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**MEASUREMENTS FOR
IMPROVEMENT OF
RUNNING CAPACITY.
PHYSIOLOGICAL AND
BIOMECHANICAL
EVALUATIONS**

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*Dedicated to the memory of my
parents,
Ann-Britt and Oskar*

ABSTRACT

Introduction: Running is included in a large number of sports and one of the most well investigated modes of locomotion in both physiology and biomechanics. This thesis focuses on how some new methods from both areas may be used to capture running capacity in mid-distance and distance running from laboratory and field recordings. Measurement of running economy is included and defined as oxygen uptake at a given submaximal velocity in a steady-state condition. Running economy is mostly recorded on motor driven, level treadmills and consequently does not include the frontal air resistance effect. However, running economy is the sum from of a number of sub-factors. Stride characteristics and vertical displacement (V_{disp}) of the centre of mass (CoM) are two of them and here novel measuring methods are described and validated to get a wider spectrum of factors that influence running economy.

Aims: The aim of the work presented in this thesis was to describe and validate novel and easy-to-handle methods for improved capture of running economy with some of its sub-factors. The intention is later to integrate and refine the methods mentioned for regular use when analyzing and monitoring runners' capacity.

Methods: The outcome of an incremental lactate-threshold test (4x4 min) was compared with and without 30 s stops for blood sampling on a treadmill (n=10).

A lightweight, portable, metabolic device was validated against the Douglas bag method (DBM) in a wide range of VO_2 during ergometer cycling, and thereafter used for comparison of running economy and lactate threshold measurements during treadmill and indoor track running. Further, the device was compared to the DBM during treadmill running (n=14).

An infrared radiation device emitting a dense web of 40 IR beams over the running surface was validated with respect to stance-phase duration against force plate in overground running and a contact shoe during treadmill running (n=14).

The V_{disp} of the CoM was measured with a position transducer and an accelerometer and compared to the output of an optoelectronic motion capture system during treadmill running (n=13).

Results: Lactate-threshold running-velocity results were equal during continuous running and running with 30 s intervals. During ergometer cycling the portable device was valid and reliable in a wide range of measurements and during track running the device showed a VO_2 cost approximately 6% higher than during treadmill running, most probably expressing the air resistance. The IR device demonstrated systematically an 11.5 ± 8.4 ms longer stance duration than the contact shoe over a wide range of velocities. V_{disp} measured with a one-point position transducer somewhat overestimated (7 mm) the V_{disp} CoM from the optoelectronic system, but can be compensated for.

Conclusions: Blood sampling may, preferably be performed with 30 s interruptions of running during lactate threshold testing on treadmill as no difference from sampling during continuous running was detected. Running economy measurements with the portable metabolic device were reliable for running on treadmill and track, but overestimated VO_2 with 5-6% compared to DBM on the treadmill. The convenient IR mat and position transducer may well be used to capture stride characteristics and CoM V_{disp} during treadmill running.

Key words: Running economy, treadmill, track running, measurement methods

SAMMANFATTNING

Introduktion: Löpning ingår i en rad av olika idrotter och är en av de mest undersökta rörelseformerna inom både fysiologi och biomekanik. Avhandlingen inriktar sig på hur några nya metoder från båda områdena kan appliceras för att beskriva löpkapacitet i medel- och distanslöpning vid både laboratorie- och fältstudier. Mätningar av löpekonomi (RE) definieras som syreupptagning på en given, submaximal fart under steady-state förhållande. RE mäts nästan uteslutande på plant löpband och innefattar därmed inte faktorn frontalt luftmotstånd. RE representerar summan av ett antal delfaktorer, varav löpstegsutförande och vertikal förflyttning (V_{disp}) av masscentrum (CoM) är några viktiga. Här beskrivs och valideras nya mätmetoder för att få ett bredare spektrum av löpekonomi-relaterade faktorer.

Syfte: Att beskriva och validera nya och lätthanterliga metoder för att lättare kunna mäta och analysera underfaktorer som påverkar löparens löpekonomi. Den nära framtida visionen är integrering av metoderna för att kunna användas mer standardiserat när löparens analyseras och monitoreras avseende löpkapacitet.

Metoder: Resultaten av stegrat laktat-tröskeltest (4x4 min) jämfördes med blodprovstagning under 30 s vila och under kontinuerlig löpning på löpband (n=10).

Efter validering mot Douglas säck metod (DBM) under ergometercykling användes en ny, lätt och bärbar syreupptagningsutrustning för jämförelse av RE och laktatröskel mätningar på löpband och inomhus 200 m bana. Apparaten jämfördes dessutom mot DBM vid löpning på löpband (n=14).

En utrustning som emitterar ett tätt nät av infrarött ljus (40 strålar) över en del av löpytan, validerades avseende stödjefasens tid mot kraftplatta (FP) vid vanlig löpning och en kontaktsko (CS) på löpband och (n=14).

V_{disp} av CoM registrerades med en positionsgivare (PT) och accelerometer (AM) och jämfördes med ett sofistikerat optoelektriskt system vid löpbandslöpning (n=13).

Resultat: Laktat-tröskeltest visade på samma resultat när blodprov togs under 30 sek vila som under kontinuerlig löpning. Den nya bärbara utrustningen var både reliabel och valid i ett brett spektrum av mätningar i jämförelse med VO_2 mätningar med DBM på ergometercykel. RE var under banlöpning med den nya bärbara utrustningen ca 6 % högre än vid löpbandslöpning, sannolikt beroende på skillnaden i luftmotstånd. IR mattan visade systematiskt 11.5 ± 8.4 ms längre tid för stödjefasen jämfört med CS i hastigheter från 2.8-5.6 $\text{m} \cdot \text{s}^{-1}$. V_{disp} av CoM mätt med enpunkts PT var i medeltal 7 mm större än med det opto-elektriska referenssystemet, men kan kompenseras för

Konklusioner: Blodprovstagning kan med fördel ske under 30 sek paus mellan de olika löphastigheterna under ett tröskeltest, eftersom ingen skillnad hittades mot provtagning under kontinuerlig löpning. Den portabla utrustningen befanns vara tillförlitlig vid löpning på löpband och bana, men mätte 5-6 % högre VO_2 jämfört med DB vid löpbandslöpning. Den enklare IR mattan och positionsgivaren kan mycket väl användas för att korrekt registrera stegvariabler respektive vertikalledsförflyttningar vid mätningar på löpband.

Nyckelord: Löpekonomi, löpband, banlöpning, mätmetoder.

PUBLICATIONS

- I. Gullstrand L, Sjödin B and Svedenhag J. Blood sampling during continuous running and 30-second intervals on a treadmill. Effects on the lactate threshold results? *Scand J Med Sci Sports* 1994; 4: 239-242
- II. Rosdahl H, Gullstrand L, Johansson P, Salier-Eriksson J and Schantz P. Evaluation of the Oxycon Mobile metabolic system against the Douglas bag method. (Submitted).
- III. Gullstrand L, Elgh T and Svedenhag J. Running economy on treadmill and indoor track determined with portable and/or Douglas bag equipment. (In manuscript).
- IV. Gullstrand L, Halvorsen K, Tinmark F, Eriksson M and Nilsson J. Measurements of vertical displacement in running, a methodological comparison. *Gait & Posture* 30 (2009) 71-75
- V. Gullstrand L and Nilsson J. A new method for recording the temporal pattern of stride during treadmill running. *Sports Engineering* (2009): 11:195-200

And some unpublished observations and pilot studies.

