lange skin calliper, (Beta Technology, Santa Cruz, CA, USA). Measurements of vertical forces in study IV were made by Pedar-X contact soles from (Novel, Munich, Germany). To measure horizontal forces in this study, the front of the treadmill was placed upon a force platform, Bioware (Kistler, Switzerland), with the rear end of the mill hanging freely in a special device designed for this purpose at the Department of Circulation and Imaging, Faculty of Medicine, Norwegian University of Science and Technology. CT and stride frequency were also measured using this system.

Assessment of LT – In studies I, II and III, the subjects started at an individual warm-up velocity corresponding to approximately 60% VO_{2max}, which was maintained for either 5 or 10 minutes. Every five minutes from there on, the speed was increased by 1.5 $km \cdot h^{-1}$. The protocol terminated at more than 1.5 $km \cdot h^{-1}$ above the subjects' lactate threshold (LT). LT was defined as the warm up $[La^-]_b$ value (i.e. measured after the lowest velocity) + 1.5

mmol·L^{-1}. This is the protocol proposed by Helgerud et al. (1994). In study V, the subjects started at an individual warm-up intensity corresponding to approximately 40-50% VO_{2max}, that is between 100 and 200W, which was maintained for either 5 or 10 minutes. Each of two subsequent five minute steps from there on, the brake power was increased by either 25 or 50W, after subjective evaluation. Every five minutes after the first two steps, the brake power was increased by 10 to 25W, until the protocol terminated at more than 25W above the subjects' LT, defined as the warm up $[La^-]_b$ value (i.e. measured after the lowest velocity) + 1.5 mmol·L^{-1}, as for running. Note that for the studies where Arcray Lactate Pro LT-1710 analyzer was used (studies II, III and V), 1.5 mmol·L^{-1} equals 2.3 mmol·L^{-1} as the Lactate Pro measures 40% higher values than the YSI.

Assessment of VO_{2max} – VO_{2max} was tested in all studies, by use of an incremental protocol. In studies I to IV, all subjects were running at 5 % inclination throughout the test. In study V, the subjects used the same ergometer cycle as previously described, and cycled at a self-selected cadence. In all five studies, the subjects started at a velocity or intensity representing approximately their individual LT intensity level. Every 30 or 60 seconds, the speed or power was increased by 0.5 or 1.0 km·h^{-1} or by 10 or 25W, based on the subjective evaluation of the test leader. The test terminated at voluntary exhaustion by the subjects. HR ($\geq$ 98 % HR_{max}), R ($\geq$ 1.05) and $[La^-]_b$ ($\geq$ 8.0 mmol·L^{-1}) values, as well as a possible flattening of the VO_2 curve, was used to evaluate if VO_{2max} was obtained. Measurements of VO_2 values were made every 10 seconds when the Metamax II was used (studies I and IV) and every 20 seconds when the Vmax Spectra (studies II, III and V) was used. VO_{2max} was computed as the average of the three highest (Metamax II) or the two highest (Vmax Spectra) VO_2 values at the end of the test.

Assessment of C_R, C_C, *MAS and MAP* – C_R or C_C at set velocities were calculated as the average of four (three with the Vmax Spectra) VO_2 values between 3.30 min and 4.30 min, and divided by running velocity or brake power at each 5 min work in study II, III and V. In study I, C_R at set velocities was calculated as the average of four VO_2 values between 4.00 min and 4.30 min, and divided by running velocity. At relative intensities such as 70% VO_{2max} (study II, III and V); linear regressions between velocity or brake power and VO_2 for each subject provided both the VO_2 and the velocity or brake power values needed. By use of the linear regression equation, velocity or brake power at a certain per cent of VO_{2max} could be calculated. An example is presented in figure 2. MAS was calculated on the basis of the submaximal measurements and VO_{2max}, and was defined as the velocity point where the horizontal line representing VO_{2max} meets the extrapolated linear regression representing the sub maximal VO_2 measured in the LT assessment. MAP was calculated using the same method, only using brake power (W) instead of velocity. Further, in study I, the subjects were also tested for C_R at LT velocity with initial $[La^-]_b$ of either 3 $mmol·L^{-1}$ or 5 $mmol·L^{-1}$. After a VO_{2max} test, four of the subjects in study I were randomly selected to run at a lower intensity in order to decrease $[La^-]_b$ values to target 3 $mmol·L^{-1}$. When reaching this target, they ran at LT velocity for 5 minutes with continuous registration of VO_2 and HR. Thereafter, the speed was increased in order to increase $[La^-]_b$ values to target 5 $mmol·L^{-1}$. When reaching this target, they ran at LT velocity for 5 minutes with continuous registration of VO_2 and HR. The same procedure was repeated for the three remaining subjects, but in the opposite order, i.e. starting with a $[La^-]_b$ value of 5 $mmol·L^{-1}$. C_R was calculated from VO_2 measures and running velocity as described above.

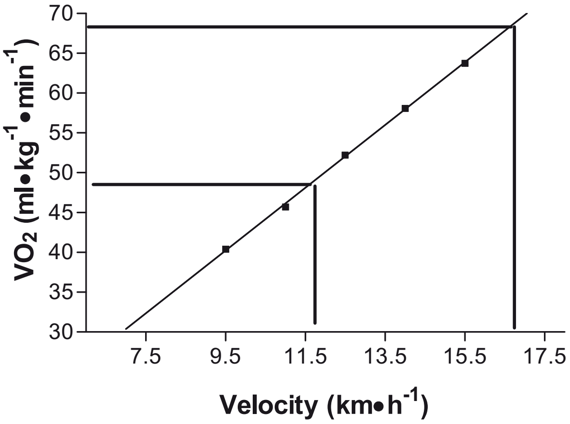


Figure 2 Linear regression between running velocity and VO_2.

The linear regression equation in figure 2 is: **$y = 3.9393x + 2.7963$. $R = 0.9997$.** VO_{2max} for this runner is 69.2 $ml·kg-^1·min^{-1}$. 70 % VO_{2max} for this runner is 48.4 $ml·kg-^1·min^{-1}$. From the equation, the corresponding velocity is 11.7 $km·h^{-1}$, which equals 195 $m·min^{-1}$. C_R expressed as $ml·kg-^1·m^{-1}$ is thus 0.284 $ml·kg^{-1}·m^{-1}$. MAS is the velocity point where the horizontal line representing VO_{2max} meets the extrapolated linear regression representing the sub maximal VO_2 measurements. Here represented by a velocity of 16.9 $km·h^{-1}$.

Assessment of Maximal strength (1RM) and RFD – Both in studies III, IV and V, half-squat was used as the exercise in the assessment of 1RM and RFD. Only 1RM was tested in study IV. Free weights were used in study III, whereas a leg-press machine was used in study IV and a Smith-machine was used in study V. Each lift was performed with a controlled slow eccentric phase, a complete stop of movement for approximately one second in the lowest position, followed by a maximal mobilization of force in the concentric phase ensuring a follow up by use of plantar flexors. In study III and V, the measurements of lifting time, distance of work and thus RFD were performed using the Muscle Lab system (Ergo test Technology, Langesund, Norway). This test started using 10 reps at a weight load assumed to be approximately 50% of 1RM. After 3 minutes of rest: 5 reps at app 60% 1RM. After another 3 minutes rest: 3 reps at app 70% 1RM, then 3 minutes of rest before 1 rep at app 80% 1RM. From there on: 1 rep at a weight load increased by 2.5 kg – 5 kg from the subsequent lift, followed by 5 minutes of resting, until reaching 1RM. The time spent in each lift, as well as the work distance was measured. As the external force of each lift is represented by the weight of the lifted bars, the rate of force development (RFD) can be calculated and expressed as $N \cdot m \cdot s^{-1}$ or watt (W). In study IV, The test started with one repetition at approximately 70% of predicted one repetition maximum (1RM). The loads were gradually increased (approximately a total of 10 lifts) until the athlete could no longer manage to overcome the load.

Assessment of peak average horizontal and vertical forces during running – In study IV, after five minutes warm up, the subjects ran for one minute at 15 $km \cdot h^{-1}$ on a level treadmill. They were wearing contact soles, and the treadmill was adjusted as described previously. Average peak force (APF) for both vertical and horizontal forces was the average of peaks over a 10 seconds period. CT and stride frequency were calculated from the force measurements, running velocity and time. An example of one step force characteristics is presented in figure 3.

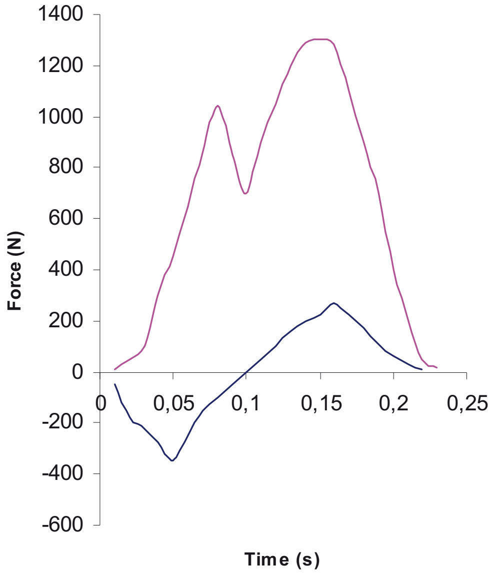


Figure 3 Force characteristics in one step from one runner

Figure from study IV. This is an example of the force characteristics in a single step by one of the runners. Force is displayed on the vertical axis, and time is displayed on the horizontal axis. N, Newton. S, seconds. The axis on top represents vertical forces, while the axis at the bottom represents horizontal forces.

Training procedures

Strength training intervention – In studies III and V, the intervention group completed an 8 week intervention whereas the controls completed an 8 week normal training period. During these weeks, both the intervention group and the control group were thus performing their running or cycling training as normal. To control the training, each subject had to report weekly the exact amount of time spent in the different training intensity zones 60-85%, 85-90% and 90-95% of HR_{max}. In addition to their normal endurance training, the intervention group completed a MST session consisting of 4 sets of 4RM half-squats, divided by 3 minutes of rest between each, three days a week. Each lift was performed with a controlled slow eccentric phase, a complete stop of movement for approximately one second in the lowest position, followed by a maximal mobilization of force in the concentric phase ensuring a follow up by use of plantar flexors. Every time a subject managed to do 5 repetitions during a set, 2.5 kg were added for the next set. The subjects used free weights in study III, and a Smith-machine in study V. Guidance and instructions were given all participants during the training period, and training logs for the MST were made by all participants in the intervention groups.

Statistical analysis

All statistical analyses were performed using the software program SPSS, version 13.0 (Statistical Package for Social Science, Chicago, USA). In all cases, $p<0.05$ was taken as the level of significance in two-tailed tests. Descriptive statistical analysis was made to display means and standard deviations (SD). To compare means, paired T-tests and independent samples T-tests were used in studies I, II and III. Non-parametric statistics (Wilcoxon`s and Man Whitney) were used in paper V. In paper II, changes in C_R across different intensity and velocity levels were analyzed by General Linear Model. The data were tested for normal distributions using Quantile-Quantile (QQ) plots. Correlations were calculated by the Pearson correlation test.

General summary of experiments

Paper I: High blood lactate levels deteriorates running economy in elite endurance athletes

7 elite endurance athletes (4 orienteers and 3 cross country skiers) participated in this study. The athletes were first tested for C_R at 10 km·h^{-1} and for LT on a treadmill with 1.5% inclinations, and for VO_{2max} at 5.0% inclinations. They were then tested for C_R at their LT velocity with a pre $[La^-]_b$ of either 3 mmol·L^{-1} or 5 mmol·L^{-1}, followed by a crossover of the lactate levels. The study shows that C_R deteriorated (5.5%) when pre $[La^-]_b$ was raised from 3 mmol·L^{-1} to 5 mmol·L^{-1}. $[La^-]_b$ was found to decrease (31.2%) during the run at LT velocity with a pre $[La^-]_b$ of 5 mmol·L^{-1}. This is a strong indication of an underestimation of LT velocity. Also during the running session at LT velocity with a pre $[La^-]_b$ of 3 mmol·L^{-1}, $[La^-]_b$ was found to decrease significantly (21.8%). In conclusion, increased lactate levels are accompanied by deteriorating running economy.

Paper II: Are there differences in running economy at different velocities?

15 moderately to well trained (9 male and 6 female) endurance athletes participated in this study. C_R, heart rate and blood lactate was measured during 5 minutes runs at velocities ranging from 8.0 to 17 km·h^{-1}, representing intensities ranging from 60% to 90% of VO_{2max} on two different days. The athletes were also tested for LT, VO_{2max}, MAS and $_t$MAS. There was found no differences in C_R between the different relative velocities or the different set velocities for the male or the female athletes. All athletes reached their VO_{2max} while running to exhaustion at MAS. The females showed significantly lower VO_{2max} (25.3%) but significantly better running economy (9.8%) than the males. In conclusion, running economy measured as oxygen cost of running is reliably calculated up to running intensities representing 90% of VO_{2max}. An incremental protocol for measuring VO_2 at different velocities does not affect the reliability of these measurements.

Paper III: Maximal strength training improves running economy in distance runners.

17 well trained (9 male and 8 female) runners were randomly assigned into either an intervention or a control group. The intervention group (4 males and 4 females) performed half-squats, 4 sets of 4RM, three times per week for 8 weeks, in addition to their regular endurance training. The control group continued their normal endurance training during the same period. The intervention manifested significant improvements in 1RM (33.2%), RFD

(26.0%), C_R (5.0%), and time to exhaustion at pre test MAS (21.3%). No changes were found in VO_{2max} or BW. The control group exhibited no changes from pre to post values in any of the parameters. In conclusion, maximal strength training for 8 weeks improved C_R and increased $_t$MAS among well trained long distance runners, without change in VO_{2max} or BW.

Paper IV: Running stride peak forces inversely determines running economy in elite runners
11 elite endurance athletes participated in this study. 1RM in half-squat leg press, VO_{2max}, C_R, vertical and horizontal external forces while running, BW, height, leg length, calf circumference, hip width, and body fat percentage was examined. 3 km best time results attained during the last season were collected. None of the force measures correlated significantly alone with either 3000m performance time or C_R. However, when put together, as the sum of horizontal and vertical eccentric and concentric peak forces (APFtotal) a significant inverse correlation ($p<0.05$) was found both with 3000m performance (R=0.71) and C_R (R=0.66). Moderate inverse correlations were found ($p<0.05$) between C_R and body height (R=0.61) and between C_R and body fat percentage (R=0.62).

Paper V: Strength training improves cycling economy.
16 competitive road cyclists (12 male and 4 female) were randomly assigned into either an intervention or a control group. 13 (10 male and 3 female) cyclists completed the study. The intervention group (7 males and 1 female) performed half-squats, 4 sets of 4RM, three times per week for 8 weeks, in addition to their regular endurance training. The controls should continue their regular endurance training during the same period. The intervention manifested significant improvements in 1RM (14.2%), RFD (16.7%), C_C (4.8%), WE (4.7%) and $_t$MAP (17.2%). No changes were found in VO_{2max}, BW or cadence. The control group improved WE by 1.4%, but there was a significant difference in improvements between the intervention and the control group. In conclusion, maximal strength training for 8 weeks improved C_C and WE and increased $_t$MAP among competitive road cyclists, without change in VO_{2max}, cadence or BW.

Discussion across the experiments

General discussion

Paper I demonstrated that C_R deteriorates with increased $[La^-]_b$. Previous studies have reported deterioration in C_R of 3-5% after intensive training (Collins et al 2000, Thomas et al 1995, Hunter and Smith 2007), but it is unclear whether or not these results are accompanied by increased levels of $[La^-]_b$. As in papers II, III and IV, inter-individual variability in C_R expressed as $ml \cdot kg^{-0.75} \cdot m^{-1}$ was found to be approximately 5-6%. Previously, Helgerud (1994) has found a variability of approximately 5% among marathon runners when expressing the C_R as VO_2 $ml \cdot kg^{-0.75} \cdot m^{-1}$. These values are also in agreement with those found among soccer players (Helgerud et al 2001, Helgerud et al 2003, Hoff and Helgerud 2003, Hoff et al., 2005). No significant difference in C_R when the subjects were running at 10 $km \cdot h^{-1}$ compared with LT velocity (paper I) was observed. This finding was supported in paper II, where no significant differences in C_R between the different relative velocities or the different set velocities were found for neither male nor female athletes, up to 90% of VO_{2max}. These results are in line with previous results from di Prampero et al. (1986) and Helgerud (1994), but not in agreement with the results from Daniels & Daniels (1992) who found worsened C_R when relative running intensity increased in the area between 70% and 100% VO_{2max}. Paper II also demonstrated a significantly better C_R (approximately 10%) and a significantly poorer VO_{2max} (approximately 25%) among the females than among the males. The two genders were not matched for performance. Study III also contained both male and female subjects. When combining C_R results from these two studies, there is still a significantly ($p<0.01$) better C_R among the female subjects (0.663 ± 0.039 $ml \cdot kg^{-0.75} \cdot m^{-1}$) than among the male subjects (0.724 ± 0.057 $ml \cdot kg^{-0.75} \cdot m^{-1}$). Since men and women were not matched for performance, we have no explanations as to why the women had better C_R than the men. However, the women had lower VO_{2max} ($ml \cdot kg^{-0.75} \cdot m^{-1}$) than the men, which was also the case in the study by Helgerud (1994). The incremental protocol evaluated in study II, was found not to affect the reliability of VO_2 measurements at different intensity levels in that study. The protocol was thus used in parts of study III and study V.

In paper II we also demonstrated that all the subjects reached their VO_{2max} when running to exhaustion at MAS. The protocol for assessing MAS was thus repeated in study III, and for MAP in study V. All subjects reached their VO_{2max} when running or cycling to exhaustion at

MAS or MAP. $_t$MAS was in paper III shown to increase significantly (21.3%) as a result of a better C_R (5.0%), due to eight weeks of MST. The better C_R after MST is in agreement with previous results by Hoff and Helgerud (2003), Millet et al. (2002), Paavolainen et al. (1999) and Johnston et al. (1997). This was supported in study V regarding cycling, expressing an improvement of 4.8% in C_C accompanied by an improvement of 17.2% in $_t$MAP. In cycling unlike running, vertical movement of the centre of mass is minimal, unless riding uphill. The braking forces are first and foremost represented by the resistance to the cyclist and bicycle moving forward, or by the artificial braking of the flywheel if riding an ergometer cycle, and transferred to the pedals. Consequently elastic storage of energy that plays an important role in running economy should logically not be as important in cycling. Our results may indicate that an improvement in muscle-tendon stiffness leading to an improvement in elastic recoil is not the main adaptation from MST in these two studies.