ABBREVIATIONS

AM	Accelerometer
BBB	Breath-by-breath
CoM	Centre of mass
CS	Contact shoe
CONT	Continuous
DBM	Douglas bag method
FP	Force plate
HR	Heart rate
INT	Interval
IR ₄₀	Infrared mat with a 40-beam web
PMD	Portable metabolic device
PT	Position transducer
RE	Running economy
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
Stance phase	Foot contact duration, from touch-down to toe-off
Swing phase	Air phase duration, from toe-off to touch-down
Stride	Stance and swing phases of one leg
TD	Touch-down
TO	Toe-off
TM	Treadmill
VO ₂	Oxygen uptake (L · min ⁻¹)
VO _{2 max}	Highest possible oxygen uptake during running
VO _{2 peak}	Highest possible oxygen uptake during other work modes
V _E	Ventilation (L · min ⁻¹)
W	Watt
V _{disp}	Vertical displacement

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1 INTRODUCTION

Running as a basic mode of locomotion has been a research topic in a variety of scientific disciplines. For decades, excellence in distance running performance has been associated mostly with physiological variables such as oxygen consumption. Especially the maximal oxygen uptake (VO_2 max) has been focused on as an expression for aerobic power (*Hill and Lupton 1924, Costill 1967, Saltin and Åstrand 1967*).

Later, running economy (RE) was introduced as the steady-state oxygen cost per kg body weight when running at a given velocity. This is more closely related to distance-running performance than VO_2 max (*Costill, Winrow, 1970, Conley, Krahenbuhl 1980, 1981*). Further, running velocity at blood lactate threshold was used to mirror the more peripheral processes (*Bang 1936*). This also correlates better to performance and actual time in marathon running ($r=0.95$) than VO_2 max ($r=0.85$) does (*Sjödin and Svedenhag 1985*).

The term aerobic running capacity or fractional utilization of VO_2 max is often used to take into account individual differences in VO_2 max and RE and is expressed as a percentage of VO_2 max at a given submaximal velocity (*Costill et al. 1973, Sjödin and Svedenhag 1985*).

Svedenhag 1992, Anderson 1996 and Saunders 2004 have in review articles suggested that other factors than metabolism influence running economy, as included in Figure 1 below. In the present work, methods for measuring *metabolism* and, to some extent, *biomechanics* represented by external mechanical work, have been investigated.

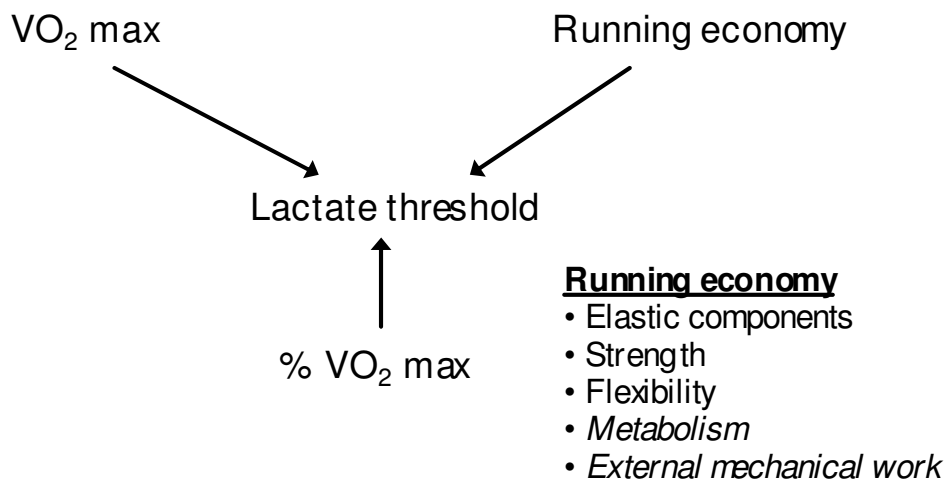


Figure 1. Important variables for running performance in middle- and long-distance running (*Svedenhag 1992*).

1.1 TREADMILL RUNNING

Measurements during running under well-controlled conditions have for decades been performed on motor driven treadmills (TM). Opinions diverge, however as to whether TM running fully represents overground running, and a number of investigations have been attempted to clarify this question (*McMiken, Daniels 1976, Pugh 1970*).

Nigg et al. (1995), Savelberg et al. (1998) and Schache et al. (2001) consider that air resistance and possibly visual and auditory surroundings are the only difference between TM and track running, assuming that the treadmill has a number of qualities such as:

- a motor strong enough to move the belt without speed variations during the strides
- a foundation rigid enough not to cause elastic or rebounding effects during the strides
- a running surface big enough to make the runner feel secure (perceptual information)
- a working security system (handlebars, safety line, etc..) for the runner's safety
- a speed-controlling system able to set and monitor desired velocities

Treadmills not fulfilling these requirements may jeopardize correct results and conclusions from investigations including physiological and biomechanical aspects of running. The two treadmills used in the main studies of the present work were solid constructions with powerful electrical motors:

Treadmill 1 (study I): Running surface: 0.70 x 2.50 m, power: 4.0 kW AC, weight 350 kg (Mega, LIC/Biab, Sweden). The floor under the TM was concrete covered with linoleum.

Treadmill 2 (studies III-V): Running surface: 2.50 x 4.50 m, power: two 5.0 kW AC motors, weight 1700 kg (Rodby Innovision, Sweden) standing in a concrete pit with the running surface level with the floor.

1.2 INDOOR TRACK RUNNING

Most tests and study measurements are performed on a treadmill, but the results are frequently applied during track training sessions. It was therefore of a great interest to compare results from TM and track running (main study III and pre-study IV).

The experiments were performed on a three-lane 200 m indoor track (at The Swedish National Sports Complex, Bosön, Lidingö). One curve has a permanent inclination of 11° and the other can be varied between 0 and 12 degrees (measured at mid-curve points). The inner lane was used during the experiments. The surface is rubber-based (Scan Sport EPDM, DIN norm 18032:6) as used on several indoor and outdoor tracks in Europe. Temperature and relative humidity during the measurements were 18.9 ± 0.9 °C and 43.5 ± 6.0 %, respectively.

Running velocity was monitored by timing and verbal reporting each 100m lap. The trained runners participating in the studies were used to run at pre-set speeds and kept the expected speeds with the highest accuracy in all studies.

2 AIMS

The overall aim was:

To broaden our understanding of the concept of running economy by introducing and evaluating new and easy-to-handle measurement methods.

With these findings, integrated/simultaneous measurements of both physiological and biomechanical characteristics may be performed for more in-depth analysis and monitoring of training for middle- and long-distance runners.

The specific aims were:

- To evaluate whether the results of a lactate-threshold test on a treadmill may be influenced by a short rest interval for blood sampling instead of the more hazardous sampling during continuous running (Study I).
- To measure running economy during treadmill and indoor track running with a previously validated (in study II) portable device and compare its precision to that of Douglas bag results during treadmill running (Study III).
- To investigate how well a single-point V_{disp} from a convenient position transducer and accelerometer corresponds to the CoM V_{disp} measured with the more sophisticated ProReflex optoelectric system (Study IV).
- To evaluate the precision of stance-phase duration measured with a 40-beam infra red web during treadmill running compared with that of a validated contact shoe (Study V).

3 MATERIAL AND METHODS

3.1 STUDY POPULATION AND DROP-OUTS

All studies included well-trained athletes from a variety of endurance sports and predominantly elite running. Generally, many of the participants were competing at a high national level and, in some cases, internationally.

The participants included both track and field mid- and long-distance runners and elite orienteers. They were recruited from clubs, sports schools and individuals regularly attending routine testing in our laboratory.

In Study II parts b and d, 12 and 15, respectively, moderately-trained or sedentary people participated in a low-work-rate group (LWR).

As study II (parts a and c) and III dealt with measurements of high range VO_2 max and long durations of high-intensity steady-state work-loads, it was of great importance to include extremely well-trained persons (rowing, triathlon, road cycling, track and orienteering running).

In Studies IV and V track and orienteering runners, but also soccer players, were included with the criterion to being comfortable with treadmill running at velocities up to $6.1 \text{ m} \cdot \text{s}^{-1}$.

In study III one runner dropped out after one session due to a microrupture in the left calf muscle and one after session three due to a prolonged cold.

Table 1. Characteristics of the participants in Study I-V. Means and \pm SD.

	Age (yrs)	Mass (kg)	Height (cm)	VO_2 max ($\text{L} \cdot \text{min}^{-1}$)	VO_2 max ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	V_E max ($\text{L} \cdot \text{min}^{-1}$)
Study I n=10	21 ± 3	68.5 ± 5.8	180.3 ± 8.8			
Study II a* n=14	26 ± 5	79.9 ± 12.2	183 ± 9.3	4.86 ± 0.78	60.8	192 ± 33.1
Study II b n=12	35 ± 10	85.1 ± 11.4	179.6 ± 7.4			
Study II c n=15	30 ± 4	82.4 ± 6.2	185.5 ± 4.5	5.10 ± 0.37	61.9	196.4 ± 29.6
Study II d n=15	29 ± 5	82.9 ± 6.5	184.0 ± 7.1			
Study III n=14	24 ± 5	68.3 ± 5.9	179.3 ± 5.1	4.59 ± 0.34	67.4 ± 4.0	167.8 ± 19.9
Study IV n=13	23 ± 2	71.2 ± 7.9	180.2 ± 5.7			
Study V n=9	25 ± 6	69.4 ± 7.6	175.5 ± 5.8			

* Including two females. Participants in all other studies were male

3.1.1 Genus perspective

Several studies deal with validations using the human as a biological standard, assuming the least possible variation under standardized conditions.

Results on how variables measured in the present studies (VO_2 , V_E , submax and max, blood lactate levels, RER, Hb and Hct) are influenced by follicular and luteal phases in endurance-trained female athletes have been inconsistent (*Leburn, review 1993*).

As most of the measurements in studies I-III were performed over periods from one to several weeks it was judged that a further possible factor of variation would be to include female participants. Further, as one aim was to challenge the equipment validated with the highest possible VO_2 and V_E , the inclusion of well-trained male athletes was less disputed.

3.2 BLOOD LACTATE MEASUREMENTS

Blood lactate was analysed to establish lactate thresholds (studies I and III), and for control of steady-state levels and post-peak levels (studies II and III). Micro blood samples (~ 10 μL) were taken from punctured fingertips and analysed according to the manufacturers' manuals. In study I a non-lysing method was used (Analox GM7, Analox Instruments Ltd, UK), and in Studies II and III a haemolysing method (Biosen C-Line, EKF-Diagnostic GmbH, Germany).

3.3 MEASUREMENTS OF OXYGEN UPTAKE

3.3.1 The Douglas bag equipment

In studies II and III, a new Douglas bag (DB) system was used as gold standard (*Åstrand, Rodahl 1968, Casaburi et al. 2003*). The equipment consisted of O_2 and CO_2 analysers (Analyzer Mod. 17518^A and 17515^A VacuMed, Ventura, Cal. USA), a custom-made, balanced, 160 L spirometer, air- and gastight bags and a custom-made bag stand (Fabri AB, Spånga, Sweden) and a three-way valve with stop-watches. The 120 and 160 L bags with stopcocks were made of gastight polyurethane and coated with polyamide fabric (Trelleborg Protective Industries AB, Ystad, Sweden). Combitox face masks (Dräger Safety AG, Lübeck, Germany) were used with both DBM and the portable metabolic device (PMD, see below). When measuring with the DBM, a mask with non-re-breathing valve air inlets and a Radiax Valve[®] (Viasys Healthcare GmbH, Hochberg, Germany) was used. The exhaled air was led through a 1.75 m lightweight hose to the bags via the three-way stopcock. Before using the DB system the function of each part was separately checked as well as that of the entire system.

3.3.2 The portable metabolic device

In study II the portable metabolic device, PMD, (Oxycon Mobile, v. 5.10, Viasys Healthcare GmbH, Höchberg, Germany) was validated against the DBM (study II) during ergometer cycling and thereafter used in study III for treadmill and track running. The device consists of four units; a transmitter unit (DEx), a measuring unit (SBx) with mask and flow meter, a receiver/interface/calibrator (PCa) and a computer (PC). The DEx and SBx units were attached to a special harness, here worn on the back. The total weight of the equipment carried was 1.3 kg. During DB measurements the same harness was worn but with the DEx and SBx units replaced by dummies of the same size and weight to maintain standardised conditions in all the measurement sessions. The PMD was calibrated according to the manufacturer's manual using the automatic volume-and gas-calibration functions. The Dräger face mask used with the PMD has its only air inlet and outlet in front of the mouth, with a

flow turbine fitted by in a housing. The Nafion sample line, leading inhaled and exhaled air samples from the housing to the analysers, was changed after each measurement in order to prevent reduced humidity equilibrium capacity.

3.3.3 Expressing oxygen uptake during running

When body mass is increased by adding weight, the oxygen uptake per kg transported mass decreases in children and adults. Thus the increase in the mass carried will be greater than the increase in metabolic demand. Bergh et al. (1991) found when studying endurance-trained male and female athletes from different sports that both submaximal and maximal VO_2 ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) decreased with increased body weight. A more suitable expression of VO_2 submax, when comparing light with heavy, female with male athletes would be ($\text{mL} \cdot \text{kg}^{-0.76} \cdot \text{min}^{-1}$). For VO_2 max values the $\text{mass}^{0.71}$ fitted better than M^1 .

Sjödin and Svedenhag, (1994) investigated growing boys and suggested that VO_2 was related to $\text{kg}^{0.75}$. Using this expression, VO_2 submax remained unchanged for both untrained and trained boys during growth. Another article (Svedenhag 1995), with an enlightening comparison between two equally performing distance runners, but with very different body mass, showed possible misinterpretations of the runners' running economy and VO_2 max when using kg^1 instead of $\text{kg}^{0.75}$. In the present Study III in mass-related VO_2 is expressed with both exponents.

3.4 MEASUREMENTS OF VERTICAL DISPLACEMENT

In study IV, V_{disp} was measured with three methods; an optoelectronic motion-capture system, a position transducer and accelerometers. Signals from all three systems were synchronously acquired at 1500 Hz through an A/D convertor with 16 bit resolution.

3.4.1 Optoelectronic motion capture system

The eight cameras of the 3D motion capture-system (ProReflex MCU 1000 System, Qualisys AB, Gothenburg, Sweden) were mounted on the walls close to the ceiling around the treadmill. The cameras emitted infrared light at 150 Hz to 36 spherical reflective markers mounted on the participants and collected its trajectories with great precision.

3.4.2 Position transducer

The position transducer (Mod. 1850-50, HIS-Houston Scientific International Inc, Houston, US) was mounted 2.5 m above the treadmill. The transducer has a variable electrical resistor and a thin inextensible wire connected to a spring-loaded axis. The voltage output was proportional to the change in the wire length. The position transducer wire was connected to the back of a strap around the participant's waist. The strap was tightened just below the crista iliaca anterior superior and secured with surgical tape.

3.4.3 Accelerometers

Two single-axis accelerometers (Mod. 8325B10 Kistler Instrumente AG, Winterthur Switzerland) with an acceleration range of ± 10 g were placed at the sacrum orthogonal to each other. They were oriented in the sagittal plane, approximately perpendicular to the coronal and transversal planes. We assumed that all motion was in the sagittal plane.