Based on the papers I, II and II, and previously published studies regarding C_R, we sought to find some determining factors for C_R in study IV. In paper IV, we demonstrated that APFtotal was found to be negative related to C_R and 3000m running performance. None of the force measures correlated, however, significantly alone with either performance or C_R. APFtotal gave a significant negative correlation ($p<0.05$) both with 3000m performance ($R=0.71$) and C_R ($R=0.66$). The only relationships observed between anthropometric variables and C_R were moderate inverse correlations between C_R and body height ($R=0.61$) and between C_R and body fat percentage ($R=0.62$). This is probably because the subjects participating in this study were relatively homogenous regarding anthropometric variables. As in studies III and V, there was no direct relationship between 1RM half-squat and C_R. No correlations between 1RM and CT or time to peak force in study IV were observed. In previous intervention studies as well as in study III and study V, MST improved C_R and C_C by approximately 5%. The finding in study IV thus supports Hoff and Helgerud (2003) and Østerås et al (2002) that neuromuscular rather than hypertrophic responses to the MST is the main source of the reported improvements in these interventions.

Cost of running and cycling

In the four studies concerning C_R in this thesis, we found inter-individual variations between 6.3% (study I) and 7.0% (study IV). If results from all studies are combined, mean C_R was 0.691 ± 0.042 $ml \cdot kg^{-0.75} \cdot min^{-1}$, with an inter-individual variation of 7.3%. The variation of means between the different studies was 5.4%. These results are in accordance with results from previous studies on running where body weight has been scaled ($kg^{0.75}$), like Helgerud et al. (2001), Helgerud et al (2003), Hoff and Helgerud (2003) and Hoff et al. (2005).

Table 2 Physical and physiological factors in paper I to V

Paper	I (n=7)	II (n= 15)	III (n=8)	IV (n=11)	V (n=8)
Type of study	Intervention (Incr. $[La^-]_b$)	Intervention (Incr. $Km \cdot h^{-1}$)	Intervention (8 weeks MST)	Descriptive	Intervention (8 weeks MST)
VO_{2max}					
$ml \cdot kg^{-1} \cdot min^{-1}$	80.7± 2.7	65.3± 7.0	61.4± 5.1	75.8± 6.2	63.4± 6.0
$ml \cdot kg^{-0.75} \cdot min^{-1}$	235.0± 8.8	190.0 ± 17.8	170.6 ± 15.3	220.2 ± 7.0	185.0 ± 15.4
$ml \cdot kg^{-0.67} \cdot min^{-1}$	331.0± 18.6	266.5± 23.7	237.5 ± 19.9	310.2 ± 15.3	259.7± 24.7
C_R					
$ml \cdot kg^{-0.75} \cdot m^{-1}$	0.704±0.044	0.725±0.040	0.679±0.036	0.652 ± 0.043	
C_C					
$ml \cdot kg^{-0.67} \cdot W^{-1}$					0.840± 0.065
C_R or C_C Change (%)	5.5 ± 0.4**	0.7 ± 0.8	-5.0 ± 0.9*		-4.8 ± 1.5*
LT					
% VO_{2max}	82±4	83±4	83±4		77±5
$km \cdot h^{-1}$	16.4 ±0.8	12.8±1.0	12.9 ± 1.4		
1RM					
kg			73.4 ± 20.5 (free weights)	247.3 ± 52.7 (leg press)	155.0± 40.6 (Smith-machine)
Change (%)			33.2 ± 1.1**		14.2± 2.2*
RFD					
W			466.7 ± 163.2#		832.6± 171.6#
Change (%)			26.0 ± 3.3**		16.7± 6.6*

Values are Mean ± SD. VO_{2max}, maximal oxygen uptake. C_R, oxygen cost of running. C_C, oxygen cost of cycling. LT, lactate threshold. 1RM, one repetition maximum in half-squat. RFD, rate of force development in half-squat. Incr, increase in. MST, maximal strength training. $[La^-]_b$, blood lactate concentration. Min, minutes. M, metres. W, watts

*$p<0.05$ intervention difference, **$p<0.01$ intervention difference.

#$p<0.05$ significant correlation with C_R or C_C.

In study II, the female athletes displayed significantly better C_R than the males. Study III also contained both male and female subjects, and when combining C_R results from these two studies divided by gender, there is still a significantly ($p<0.01$) better C_R between the female subjects (0.663 ± 0.039 $ml \cdot kg^{-0.75} \cdot min^{-1}$) than the male subjects (0.724 ± 0.057 $ml \cdot kg^{-0.75} \cdot min^{-1}$). The gender differences found in study II and III are in accordance with results from Helgerud (1994), who found that in performance matched male and female marathon runners, the women had better C_R than the men. However, in the study by Helgerud (1994), the female runners had a higher weekly mileage than the male runners. This was not the case in study II or in study III. When results from study I, II and III are put together, there is no correlation between C_R and LT expressed as $\%VO_{2max}$ or LT velocity. As Franch et al (1998) relates improved C_R to reduced ventilatory demand, and since paper III in this thesis demonstrates a significantly improved C_R from pre to post intervention we evaluated if VE in study III decreased according to the shown decrease in C_R. There was a significant ($R=0.74$, $p<0.05$) correlation between pre intervention VE expressed as $L\cdot kg^{-0.67}\cdot min^{-1}$ and C_R, indicating a possible relationship between these variables, but there were no correlation between changes in VE and changes in C_R. The correlation between C_R and VE was supported in study IV ($R=0.82$, $p<0.01$), as depicted in figure 4.

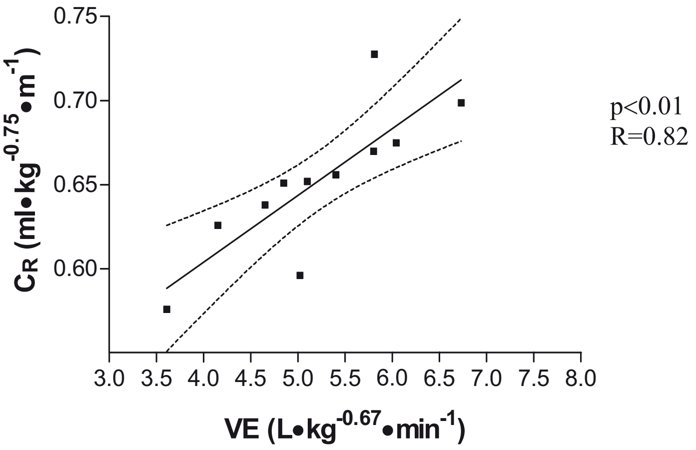


Figure 4 Linear regressions between VE and C_R in study IV.

C_R, oxygen cost of running ($ml\cdot kg^{-0.75}\cdot m^{-1}$) measured at 15 $km\cdot h^{-1}$ on a level treadmill. VE, total pulmonary ventilation ($L\cdot kg^{-0.67}\cdot min^{-1}$) measured at 15 $km\cdot h^{-1}$ on a level treadmill. $p<0.01$, $R=0.82$. N=11.

In study V, the cyclists showed a 7% improvement in brake power from pre to post intervention at the same relative intensity (70% VO_{2max}). VE ($L\cdot kg^{-067}\cdot w^{-1}$) stayed approximately the same from pre to post intervention when measured at both pre and post test brake power. This shows that the changes in VE are only apparent when measured at a set velocity or brake power, and must be taken into account when relating changes in VE to changes in economy.

Maximal strength

The long distance runners participating in study III had a considerably lower 1RM pre intervention in 90° half-squat (73±21 kg) than soccer players (161±25 kg) in Hoff and Helgerud (2003) and soccer players (130±16 kg) in McMillan et al (2005). The runners managed in average to lift approximately 5 kg per kg body weight raised to the power 0.67

pre intervention, compared to the approximately 8 kg per kg body weight raised to the power 0.67 among the soccer players. The finding in study III that pre intervention 1RM did not correlate with C_R is interesting. Neither did improvements in 1RM correlate with improvements in C_R. This indicates that not only improvement in muscle strength measured as 1RM, but also other factors affecting C_R were improved by the MST.

A possible way to improve C_R might be to increase the amount of energy from the braking forces that can be stored in elastic elements in muscle-tendon units (elastic recoil). In this respect strength training has been reported to increase muscle – tendon stiffness (Kubo et al 2001). Neither muscle–tendon stiffness nor elastic recoil was measured in any of the studies presented in the present thesis. The improvements in C_R after an MST intervention shown in study III may thus be due partly to an improvement in the ability to store energy from the braking forces in elastic elements in muscle-tendon units, but to investigate this, muscle–tendon stiffness should have been measured pre- and post the MST intervention.
Another way in which C_R may be improved is by increasing muscular efficiency. The MST intervention for running (study III) may thus also have improved muscular efficiency. In study V the same improvements in economy as in study III were echoed, this time regarding cycling. Elastic storage of energy should logically not be as important in cycling as in running. Since the same improvements in economy as in running were found in cycling after the MST intervention, we suggest that muscular efficiency adaptations have exceeded adaptations regarding elastic recoil in the two studies. Muscular efficiency covers a variety of factors (Alexander 1984, Tokui and Hirakoba 2007).We suggest that the main sources to the economy adaptations to MST found in study III and study V are neural adaptations, discussed more thoroughly in the next passage. Theoretically the MST could also have led to hypertrophic adaptations. But neither the runners in study III nor the cyclists in study V changed their body weight from pre- to post intervention, as shown previously by Hoff et al (2002), Hoff et al (2002), Helgerud et al (2003), Hoff et al (2005) and McMillan et al (2005). A possible hypertrophic response to MST among well trained athletes should be detected as an increase in body weight.