3.5 MEASUREMENTS OF STRIDE

The temporal pattern of the stride from touch-down (TD) to toe-off (TO) was recorded with two methods; a contact shoe and an infrared light device. Both methods permitted measurements of consecutive strides on the treadmill, and data were sampled simultaneously at 500 Hz from both devices. The signals were connected to an A/D convertor and stored on a hard disk for later analysis. The stride graphs were analysed manually with the analyzing tool in the Data Studio software (Pasco Scientific, CA, US). The change in the CS and IR₄₀ graphs (>0.01 and >0.05 V respectively) before TD was used as identification level of TD and TO.

3.5.1 Contact shoe

The contact shoe was prepared by gluing silicon rubber tubing to the outer perimeter of the sole. At TD and TO the pressure change in the tube was converted to a voltage change by means of a pressure transducer. In a previous investigation the contact shoe was validated against a force plate, showing a device difference at TD and TO of less than 3 ms according to Nilsson et al. (1985).

3.5.2 Infrared light device

One bar with 10 emitters and one with four receivers gave a tight web of 40 IR (880-940 nm) beams pulsing at 10 kHz, 10 mm above the treadmill surface. The bars were mounted in front and at the end of the treadmill, covering an area of 240 x 3400 mm. Disconnecting and reconnecting any part of the web was recorded as TD and TO of that stride.

3.6 TERMINOLOGY AND DEFINITIONS

In Studies I and III *lactate thresholds* were measured. This refers to the concept of calculating running velocity (and HR) at a blood lactate concentration of 4 mmol · L⁻¹, described as onset of blood lactate accumulation (OBLA) (Sjödín et al. 1981).

In study II *peak oxygen uptake* was measured. The term refers to the highest possible oxygen consumption achieved for a particular mode of exercise, in this case ergometer cycling (Adams 2002).

In study III *maximal oxygen uptake* was recorded, defined as the highest value achieved among all measurements modes, usually during treadmill running (Adams 2002).

In study III the term *running economy* (RE) was frequently used to refer to oxygen uptake in submaximal level treadmill running (different velocities) during steady-state conditions (Costill et al. 1970, 1973).

The term *aerobic running capacity* or *fractional utilization* relates to the percentage of VO₂ max values used when running at a specific submaximal velocity and at the calculated threshold velocity (study III).

Concerning definitions of stride variables (studies IV and V) the *stance phase* (or *support phase*) is the phase from touch-down (TD) to toe-off (TO) of the foot. *Swing phase* is the phase between TO and TD of the same foot in the subsequent stride. The stance phase plus the swing phase of the same leg is defined as the *stride cycle*. Finally, a *step* is the phase from TD of one foot to TD of the other (Nilsson, Thorstensson & Halbertsma 1985, Cavanaugh & Kram 1989).

3.7 STATISTICAL METHODS

Results in Studies I-V are presented as mean values, with either one standard deviation (SD) and/or range and 95% confidence interval (CI). Table 2 presents the type of statistical analysis undertaken for each in each study.

Table 2 Statistical methods used in Studies I-V.

	Study I	Study II	Study III	Study IV	Study V
Students <i>t</i> test	x	x	x		x
Repeated –measures ANOVA			x		
Coefficient of variance		x	x		
Bland Altman		x	x	x	x

In all the studies the level of statistical significance was set at $p < 0.05$. STATISTICA software (7.0, Stat Soft Inc, Tulsa, OK, USA) was used for all analysis except for the Bland-Altman graphs (*Bland and Altman 1999*), which were created, with the Graph-Pad 4 package (Graph-Pad software Inc., CA, USA).

3.8 ETHICAL CONSIDERATION

After oral and written information about purposes, procedures and risks, all the participants gave their informed written consent to participate. The studies were reviewed by the Ethical Committee at Karolinska Institutet in Stockholm.

Study I: Post-reviewed study found by the Regional Ethics Committee of Karolinska Institutet to be in accordance with ethical guidelines. The Ethics Committee had no objection to the investigation. (859, 03-733, 2003-12-29).

Study II, III: Ethical approval 03-262, (2003-06-26).

Study IV, V: The studies were interpreted as quality controls and therefore not reviewed from an ethical aspect. The Ethics Committee had no objection to the investigations. (363, 03-277, 2003-06-02)

4 RESULTS

4.1 Blood sampling protocols during treadmill running (Study I).

During lactate threshold tests, none of the measured variables (blood lactate and HR) differed between continuous running and running at the same velocities but with 30s intervals. The most important variables running velocity and HR calculated at 2, 3 and 4 mmol · L⁻¹ lactate in blood, did not significantly differ (16.7 vs. 16.5, 17.9 vs. 17.8 and 18.7 vs. 18.6 km · h⁻¹ and 173 vs. 170, 179 vs. 178 and 183 vs. 182 b · min⁻¹ at 2, 3 and 4 mmol · L⁻¹ with breaks and during uninterrupted running, respectively).

These results permit the researcher to eliminate the sometimes risky (due to concentration problems for the runner) and difficult item of puncturing and collecting blood from the fingertip (related to the investigator) during running, without affecting the outcome of the threshold results. The lactate-threshold measurements included in later investigations (as in study III) were performed with the 30s-standing-still blood-sampling protocol.

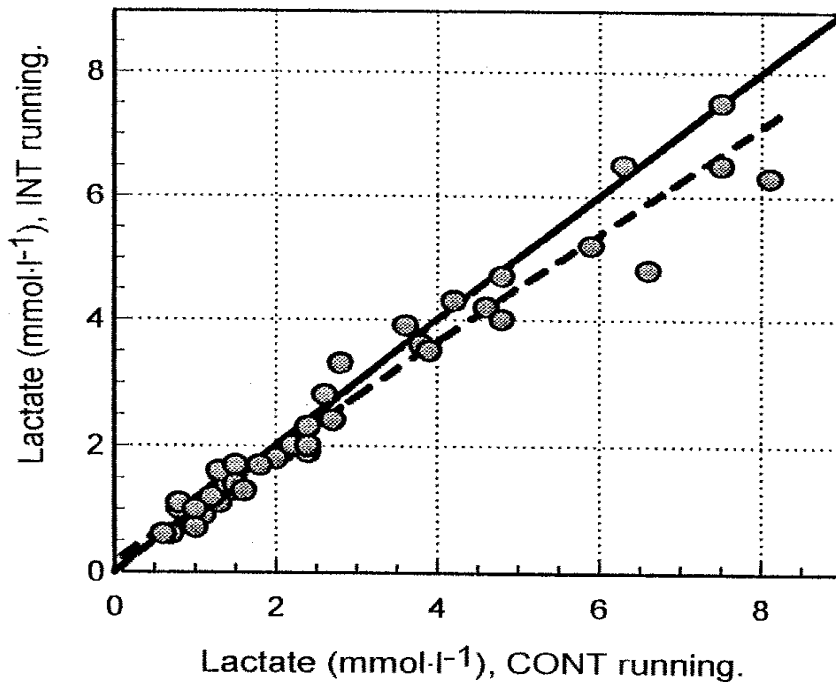


Figure 2. Blood lactate concentration during continuous and interval running at speeds from (12 to 21 km · h⁻¹).

4.2 Evaluation of Oxycon Mobile portable metabolic device against the Douglas bag method (Study II).

As a prerequisite for more field-like measurements (track running), the portable metabolic device (PMD) required evaluation under controlled laboratory conditions including ergometer biking.

Two versions of the PMD were evaluated over a wide range of oxygen uptake. In the *first version* test-retest reliability was investigated. Here the coefficient of variation (CV) varied between 2% and 7% for the metabolic parameters at different work rates (25 w to maximal work rates). The CV was in general similar to those obtained with the Douglas bag method (DBM). At submaximal work rates, systematic errors were found for PMD VO_2 (+6 to 14 %) and VCO_2 (+5 to 9 %) as compared to DBM. At VO_2 max both variables were slightly lower (-4.1 and -2.8 % respectively) related to DBM.