Rate of force development

In study III, a significant correlation between pre intervention RFD and C_R was observed. The same finding was repeated in cycling (study V). RFD also improved significantly in the two

MST interventions (study III and V). In study V highly significant correlations between improvements in RFD and improvements in $_t$MAP were found ($p<0.01$, $R=0.75$). These results may indicate a relationship both between RFD in the muscles active in running and cycling and economy, as well as a relationship between improvements in RFD and time to exhaustion at a given intensity in cycling. RFD is logically related to contraction time in working muscles. A shorter contraction time will logically prolong transit time at a given cyclus frequency. An increase in RFD could also lead to a shorter CT in a running step. However, in study IV no correlation between CT and C_R was found. The results from study IV are thus in line with Williams and Cavanagh (1987) and Kyrolainen et al (2001) who found no significant correlation between CT and C_R. Even though no correlation was found between CT and C_R in study IV, it does not necessarily mean that CT was not affected by the MST in study III, but CT was not measured in this study. The increase in RFD found in studies III and V may represent a more effective activation of motoneurons and muscle fibers as discussed in Hoff et al (2002). If less motor units need to be recruited at the same time at a given intensity, more unfatigued motor units will be available during prolonged exercise, and a longer time to exhaustion at a specific intensity might be expected. Better $_t$MAS and $_t$MAP was shown in studies III and V. The results from these studies thus support the hypothesis of a more optimal activation of motoneurons and muscle fibers.

Running and cycling characteristics and force measures

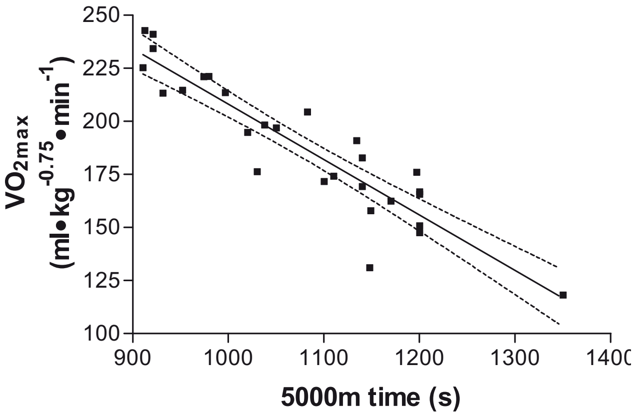
In study V, the cyclists always used a freely chosen cadence (RPM). In both the MST intervention group and in the control group, the mean cadence at 70% VO_{2max} was on average 95 RPM. There was no change in cadence after the MST intervention, although the intervention group improved their 1RM, RFD and C_C significantly. This is in line with results on double poling frequency in cross-country skiing (Hoff et al 1999, Hoff et al 2002, Østerås et al 2002). The results from study V are however in contrast to previous studies that have shown gross efficiency among elite cyclists to be significantly higher at a lower cadence than their freely chosen cadence (Foss and Hallen 2004), and that better economy is related to lower cadence (Hansen et al 2007). The cyclists in study V might have shown an even better C_C if the freely chosen cadence had been replaced by a set cadence. Theoretically, with an increased muscular strength, a cyclist can lower the cadence and still produce the same relative force in each pedal revolution at a given brake power. On the other hand, the cyclist may choose to maintain the cadence and then lower the relative force needed in each pedal revolution at the same given brake power. The latter may be the most common pattern if freely chosen cadence is primarily a robust innate voluntary motor rhythm, as proposed by Hansen and Ohnstad (2008). If, as a result of MST, RFD increases, it would be an indication of a higher maximal muscle-shortening velocity. In study V the relationship between RFD/cadence and C_C was found to be highly significant ($p<0.01$, $R=0.84$) and the correlation was higher than that between RFD alone and C_C ($p<0.01$, $R=0.76$). This may indicate that the lower the relative muscle-shortening velocity needed for a given cadence, the better cycling economy.

There is a difference between cadence in cycling and stride frequency in running. Within a small range of pedal arm lengths available, the cyclist has to choose one. Once the pedal arm length is chosen, it stays the same throughout training or the race. Runners can vary stride lengths within a much larger range compared to the range of different pedal arm lengths in cycling. Also, the runners may vary stride lengths during training or a race. Previous studies on stride frequency in running have shown that the runners freely chosen stride frequencies correspond well with the optimal stride frequencies regarding C_R. In a study by Hunter and Smith (2007), the self optimized stride frequency among 16 experienced runners, which was both the self-selected one and the one expressing the best C_R, averaged 87 steps per minute. In study IV the mean stride frequency averaged 89 steps per minute and the result is thus in line with Hunter and Smith (2007). The stride frequency measured in study IV was also found to have a low variation between the subjects. Corrected for leg length, all runners chose approximately the same ratio between stride length and stride frequency. It seems thus logical that no correlation between stride frequency and C_R was found in study IV.

When maintaining a given running velocity on a treadmill, the sum of horizontal brake forces and the sum of horizontal propulsive forces in each step must be equal. The same applies for the vertical forces regarding the position of centre of gravity. In study IV we measured horizontal and vertical brake and propulsive forces. Average peak braking and propulsive forces, horizontal or vertical, need of course not be equal in each step, as it is possible to change position on the tread mill. However, the brake forces measured are approximately of the same size. In study IV none of the average peak force measures correlated significantly with C_R. However, the sum of horizontal and vertical eccentric and concentric peak forces (APFtotal) showed a significant inverse correlation with C_R ($p<0.05$, $R = 0.66$). If the braking forces are large, the runner will consequently need large propulsive forces to maintain the velocity (horizontal) or maintain position of the centre of gravity (vertical). Thus, if only braking forces are taken into account, only about half of the size of the peak forces actually produced is measured. This may reduce the differences between runners. Both vertical and horizontal forces are each previously found to influence C_R. Farley and Mcmahon (1992) and Kram and Taylor (1990) have found C_R to be inversely proportional to the weight supported, i.e. directly dependent on the vertical forces, whereas Chang and Kram (1999) have found horizontal forces to constitute more than 33% of the total metabolic cost of horizontal running on treadmill. And for running on track, Kyrolainen et al (2001) actually found that the average horizontal forces in the braking phase of the step could explain more than 80% of C_R.

Maximal oxygen uptake

In studies I and IV, the subject groups are homogenous regarding VO_{2max}. In studies II, III and V the groups of subjects are more heterogeneous regarding VO_{2max}. Data from studies I, II and III (n=39) show a significant correlation between VO_{2max} and LT velocity (R = 0.85, p<0.01). This indicates that among these subjects VO_{2max} explains 72% of the inter-individual difference in LT velocity. In cycling in study V (n=13), there is also a high, although somewhat lower correlation between VO_{2max} and LT brake power (R= 0.75, p<0.01), indicating that among these subjects VO_{2max} explains 57% of the inter-individual difference in LT brake power. Time performance data were collected from the athletes at 5000m and 3000m in studies III and IV respectively. Recalculating the 3000m times from study IV by using the equation by Riegel (1981): $t2 = t1 * (d2 / d1)^{1.06}$ (equ. 4), 5000m performance times for all the athletes in study III and IV can be put together. The heterogeneity regarding VO_{2max} then consequently increases, as the athletes in study III are well trained whereas the athletes in study IV are elite and have much higher VO_{2max} values. A highly significant correlation (R= 0.92, p<0.01) then appears between competition time performance and VO_{2max}, as depicted in figure 5. This points at a larger relative importance of VO_{2max} in groups that are more heterogeneous regarding VO_{2max}.



p<0.01
R=0.92

Figure 5 Linear regressions between VO_{2max} and 5000m time performance in study III and V

VO_{2max}, maximal oxygen consumption ($ml \cdot kg^{-0.75} \cdot min^{-1}$). 5000m time, seasonal best time performance in 5000m competition (in seconds). $p<0.01$, $R=0.92$. $N=28$.

Lactate threshold

In study I $[La^-]_b$ was found to decrease 31.2% during the 5 minute run at LT velocity with a pre $[La^-]_b$ of 5 $mmol \cdot L^{-1}$, determining LT velocity from running velocity at 1.5 $mmol \cdot L^{-1}$ above post warm up values according to Helgerud (1994). This is a strong indication of an underestimation of LT velocity. Also during the running session at LT velocity with a pre $[La^-]_b$ of 3 $mmol \cdot L^{-1}$, $[La^-]_b$ was found to decrease significantly by 21.8%.

In studies I, II and III put together we found LT velocity to correlate highly with VO_{2max} but not with C_R alone. The high correlation between aerobic endurance performance and LT velocity is not surprising since the velocity then will depend on both VO_{2max} and C_R. Also in studies III and IV performance characteristics measured as time performance in 5000m and 3000m running respectively were collected. The results from study III correlated highly with LT velocity among the subjects, whereas LT was not measured in study IV. But although LT velocity in intervention studies has been shown to change with the alteration of VO_{2max} and-or C, in terms of the percentage of VO_{2max} the adaptability has been found to be minor (Bangsbo 1994, Helgerud et al. 2001). The latter thus seem to be in accordance with the results from studies I, II and III that LT expressed as $\%VO_{2max}$ does not correlate with either time performance in 5000m or 3000m running, or with MAS. In table 2, LT expressed as %

VO_{2max} is very consistent between all three groups of athletes regarding running, with no significant difference of means. The variation between means in these three different studies is only 0.7%.

Only study III contains data from VO_{2max}, C_R, LT and time performance (5000m). If a performance equation (VO_{2max} / C_R) is used in study III, the correlation between VO_{2max} / C_R and time performance in 5000m is high ($R= 0.82$, $p<0.01$). If this performance equation is expanded, multiplying (VO_{2max} / C_R) with LT expressed as % VO_{2max}, the correlation gets even higher ($R=0.86$, $p<0.01$). This indicates that among these athletes, the relative importance of LT expressed as % VO_{2max} is approximately 7% (figure 6).

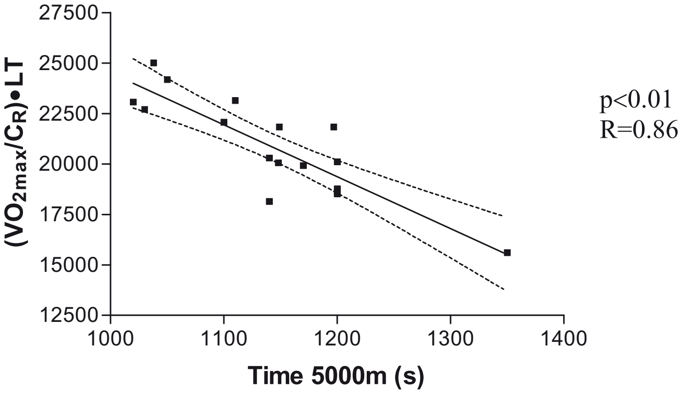


Figure 6 Relationship between endurance performance equation including LT and 5000m time performance in study III

Endurance performance equation, (VO_{2max} / C_R) · LT expressed as % VO_{2max}. VO_{2max}, maximal oxygen consumption ($ml \cdot kg^{-0.75} \cdot min^{-1}$). C_R, oxygen cost of running at 70% VO_{2max}. LT, lactate threshold. 5000m time, seasonal best time performance in 5000m competition (in seconds). $p<0.01$, $R=0.86$. N=15.

The relative importance of cost of running on distance running performance

When the seasonal best time performance data from the athletes in study III and IV are put together, there is significant correlation ($R= 0.92$, $p<0.01$) between 5000m time performance and VO_{2max} (figure 4). The heterogeneity regarding VO_{2max} is consequently high (variation of 17.4%), as the athletes in study III are well trained whereas the athletes in study IV are elite and have much higher VO_{2max} values. The correlation between VO_{2max} / C_R and 5 km performance show an $R = 0.94$ ($p<0.01$), indicating that C_R should account for 4% of the difference in 5 km performance between subjects. In study IV alone, with a more homogenous group regarding VO_{2max} (variation of 7.0%), the combination of VO_{2max} and C_R correlated with time performance with an R = 0.93 ($p<0.01$). The correlation between VO_{2max} alone and time performance showed an R = 0.85 ($p<0.01$). This indicates that C_R accounts for 13% of the difference in time performance between subjects in study IV, and that the relative importance of C_R on distance running performance increases with increasing homogeneity regarding VO_{2max}. This supports the finding by Conley and Krahenbuhl (1980) in highly trained and experienced runners with similar VO_{2max}, where running economy accounted for 65% of the variation observed in performance on a 10 km race.

The relative importance of Cost of cycling on cycling performance

In study V, competition time performance results were not collected from the cyclists as road racing results are not comparable. But a performance equation $(VO_{2max} / C_C) \cdot LT$ gives a good picture of physiological performance capacity. The performance equation thus shows a high correlation with VO_{2max} (R = 0.77, $p<0.01$) and a much better correlation with VO_{2max} / C_C (R = 0.94, $p<0.01$), indicating a relative importance of C_C of approximately 29% for physiological performance capacity in cycling among the cyclists in study V. This is higher than the relative importance of C_R on running performance in studies III and IV. Of course the studies can not be uncritically compared as time performance results were not directly measured among the cyclists.

Limitations of the studies in this thesis and future research

The discussion of gender differences in C_R in paper II would have benefited from a larger number of female athletes. Although the gender differences were large and highly significant, the statistical power would have increased with more than 6 female athletes. With 10 female athletes, given the same average gender differences in C_R, the statistical power would increase by approximately 25% .To repeat this study design with more female runners would thus be of interest. The improvements in C_R after an MST intervention shown in study III may be due partly to an improvement in the ability to store energy from the braking forces in elastic elements in muscle-tendon units. To confirm or disprove this hypothesis, muscle–tendon stiffness could have been measured pre- and post the MST intervention, but this was not done in study III. To repeat this study design with the addition of muscle–tendon stiffness measurements as well as measurements of contact time and time to peak force may increase the knowledge about the causes of C_R adaptations to MST.

Running performance data expressed as time results in long distance running were only collected in papers III and IV. Papers I and II would have benefited from such data to classify the athletes running ability. Also these data would have provided a more thorough discussion of the relative importance of C_R on distance running performance in this thesis. The same applies for study V on cycling. An ergometer cycle time trial could have given directly measured time performance results. To repeat the study design of study V with the addition of ergometer cycle time trials could thus be valuable. In studies III and V, RFD pre intervention was found to negatively correlate with C_R and C_C, meaning that the subjects with the best RFD had the best work economy. Study IV would have profited on measurements of RFD in addition to maximal strength measurements. The study design of study IV should thus be repeated with additional measurements of RFD.

Conclusions

Running economy was found to correlate significantly inverse with the sum of average peak horizontal and vertical forces in each running step. Running economy was found to deteriorate with increased levels of lactate. Women were found to have better running economy than men. Both running and cycling economy was found to correlate significantly positive with rate of force development in half-squat. Body fat percentage and height were found to correlate moderately inverse with running economy. From the investigations presented in this thesis, the sum of average peak horizontal and vertical forces in each running step, blood lactate concentration, rate of force development, gender, body fat percentage and height were found to be determining factors for running economy, while rate of force development was found to be a determining factor for cycling economy.

An incremental protocol for assessing running economy was found to reliably calculate running economy in a cross-over study. Running economy was found to be unaffected by running intensity in the area between 60% and 90% of maximal oxygen consumption.

Both running and cycling economy was found to be improved significantly after eight weeks of maximal strength training in half-squats. These improvements led to improved time to exhaustion at maximal aerobic speed and time to exhaustion at maximal aerobic power. The maximal strength training interventions did not alter body weight or maximal oxygen consumption.

Practical applications

Practical implications from the research presented in this thesis is first and foremost based on the finding that maximal strength training, with emphasis on maximal mobilization and thus neural adaptations, improves both running economy and cycling economy, as long as the maximal strength training is a supplement to the subjects regular endurance training. Maximal strength training can thus serve as a useful tool for enhancing endurance running and cycling performance.

Evaluation of running economy in long distance runners can be based on testing at any running velocity representing intensity between 60 – 90% of maximal oxygen consumption. The finding that running economy is impaired with increasing blood lactate concentration, points to the importance of finding a suitable intensity, with as little accumulation of blood lactate as possible at the start of an endurance race. The sum of average peak horizontal and vertical forces in each running step is found to be negatively related to running economy. This indicates that a minimizing of the external vertical and horizontal forces during running may improve running economy. How to make such adaptations through training is however a complex task, but one logical approach may be to try to minimize the vertical movement of the centre of mass.

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PAPER I

Hoff J, Støren Ø, Finstad A, Wang E, Helgerud J (2009)

High blood lactate levels deteriorates running economy in elite endurance athletes.

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PAPER II

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Are there differences in running economy at different velocities?

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Are there differences in running economy at different velocities for well trained distance runners?

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ABSTRACT

Purpose: The present study investigated if there are differences in running economy at different velocities for well trained distance runners, and to what extent a commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities affects the reliability of these measurements.

Methods: 15 well trained distance runners (9 male and 6 female) participated in this study. Gross oxygen cost of running (C_R), heart rate (Hf) and $[La^-]_b$ during 5 minute runs at velocities ranging from 8.0 to 17 $km \cdot h^{-1}$, representing intensities ranging from 60% to 90% of maximal oxygen consumption (VO_{2max}) was measured on two different days in random order. The athletes were also tested for lactate threshold (LT), VO_{2max} and time to exhaustion at MAS ($_t$MAS).

Results: No significant differences in C_R between the different relative velocities or the different set velocities were found up to 90% of VO_{2max}. The incremental protocol for measuring VO_2 at different velocities was found not to affect the reliability of these measurements. All athletes reached their VO_{2max} while running to exhaustion at MAS. The females showed significantly lower VO_{2max} but significantly better C_R than the males.

Conclusion: At velocities representing intensities between 60% and 90% of VO_{2max}, no differences in C_R were found. The commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities was found not to affect the reliability of these measurements. This means that C_R measured at sub maximal velocities are representative for C_R at race velocity for distances above 10 000 metres for most runners.

Keywords: Oxygen cost of running; running velocities; test protocol.