With the *second version* of the PMD, VO_2 was measured accurately within a wide range (1-5.5 $\text{L} \cdot \text{min}^{-1}$), while VCO_2 was overestimated (3-7 %). V_E was accurate at submaximal work rates with both PMD devices, whereas there were underestimations (4-8 %) at VO_2 max.

The recent study demonstrates for the first time that a wide range of VO_2 can accurately be measured with the second-generation of the Oxycon Mobile PMD.

4.3 Running economy on treadmill and indoor track determined with portable and/or Douglas bag equipments (Study III).

PMD treadmill and track running economy: VO_2 (Figure 3a) and V_E were significantly higher during 30-min track running than during treadmill running at 0.25 and 8.2 $\text{L} \cdot \text{min}^{-1}$ (6 and 8%) respectively; whereas RER was similar. All PMD VO_2 and those during the 4-x-4-min threshold measurements were significantly higher (~5%, Figure 3c), whereas V_E did not differ between track running and treadmill running.

PMD vs. DBM during treadmill running: The accuracy test reveal that the PMD mean VO_2 value was biased somewhat higher (~ 0.2 $\text{L} \cdot \text{min}^{-1}$) than that for the DB, corresponding to an overestimation of 3.5-6.5 % for the PMD. The ± 95 % level was some $\pm 0.3 \text{ L} \cdot \text{min}^{-1}$. No bias was detected in V_E mean value and the 95 % limit of agreement was $\pm 15 \text{ L} \cdot \text{min}^{-1}$. However, a tendency to a lower V_E in the higher range was seen for the PMD (-5.5 % during maximal work load). The mean RER value was positively biased for the PMD. The incremental threshold tests (Fig. 3c) and the 30-min treadmill runs showed a significant 5% to 6 % higher VO_2 when measuring with the PMD, whereas no difference was detected in V_E . PMD RER was about 3% higher than that for DB. In the maximal test, the PMD VO_2 was significantly higher and V_E max significantly lower than for the DB.

Both DB and PMD fractional oxygen uptake was stable during the 30-min treadmill runs, corresponding to 81 and 83 % of VO_2 max respectively. The within-test CVs were 2.3 and 2.4 % between mins 10 and 30 for DB and PMD, respectively. VO_2 was also stable for the PMD during the 30-min run on the track and was 88 % of the max value. The within-test CV was 2.5 % between mins 10 to 30.

HR and Blood measurements: The 30-min track runs showed a tendency to higher HR and blood lactate compared to treadmill running, increasing over time. Lactate threshold velocities calculated from three occasions (on the treadmill with PMD and the DB and from the 200 m track with the PMD) were 16.7 ± 1.0 , 16.7 ± 1.0 and $16.3 \pm 0.9 \text{ km} \cdot \text{h}^{-1}$, respectively, with no significant difference in between (Figure 3 b). No differences were detected in HR or blood

lactate from treadmill and track measurements on 12, 14, 16 and 18 km · h⁻¹ respectively. Likewise, no difference was found in mean blood haemoglobin values (reflecting the oxygen-carrying capacity) between the three measurement days (155.7 ±7.6, 155.0 ±8.4 and 153.7 ±8.3 g · L⁻¹).

Conclusion: Running economy during track running on submaximal and at threshold velocities is lower than that in treadmill running. Calculated 4 mmol · L⁻¹ velocity (~ 4.6 m · s⁻¹) from TM and track running was similar. The accuracy of the PMD compared to DB during running is acceptable and the reproducibility is high.

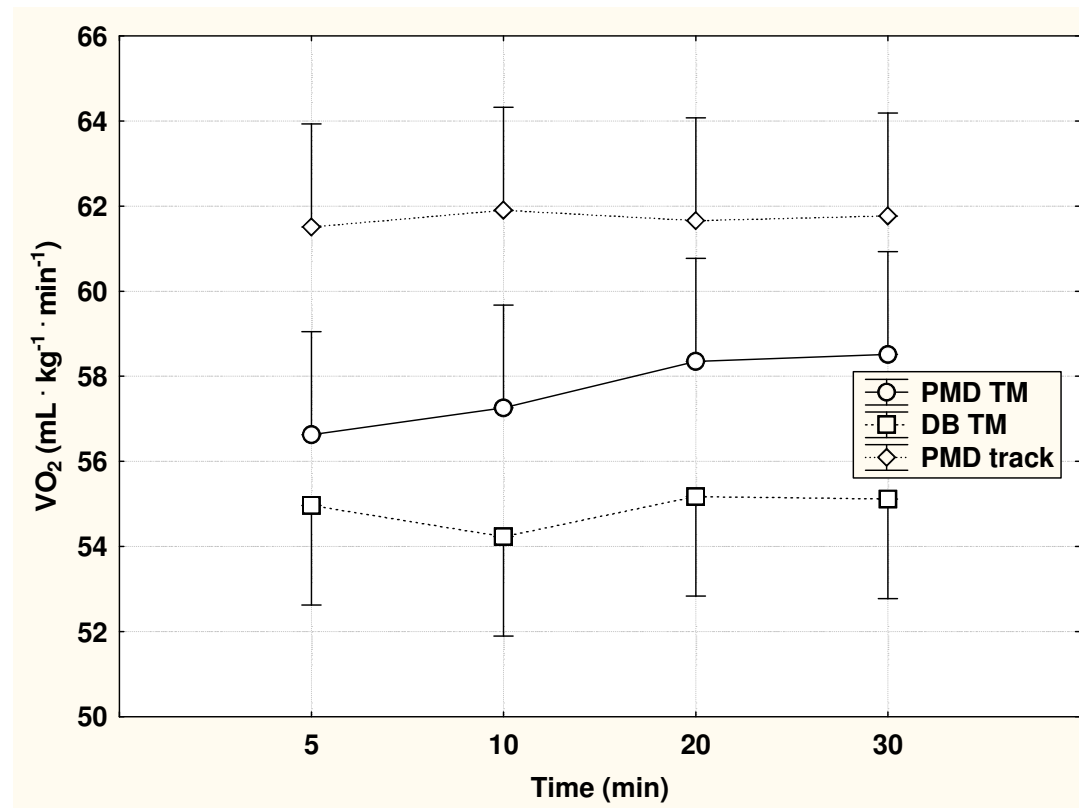


Figure 3a. Mean values of VO₂ during 30 min track and treadmill running with the PMD and during 30-min treadmill running with the DB. Significant differences were detected between DB treadmill and PMD track.