INTRODUCTION

Endurance performance, as in long distance running, imposes great demands on both the cardiovascular system and the employed locomotor organs. A model described by Pate and Kriska (1984) incorporates three major factors accounting for interindividual variance in aerobic endurance performance, namely maximal oxygen consumption (VO_{2max}), lactate threshold (LT) and work economy. This model is supported by numerous published studies (Pollock, 1977, Farell et al., 1979, Conley and Krahenbuhl, 1980, Di Prampero et al,. 1986, Bunc and Heller, 1989, Helgerud, 1994). Maximal aerobic speed (MAS), or the minimum speed needed to reach VO_{2max} (vVO_{2max}) has been explained by Morgan et al., (1989) as the VO_{2max} divided by C_R. Noakes et al., (1990) have shown that maximal speed reached during VO_{2max} testing correlates better with performances for distances between 10 and 90 km than VO_{2max} alone. In accordance with this, Lacour et al., (1990) found that C_R or VO_{2max} alone did not correlate with race velocity among well trained middle and long distance runners (800m-5000m), whereas MAS correlated well with the race velocity for distances longer than 800m. The MAS has been found to represent 1500m - 3000m velocity in elite and sub-elite distance runners (Lacour et al., 1990, Billat & Koralsztein, 1996, Bassett et al., 2003). The time to exhaustion at MAS in these studies was approximately 3-9 minutes.

C_R is commonly defined as the steady rate VO_2 in $ml \cdot kg^{-1} \cdot min^{-1}$ at a standard velocity (Costill et al., 1973, Conley and Krahenbuhl, 1980) or as energy cost of running per metre ($ml \cdot kg^{-1} \cdot m^{-1}$) (Di Prampero et al., 1986, Helgerud, 1994, Helgerud et al., 2001). It is also expressed as mechanical efficiency, which is referred to as the ratio between work output and oxygen cost (Åstrand and Rodahl, 1986).

Conley and Krahenbuhl (1980) and Helgerud (1994) have shown inter-individual variations in the oxygen cost of running (C_R). The causes of this variability are not well understood, but it seems likely that anatomical trait, mechanical skill, neuromuscular skill and storage of elastic energy are important factors (Pate and Kriska, 1984). Interindividual variability in C_R reflects the importance of this parameter for performance in long distance running. Interindividual variability in C_R expressed as standard deviations (SD) is reported by Di Prampero et al. (1986) to be ±8 %, if the C_R is expressed per kg body mass. This is in line with results from Morgan et al. (1995) and Lacour et al. (1990). These results are also expressed per kg body mass.

Energy cost for movement does not increase in the same rate as body mass (Bergh et al., 1991, Eisenmann et al., 2001, Berg, 2003). According to Helgerud (1994), a lack of allometric scaling will underestimate VO_{2max} and overestimate C_R among the heavier runners. Consequently, part of the variation in C_R in the experiments by Di Prampero et al. (1986), Morgan et al., (1995) and Lacour et al., (1990) are due to body mass differences. To use allometric scaling when expressing C_R has seemed to reveal smaller differences. Helgerud (1994) has reported SD for C_R of approximately 5% within intermediate national elite marathon runners when expressing C_R per kg body weight raised to the power of 0.75 and metre. In accordance with this, Helgerud et al. (2001, 2003) have shown SD for C_R to be 5% in junior soccer players and 3-4% in adult players including a group of players at European Champions League level. Hoff et al. (2005) report SD for C_R to be less than 5% among 36 professional soccer players.

Helgerud (1994) has reported a lower C_R at velocities equal to LT among female intermediate national elite marathon runners than in their performance-matched male counterparts when expressing C_R per kg body weight raised to the power of 0.75 and metre. Daniels and Daniels (1992) and Bunc and Heller (1989) did not report gender differences in C_R when the results are recalculated (body weight raised to the power of 0.75 and metre).

If measurements of C_R at a sub-maximal running velocity are to be used to evaluate race performance capacity among long distance runners, the measurements should be representative for the C_R at racing velocity. Previous investigations have shown C_R to be independent of running velocity up to intensities close to VO_{2max} for long distance runners (Di prampero et al., 1986, Helgerud, 1994). However Daniels and Daniels (1992) report increasing C_R at increasing relative running velocities. They also found elite middle distance runners to have better C_R at velocities at or above marathon pace than elite long distance runners. The long distance runners had better C_R at velocities below marathon pace than the middle distance runners.

In most studies that have investigated C_R at different velocities, an incremental protocol with different sub-maximal work periods over 3-10 minutes each, have been used (Di Prampero et al., 1986, Bunc and Heller, 1989, Lacour et al., 1990, Helgerud, 1994). A possible cause of error in these protocols is the incremental order in which the runs have been performed. In this context it should be of interest to assess to what extent VO_2 at one velocity is affected by previously completed runs.

The aim of the present study was to investigate if there are differences in running economy at different velocities for well trained distance runners, and to what extent a commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities affects the reliability of these measurements.

The hypothesis of the present study was;

1. There are no differences in C_R at different velocities in male and female distance runners between 75-90% VO_{2max}.
2. The commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max}.

MATERIALS AND METHODS

Subjects: 15 moderately to well trained runners, 9 males and 6 females, aged 29.3 ± 7.0 years, with an average VO_{2max} of 65.2 ± 10.4 $ml \cdot kg^{-1} \cdot min^{-1}$ were included in the study, after giving their written consent to participate.

Test procedures: The subjects were tested on two different days, with a minimum of one day and a maximum of seven days of rest or easy training in between. The first day consisted of measurements of heart rate (HR), blood lactate concentration ($[La^-]_b$) and oxygen consumption (VO_2) during five minutes runs (1.5% inclination) at different velocities until exhaustion. The subjects started with a velocity assumed to be about 60% of their VO_{2max}. This was either 8.0 or 9.5 $km \cdot hour^{-1}$. After completing five minutes at this velocity, the speed was increased by 1.5 $km \cdot hour^{-1}$ to the next five minute work period. New steps were performed until the subject no longer could complete five minutes at the desired velocity. After 60 minutes of rest, a VO_{2max} test was performed, using an incremental protocol at 5.2% inclination. The VO_{2max} test terminated at voluntary fatigue by the subjects. HR ($\geq$ 98 % predicted HR_{max}), R ($\geq$ 1.05) and $[La^-]_b$ ($\geq$ 8.0 $mmol \cdot L^{-1}$) values, as well as a possible platouing of the VO_2 curve, was used to evaluate if VO_{2max} was obtained. LT and maximal aerobic speed (MAS) were calculated on the basis of these measurements. The second day of testing consisted of measurements of HR, $[La^-]_b$ and VO_2 at the same velocities as the first day, but performed in the opposite order (i.e. starting with the highest running velocity after a warm up). Following a 60 min rest, the subjects then performed a run to exhaustion at MAS. The protocol for one of the runners is presented in table 1.

Protocol for one of the runners (table 1).

The VO_2 was measured using the metabolic test system, Sensor Medics Vmax Spectra (SensorMedics 229 California, USA). The lactate measurements were performed using an Arkray Lactate Pro LT-1710 analyser (whole blood) (Arkray Inc. Kyoto, Japan). The LT was defined as the warm up $[La^-]_b$ value (i.e. measured after the lowest velocity in day one) + 1.5 mmol. This is in line with the protocol proposed by Helgerud et al. (1990), consisting of several five minute steps, at 1.5% inclination, increasing the speed by 1.5 km · hour^{-1} after each step. The oxygen cost of running was measured at the same 5-minute steps at 1.5% inclination. These steps were performed until the subjects no longer managed to run for 5 min (exhaustion). In day two the same velocities were measured, but in the opposite order. C_R was calculated as gross oxygen cost per kilo bodyweight raised to the power of 0.75, per meter of running for the set running velocities. For the relative intensities, for example 75% VO_{2max}, running velocity was calculated in the same way as for maximal aerobic speed (figure 1).

Assessment of maximal aerobic speed (figure 1).

MAS was defined at the velocity at 1.5% inclination of the treadmill, where the horizontal line representing VO_{2max} meets the extrapolated incremental line representing the sub maximal VO_2 measured in the LT assessment. By plotting VO_2 data against running velocity, individual regression equations for each subject could be obtained. Based on the findings of Helgerud (1994), values in between 60-90% VO_{2max} were used to calculate the incremental line. An example of the assessment of MAS is presented in figure 1.

Alometric scaling has been reported to decrease the SDs in C_R between subjects (Helgerud, 1994, Helgerud et al., 2001, Hoff et al., 2005). VO_2 values are thus mainly expressed in ml · kg$^{-0.75}$ in the present study.

Statistical analysis: Descriptive statistical analyses were made to display means, standard deviations, standard error and coefficient of variance. To assess whether or not the VO_2 values would be affected by the preceding step (i.e. the day to day measures described above), two way ANOVA-tests were used. Differences in C_R at different velocities and possible gender differences in C_R were also tested by using two-ways ANOVA-tests. Linear regressions were made to display the equations representing the linearity between running velocity and oxygen cost of running. Correlations were calculated by the Pearson correlation test.

RESULTS

Physical characteristics of subjects (table 2)

Physical characteristics of the subjects are presented in table 2. There was no significant gender differences in age, in LT velocity, in LT expressed as per cent of VO_{2max} or in $_t$MAS. The male subjects were taller, heavier and had a higher VO_{2max} than the females.

To compare physiological parameters at VO_{2max} and at MAS, only the participants that completed more than five minutes at MAS were included, independent of gender. They would thus have at least spent the same time at this intensity as at the set submaximal intensities. Further, five minutes should allow a possible steady rate to occur. These runners clearly reach their VO_{2max} at MAS (99.4% of VO_{2max}). Neither the results regarding HR nor $[La^-]_{b\ peak}$ were different being obtained at VO_{2max} or at MAS. However, the subjects exhibited significantly lower R-values when running at MAS compared with the R-values achieved during the VO_{2max} test. These results are presented in table 3.

Physiological variables at VO_{2max} and at MAS (table 3)

Table 4 shows the mean values in VO_2 at each of the set intensities by the 10 subjects who completed at least 15.5 km · h^{-1}, independent of gender. The results are divided into the two different test days. In day one the subjects ran at the lowest velocity first, increasing the speed for each separate run. In day two they started at the highest velocity, decreasing the speed for each separate run.

Oxygen cost of running at different test days (table 4)

There were no significant differences in oxygen costs of running (C_R) expressed as

VO_2 ml·kg$^{-0.75}$·min^{-1} between the two test days. The coefficient of variation for the mean differences between day one and day two is 0.9%. Consequently, only results from test day one, apart from the MAS results (day two) are used in the following statistical analysis.

The mean data for C_R expressed as VO_2 ml · kg$^{-0.75}$ · m^{-1} at those of the set velocities that were completed by all the fifteen subjects are shown in table 5. These results are divided by gender.

Oxygen cost of running at set velocities (table 5)

There were no significant differences in C_R expressed as VO_2 ml · kg$^{-0.75}$ · m^{-1} between the different set velocities. The females had significantly lower C_R than the males at the set velocities. Mean interindividual variability expressed as standard deviations (SD) for the males was ±7.1%. For the females, mean interindividual variability was ±5.2%.

By plotting VO_2 data against running velocity as described in the protocol for assessing MAS, individual regression equations for each subject could be used to find the cost of running at the different relative velocities. By using running intensities representing 75-90% of VO_{2max}, the data are within the area of velocity completed by all the subjects. Table 6 shows the mean data for the C_R expressed as VO_2 ml · kg$^{-0.75}$ · m^{-1} at these velocities relative to VO_{2max}.

Oxygen cost of running at relative intensities (table 6, figure 2)

No significant differences in oxygen costs of running expressed as VO_2 ml · kg$^{-0.75}$ · m^{-1} between the different relative velocities was found for the male or for the female subjects. The females had significantly lower oxygen cost of running than the males at all the relative velocities.

DISCUSSION

The major findings in this study are that oxygen cost of running (C_R) did not differ for velocities between 75% and 90% VO_{2max}, and that the commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max}.

Cost of running at different velocities and intensities

The finding that C_R did not differ at the different set velocities or relative intensities is in agreement with reports from di Prampero et al. (1986) and Helgerud (1994). These results are, however, not in agreement with the results from Daniels & Daniels (1992) who found increasing oxygen cost of running as relative running intensity increased in the area between 70% and 100% VO_{2max}.

Reliability of the incremental protocol for assessing oxygen cost of running

When comparing the C_R from test-day one and test-day two, using the two different protocols (incremental order day one, descending order day two), no significant differences were found. The coefficient of variation for the mean differences between day one and day two is only 0.9%. Thus it seems safe to assume that the commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max}.

Interindividual variability in oxygen cost of running

Interindividual variability in oxygen cost of running expressed as mean standard deviations for the three velocities completed by all fifteen subjects (SD) is ±7.1% for the males and ±5.2% for the females in the present study. The variability is lowest at the lowest velocity (9.5 $km \cdot h^{-1}$), and highest at the highest velocity (12.5 $km \cdot h^{-1}$). Interindividual variability is reported by di Prampero et al. (1986) to be ±8%, if the oxygen cost of running is expressed per kg body mass. Morgan et al. (1995) and Lacour et al. (1990) have found within group variations of about 20%. These results are also expressed per kg body mass. As energy cost for movement does not increase in the same rate as body weight, it seems likely that part of the variation in the oxygen cost of running in the experiments by di Prampero et al. (1986), Morgan et al. (1995) and Lacour et al. (1990) is due to weight differences. If allometric scaling had been used, these results would assumingly be more in line with those reported in the present study, since the use of allometric scaling when expressing running economy has revealed smaller differences (approximaltely ±5%) in previous investigations (Helgerud, 1994, Helgerud et al., 2001, Helgerud et al., 2003, Hoff and Helgerud, 2003, Hoff et al., 2005).

Gender differences

Although possible gender differences was not one of the original aims of the present study, the results showed better C_R among the females than among their male counterparts. The populations are however small (9 males and 6 females). These results are in agreement with results from Helgerud (1994), but seemingly in contrast to results from Daniels and Daniels (1992) and Bunc and Heller (1989). If we recalculate the oxygen cost in the two studies by Daniels and Daniels, (1992) and Bunc and Heller (1989) by raising the body mass to the power of 0.75 and metre, the results tend to be more in agreement with the results in the present study and in Helgerud (1994). This phenomenon has not been explained in previous literature, assumingly because it has been concealed, as the results have not been scaled by raising body weight to the power of 0.75 and metre. Since the female subjects in the present study had considerable lower VO_{2max} than the males, the gender differences in C_R could be related to differences in VO_{2max}. This would be in line with the suggestion by Woodruff et al. (2005) that runners with the highest VO_{2max} tended to be less economical with respect to the change in VO_2 from one velocity to the next. However, in our study no correlation was found between VO_{2max} and C_R when the subjects were divided by gender. We have thus no explanations to why women should have lower C_R than men. Further investigations' regarding this phenomenon is thus needed.

Maximal aerobic speed

Eight of the fifteen subjects in our study completed more than five minutes at MAS, independent of gender. This group clearly reaches their VO_{2max} at MAS (99.4% of VO_{2max} at MAS). The results regarding heart rate and lactate confirm this. However, the subjects had significantly lower R-values when running at MAS compared with the R-values achieved during the VO_{2max} test. A possible explanation for this is the lower intensity at MAS than at the end of the VO_{2max} test.

We found a significant correlation between time at MAS and LT as per cent of VO_{2max} for the male subjects, but not for the females. With LT representing a higher percentage of VO_{2max}, the anaerobic contribution to the work done per metre at MAS should logically be smaller.

Participating subjects

The participating subjects in the present study are characterised as a heterogenous group with regards to running performance, VO_{2max} and C_R. However, they are all well trained runners. Thus it seems natural that the C_R by the group as a whole is higher than reported for elite runners (Daniels & Daniels, 1992), intermediate national standard marathon runners (Helgerud, 1994) and recreational marathon runners (Helgerud et al., 1990). The mean C_R among the males ($0.755\ ml \cdot kg^{-0.75} \cdot m^{-1}$) correspond to a CR of $0.246\ ml \cdot kg^{-1} \cdot m^{-1}$, whereas the mean C_R among the females ($0.680\ ml \cdot kg^{-0.75} \cdot m^{-1}$) correspond to a CR of $0.243\ ml \cdot kg^{-1}$

$\cdot$ m^{-1}. The present results are more in agreement with results from soccer players as reported by Helgerud et al. (2001) and by Hoff and Helgerud (2003).

Conclusion

At velocities representing intensities between 60% and 90% of VO_{2max}, no differences in C_R were found. This means that C_R measured at sub maximal velocities are representative for C_R at race velocity for distances above 10 000 metres for most runners. The commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities was found not to affect the reliability of these measurements.

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Table 1 Test protocol for one of the runners

Day one				Day two			
Step	Inclination (%)	Velocity (km · hour^{-1})	Duration (min.sec)	Step	Inclination (%)	Velocity (km · hour^{-1})	Duration (min.sec)
1	1.5	9.5	5	1	1.5	15.5	5
2	1.5	11	5	2	1.5	14	5
3	1.5	12.5	5	3	1.5	12.5	5
4	1.5	14	5	4	1.5	11	5
5	1.5	15.5	5	5	1.5	9.5	5
Rest for 60 min				Rest for 60 min			
VO_{2max} test	5.2	12.5 → 17.5	6.50	MAS test	1.5	16.9	5.25

The table shows the protocol for one of the runners. The number of 5 minutes steps is individual, as well as the running velocities. Otherwise the protocol is the same for all runners. VO_{2max}, maximal oxygen uptake. MAS, maximal aerobic speed.

Table 2. Physical characteristics of the subjects

	males (n = 9)	***females (n = 6)***
Age (yr)	**30.0 ± 9.2**	27.8 ± 6.1
Height (m)	**1.80 ± 0.06**	1.68 ± 0.12*
Mass (kg)	**76.9 ± 5.0**	62.0 ± 11.2*
HR_{max} (beats· min^{-1})	**187 ± 8**	190 ± 9
VO_{2max} ($ml·kg^{-1}·min^{-1}$)	**71.4 ± 6.3**	56.2 ± 9.2*
VO_{2max} ($ml·kg^{-0.75}·min^{-1}$)	**211.3 ± 17.8**	157.8 ± 17.8*
R_{peak}	**1.09 ± 0.03**	1.08 ± 0.04
$[La^-]_{b\ peak}$ ($mmol·l^{-1}$)	**10.7 ± 1.8**	9.8 ± 1.7
LT ($km·h^{-1}$)	**13. 7 ± 1.0**	11.5 ± 1.6
LT (% Vo_{2max})	**82.6 ± 6.35**	82.2 ± 2.4
MAS ($km·h^{-1}$)	**16.5 ± 1.6**	14.0 ± 1.9
$Time_{MAS}$ (s)	**432.5 ± 170.7**	242.8 ± 92.0

Values are means ± SD., HR_{max}, maximal heart rate. VO_{2max}, maximal oxygen uptake. LT, lactate threshold. R_{peak},gas exchange ratio at Vo_{2max}. $[La^-]_{b\ peak}$, highest blood lactate concentration reached during the VO_{2max}test. MAS, maximal aerobic speed. $Time_{MAS}$, time until exhaustion at MAS

*** $p < 0.05$ Significant different from male values.**

Table 3. Physiological variables at VO_{2max} and at maximal aerobic speed (MAS)

	VO_{2max} *(n = 8) 5.2% incl.*	***MAS (n = 8) 1.5% incl.***
Vo_{2max}	**66.4 ± 8.8**	66.0 ± 8.7
HR (beats· min^{-1})	**186 ± 7**	185 ± 5
R	**1.08 ± 0.04**	1.02 ± 0.04*
$[La^-]_{b\ peak}$ ($mmol·l^{-1}$)	**10.5 ± 1.8**	10.5 ± 2.4

Values are means ± SD. VO_2, O_2 uptake. HR, heart rate. $[La^-]_{b\ peak}$, blood lactate concentration.