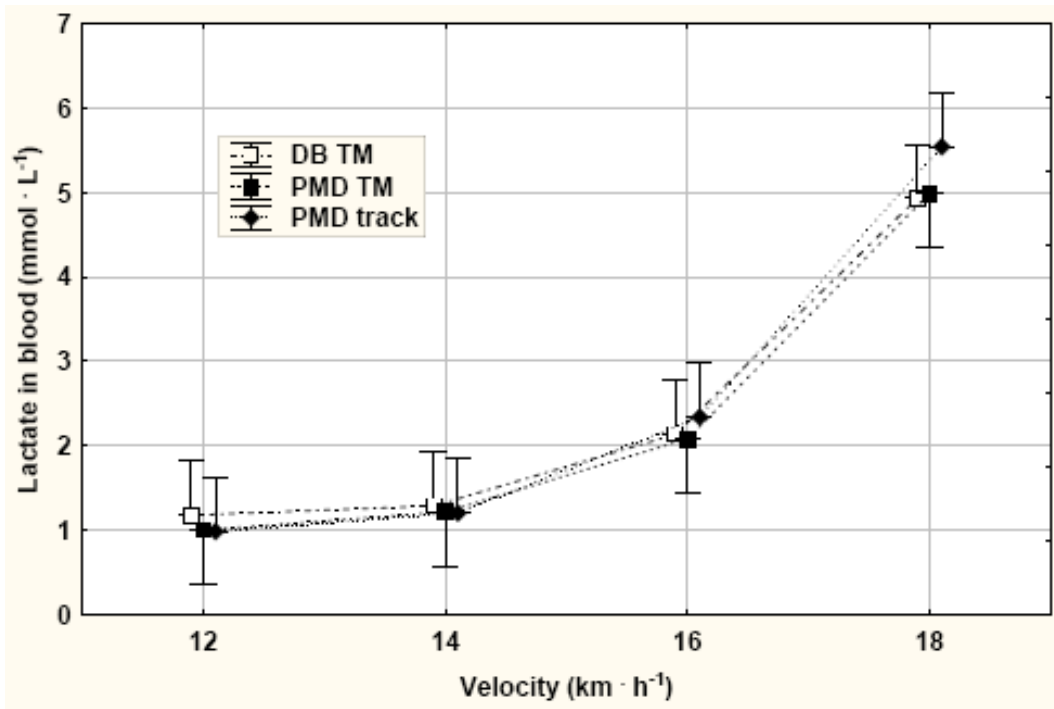


Figure 3b. Blood lactate mean values from threshold tests on track and treadmill running with a very small difference for the calculated $4 \text{ mmol} \cdot \text{L}^{-1}$ velocity.

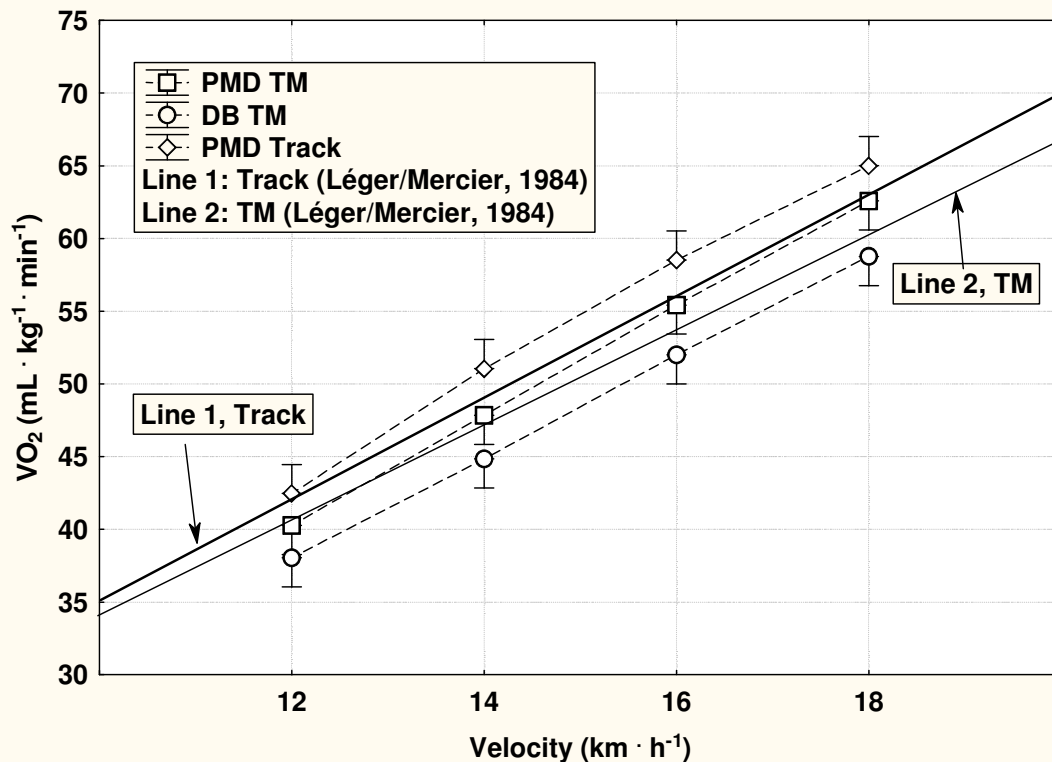


Figure 3c. Mean values and confidence interval of VO_2 during 4×4 min runs for all three modes. Differences in $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ between DB and PMD on treadmill and between PMD on treadmill and track are approximately the same. Léger's and Mercier's (1984) calculated gross energy cost for track and treadmill running are included (solid lines).

4.4 Special comments on V_E measurements in Studies II and III

In studies II and III V_E (3 measurement occasions) showed similar results from low- to high-range volumes: Low range V_E (50-100 L · min⁻¹) was equal with PMD and DB measurements in all studies, but in the higher range (100-225 L · min⁻¹), the PMD V_E diverged increasingly, with lower values than for the DB. The PMD measured via the triple-V turbine transducer and results were compared to spirometer volumes from the Douglas bags. The technical data section in the Oxycon Mobile Manual indicates a range of 0-300 L · min⁻¹ with an accuracy of 2% or 0.05 L · min⁻¹, and must therefore be questioned.

The two first graphs (4 a and b) originate from Study II where two versions of the PMD were validated during ergometer cycling. The third graph (4 c) is from study III during treadmill and track running where the latest version of the PMD was also compared to the DB.

Graphs 5 a and b, originate from validation of the stationary Oxycon Pro device compared to the DB (*unpublished data, Gullstrand et al.*). The same triple-V volume sensor as in the PMD was used in the Oxycon Pro. The mixing chamber mode was used in separate measurements (Figure 5 a) and connected serially (Figure 5 b) to the bags where only the expired volume was measured, including no turbine change of direction. With the mixing chamber setup, no tendency of divergence between the devices was seen from low ventilation to the highest. It seems that in BBB mode (triple-V in front of the mouth) with the impeller changing direction, exposure to saliva and humid air caused lower V_E values above 100 L · min⁻¹. The change of direction at high V_E may generate a “spin-after-stop” effect, leading to significant errors, as previously addressed by Yeh et al. (1987) and Macfarlane (2001).

A further explanation of the lower V_E max with the PMD may be that the expired air temperature was not measured but set to 31 °C in the algorithm for calculating V_E . If expired air temperature increases from submaximal to maximal workloads, V_E will not be correctly compensated for. In the Oxycon Pro (see above) the exhaled air temperature was continuously measured in the mixing chamber and V_E did not differ at any work load from the Douglas bag measurements.

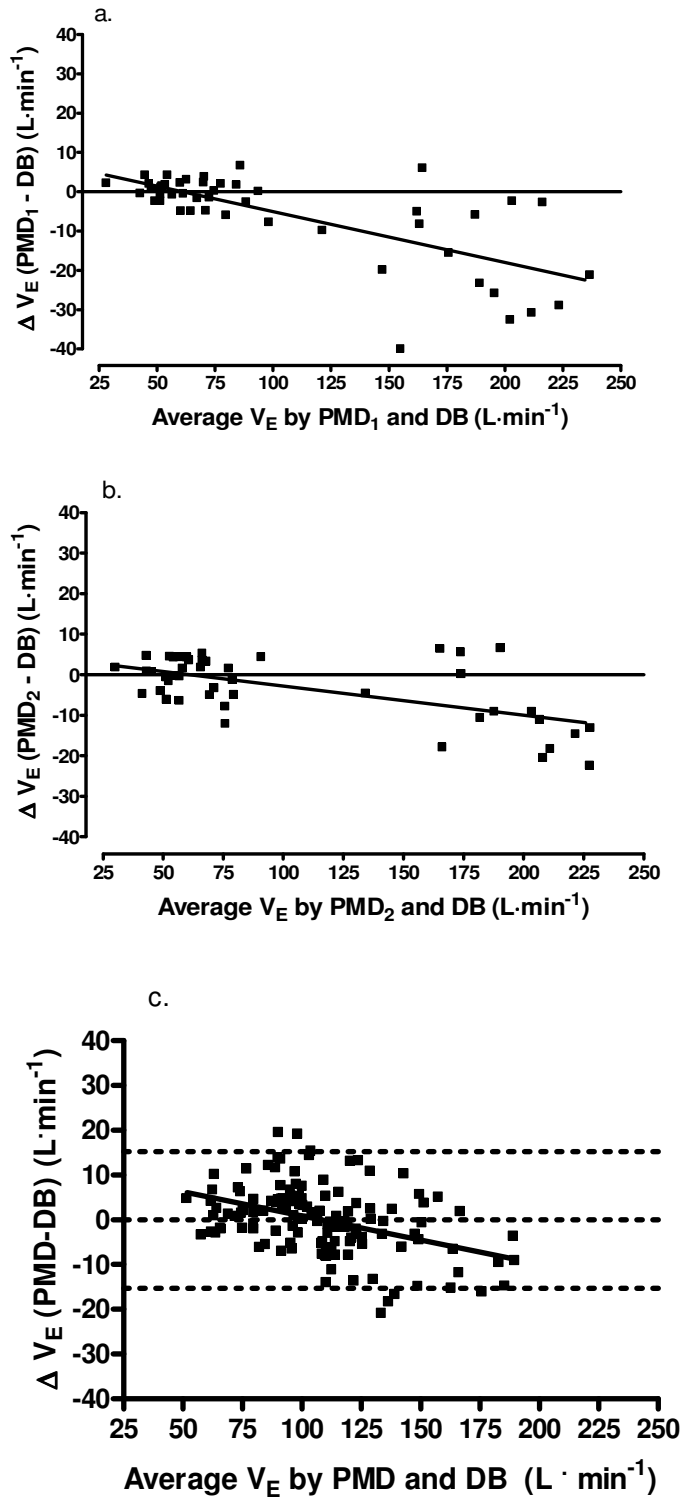


Figure 4. V_E over a wide range measured with the first and second versions of the PMD compared to the DB during ergometer biking (a and b), and with the second version during running (c). A clear and similar tendency to decrease in V_E with the PMD is detected in the higher V_E range in all graphs.

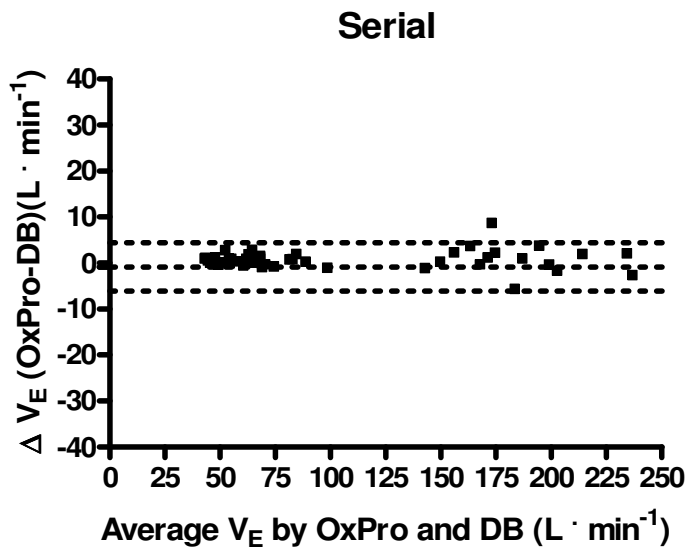
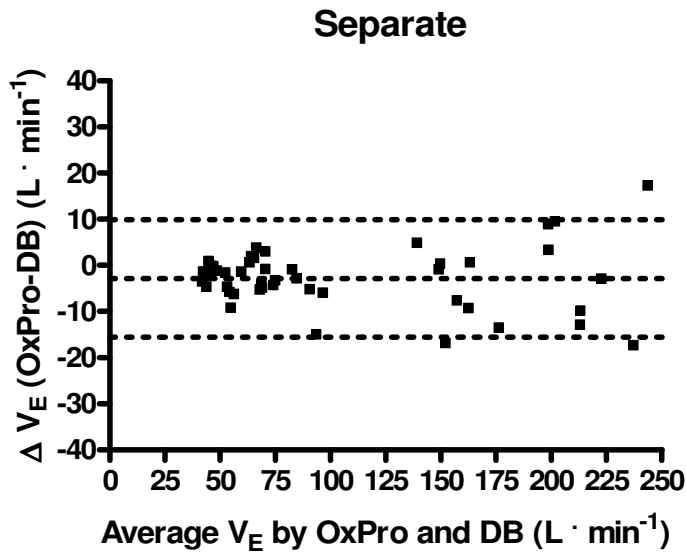


Figure 5 a and b show a V_E range similar to that in fig. 4, measured with the same turbine but with the Oxycon Pro stationary analyser in a mixing chamber setup compared to the DB, separated and series-connected. The turbine measured only the V_E of the expired air and consequently did not change direction. No tendency to deviate from the mean value with increased V_E was seen (*Gullstrand et al. unpublished data.*).

4.5 Measurements of vertical displacement in treadmill running. A methodological comparison (Study IV).

The aims of Study IV were (1) to evaluate measurements of vertical displacements (V_{disp}) of a single point on the sacrum as an estimate of the whole-body centre of mass (CoM) V_{disp} during treadmill running and (2) to compare three methods for measuring this single point. The three methods were based on a position transducer (PT), accelerometers (AM) and an optoelectronic motion capture system (SM). The criterion method was V_{disp} of whole-body CoM measured with the latter. Thirteen subjects ran at 10, 12, 14, 16, 18, 20 and 22 $\text{km} \cdot \text{h}^{-1}$ with synchronous recordings with the three methods. Four values for (V_{disp}) were derived: (1) V_{disp} of CoM calculated from a segment model consisting of 13 segments tracked with 36 reflective markers, (2) V_{disp} of the sacrum recorded with the PT, (3) V_{disp} of the sacrum calculated from the AM, and (4) V_{disp} of the sacrum calculated as the mid point of two reflective markers (sacrum marker, SM) attached at the level of the sacral bone. The systematic discrepancy between the measurements of sacrum V_{disp} and CoM V_{disp} varied between 0 and 15 mm and decreased with increasing running velocity and decreasing step duration. PT and SM measurements correlated strongly, whereas the AM showed a variability increasing with velocity. The random discrepancy within each subject was 7 mm for all three methods. In conclusion, single-point recordings of the sacrum V_{disp} may be used to monitor changes in V_{disp} of CoM during treadmill running