*** $p < 0.01$ Significantly different from Vo_{2max} values.**

Table 4. Oxygen costs of running at different test-days

	VO_2 $ml·kg^{-0.75}·min^{-1}$ (n = 10)		
Velocity ($km·h^{-1}$)	**Day 1 (incremental)**	**Day 2 (descending)**	Δ day two – day one
9.5	**117.6 ± 8.2**	**114.8 ± 7.7**	-2.8 ± 6.5
11	**135.8 ± 11.3**	**130.9 ± 12.1**	-4.9 ± 5.7
12.5	**153.4 ± 14.3**	**154.0 ± 14.7**	0.6 ± 6.9
14	**171.9 ± 14.8**	**176.4 ± 16.0**	4.5 ± 8.6
15.5	**187.2 ± 14.4**	**193.4 ± 14.5**	6.2 ± 10.8

Values are means ± SD.

Incremental, velocities run in an incremental order. Descending, velocities run in a descending order.

Table 5. Oxygen costs of running at set velocities

Velocity (km · h^{-1})	***VO_2 ml·kg$^{-0.75}$·m^{-1} Males (n = 9)***	***VO_2 ml·kg$^{-0.75}$·m^{-1} Females (n = 6)***
9.5	**0.753 ± 0.04**	0.689 ± 0.027*
11	**0.752 ± 0.053**	0.686 ± 0.038*
12.5	**0.749 ± 0.061**	0.6757 ± 0.049*

Values are means ± SD.
***p<0.01 Significantly different from males.**

Table 6. Oxygen costs of running at relative intensities

Intensity in % VO_2max	***VO_2 ml·kg$^{-0.75}$·m^{-1} Males (n = 9)***	***VO_2 ml·kg$^{-0.75}$·m^{-1} Females (n = 6)***
75%	**0.753 ± 0.049**	0.684 ± 0.037*
80%	**0.755 ± 0.051**	0.681 ± 0.038*
LT	**0.755 ± 0.055**	0.672 ± 0.043*
85%	**0.756 ± 0.054**	0.677 ± 0.040*
90%	**0.757 ± 0.056**	0.675 ± 0.042*

Values are means ± SD.
***p<0.01 Significantly different from males.**

LEGEND TABLE 1

The table shows the protocol for one of the runners. The number of 5 minutes steps is individual, as well as the running velocities. Otherwise the protocol is the same for all runners. VO_{2max}, maximal oxygen uptake. MAS, maximal aerobic speed.

LEGEND TABLE 2

Values are means ± SD., HR_{max}, maximal heart rate. VO_{2max}, maximal oxygen uptake. LT, lactate threshold. R_{peak}, gas exchange ratio at Vo_{2max}. $[La^-]_{b\ peak}$, highest blood lactate concentration reached during the VO_{2max}test. MAS, maximal aerobic speed. $Time_{MAS}$, time until exhaustion at MAS

* p< 0.05 Significant different from male values.

LEGEND TABLE 3

Values are means ± SD. $VO_{2,}$ O_2 uptake. HR, heart rate. $[La^-]_{bpeak}$, blood lactate concentration.

* $p< 0.01$ Significantly different from Vo_{2max} values.

LEGEND TABLE 4

Values are means ± SD.

Incremental, velocities run in an incremental order. Descending, velocities run in a descending order.

LEGEND TABLE 5

Values are means ± SD.

*$p<0.01$ Significantly different from males.

LEGEND TABLE 6

Values are means ± SD.

*$p<0.01$ Significantly different from males.

Figure 1.

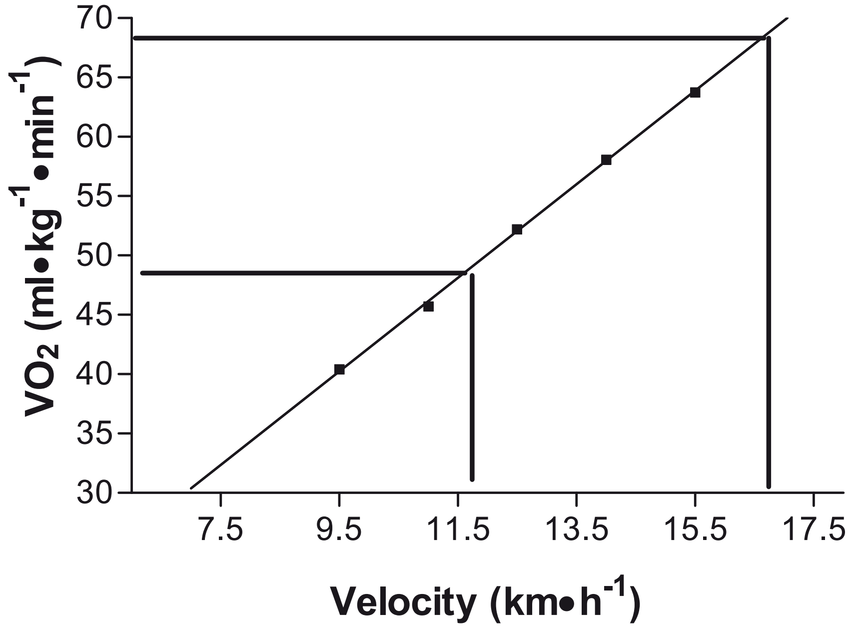
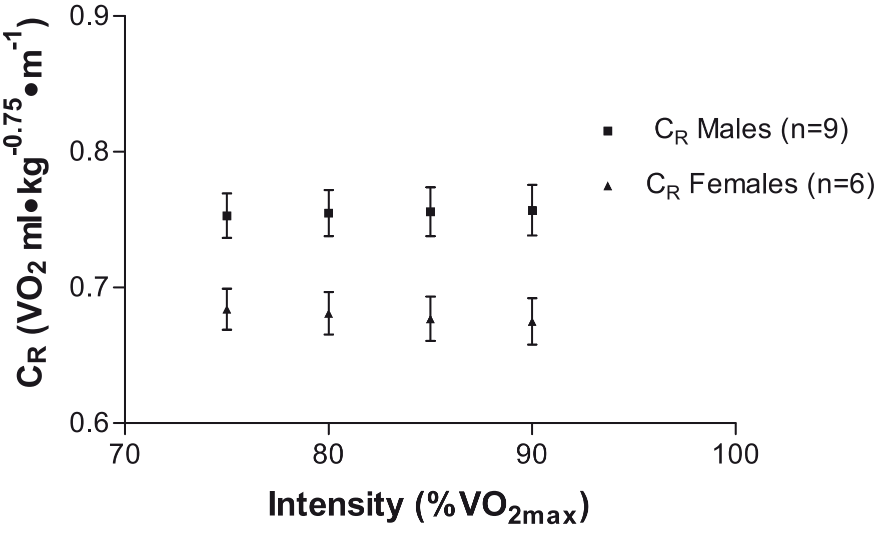


Figure 2.



LEGEND FIGURE 1

Figure 1. Assessment of maximal aerobic speed.

The linear regression equation in figure 1 is: **$y = 3.9393x + 2.7963$. $R = 0.9997$.** VO_{2max} for this runner is 69.2 ml·kg-^{1}·min^{-1}. 70 % VO_{2max} for this runner is 48.4 ml·kg-^{1}·min^{-1}. From the equation, the corresponding velocity is 11.7 km·h^{-1}, which equals 195 m·min^{-1}. C_R expressed as ml·kg-^{1}·m^{-1} is thus 0.284 ml·kg^{-1}·m^{-1}. MAS is the velocity point where the horizontal line representing VO_{2max} meets the extrapolated linear regression representing the sub maximal VO_2 measurements. Here represented by a velocity of 16.9 km·h^{-1}.

LEGEND FIGURE 2

Figure 2. Oxygen cost of running at relative intensities.

Values are means ± SD.

PAPER III

Støren Ø, Helgerud J, Støa EM, Hoff J (2008)

Maximal Strength Training Improves Running Economy in Distance Runners

***Med Sci Sports Exerc*, Vol 40, No 6, pp 1087-1092.**

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PAPER IV

Støren Ø, Helgerud J, Hoff J (2009)

Running stride peak forces inversely determines running economy in elite runners.

Submitted to *J Strength Cond Res,* April 2009.

Running stride peak forces inversely determine running economy in elite runners

Is not included due to copyright

PAPER V

Sunde A, Støren Ø, Bjerkaas M, Larsen MH, Hoff J, Helgerud J, (2009)

Strength Training Improves Cycling Economy.

Accepted in *J Strength Cond Res,* May 2009.

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178. Alexander Wahba: THE INFLUENCE OF CARDIOPULMONARY BYPASS ON PLATELET FUNCTION AND BLOOD COAGULATION – DETERMINANTS AND CLINICAL CONSEQUENSES
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