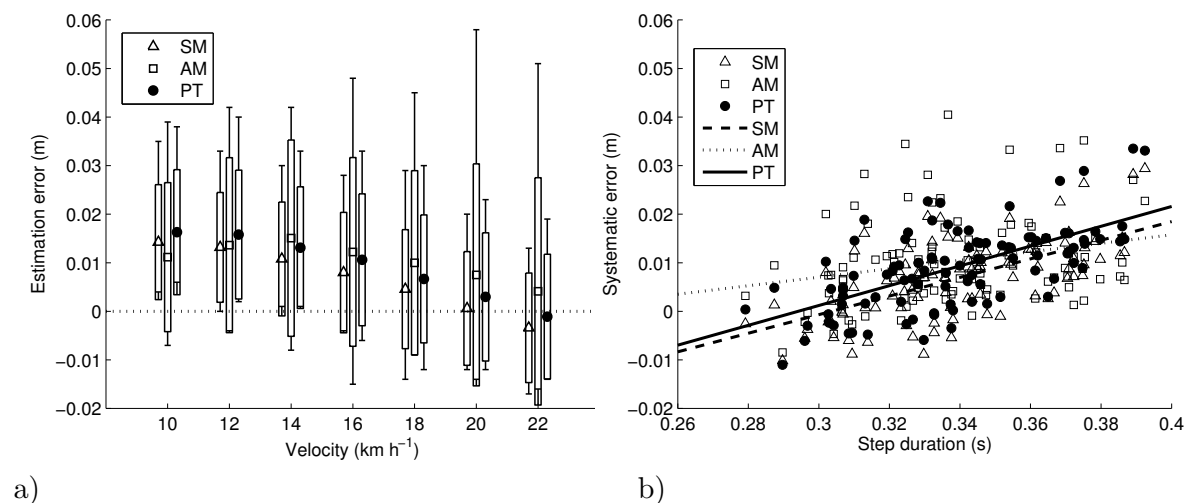


Figure 6 a) estimation error using methods SM, AM and PT at the different velocities. The error is presented with mean 95% confidence interval (box) and range (whiskers). Zero level on the y-axis represents CoM measured with the criterion method. b) Systematic error for each method and all velocities plotted against step duration.

4.6 A new method for recording the temporal pattern of stride during treadmill running (Study V).

In a pre-study, two participants ran at 2, 3, 4, 5 and 6 $\text{m} \cdot \text{s}^{-1}$, on a straightway to verify the close relation between CS and FP shown earlier. Mean support duration was 16, 16, 13, 14 and 10 ms longer during running over the IR_{40} than measured with the FP at 2, 3, 4, 5 and 6 $\text{m} \cdot \text{s}^{-1}$, respectively. The longer duration with the IR_{40} was characterised by an earlier touch-down and a delayed toe-off compared to FP-recorded stance-phase durations.

From the main study V, the mean stance phase durations of IR_{40} and CS and the difference during running at 2.8, 3.3, 3.9, 4.4, 5.0 and 5.6 $\text{m} \cdot \text{s}^{-1}$ are presented in Figure 7. The mean IR_{40} vs. CS stance duration on the treadmill was systematically and significantly longer at all velocities (11.5 ± 8.4 ms). The mean value bias was -11.5 ms with 95 % limits of agreement from -28 to 5 ms. No tendency to change in the mean value difference could be seen over the stance phase range measured. The 11.5-ms-longer stance phase for IR_{40} was related to a delayed TD (8.3 ± 6.2 ms) as well to a TO (3.2 ± 5.3 ms) that was delayed compared to CS.

The systematic and stable difference vs. the criterion CS indicate that the IR_{40} device may be used to analyse stance durations with high accuracy during treadmill running.

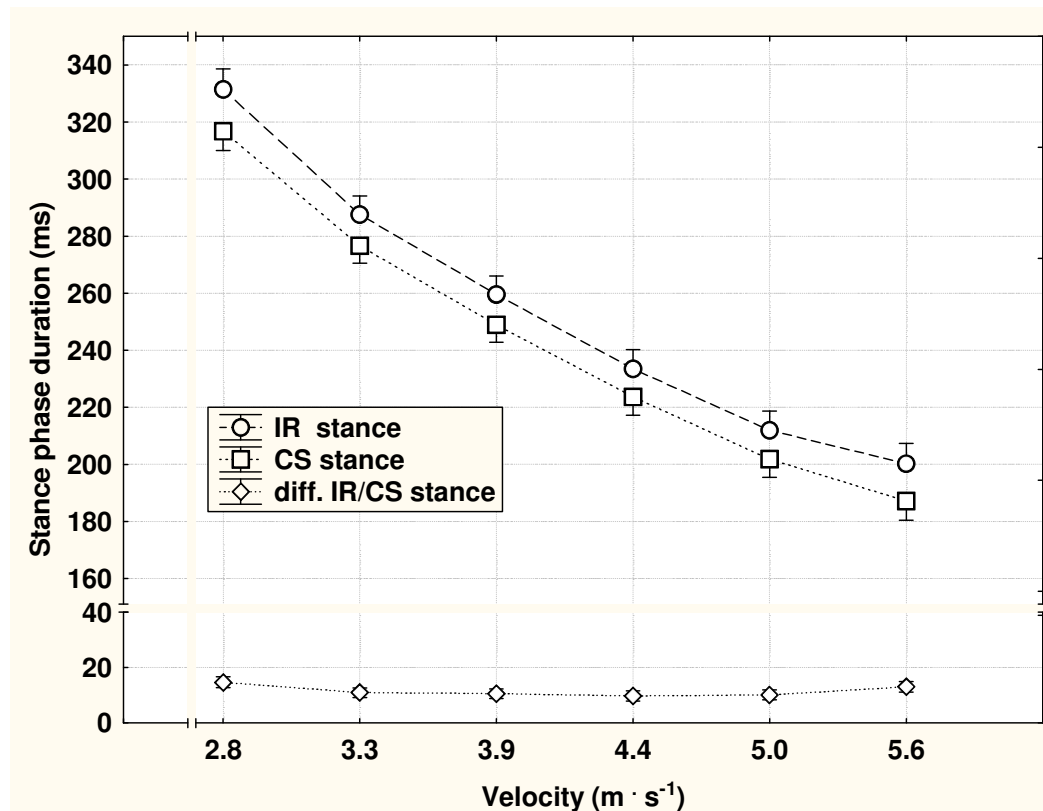


Fig. 7. Stance phase durations recorded with IR_{40} and contact shoe (CS). Differences plotted versus running velocities on treadmill (means and 95% confidence intervals). The IR_{40} and CS stance phase durations differed significantly at each velocity and both durations were significantly shorter at each higher velocity. The IR_{40} /CS difference persisted over the velocity range measured.

5 DISCUSSION

The general aim of the studies was to advance present knowledge of running capacity and to evaluate new measurement methods used for its improvement.

5.1 Blood sampling protocols during treadmill running (Study I).

Lactate in blood related to exercise has been discussed in the literature since the early nineteenth-hundreds (*Fletcher and Hopkins 1906*). The basic concept intended to identify a critical work load leading to a disproportional increase in blood lactate (*Christiansen et al. 1914*), later defined as the anaerobic threshold (*Wasserman and McIlroy 1964*). An important condition for the maintained interest in the anaerobic threshold was its much higher correlation to endurance performance ($r > 0.90$) than for example VO_2 max ($r \sim 0.65$) in marathon running (*Sjödín and Svedenhag 1985*).

During the 1970s and 1980s the development and use of lactate thresholds progressed, predominantly in the former East and West Germany for evaluating and monitoring elite athletes' training. Mader's two-point test (*Mader et al. 1976*) based on $4 \text{ mmol} \cdot \text{L}^{-1}$ as a critical concentration became widespread. Further essential circumstances for the interest were improvements in micro-sample methods ($5\text{-}50 \mu\text{L}$) with blood taken from punctured ear lobe or finger tip, plus increasingly fast and accurate analyzing methods. The previous method of inserting needles in arterial or venous blood vessels was not risk-free and not suitable in field conditions (*Hollmann 1985*).

Sjödín and Jacobs (*1981*) introduced the concept of onset of blood accumulation (OBLA), using the $4 \text{ mmol} \cdot \text{L}^{-1}$ as a rule-of-thumb concentration for critical work load. A number of reports from Sjödín et al. on runners' physical capacity were published, including OBLA measurements (*Svedenhag, Sjödín 1984, 1994, Sjödín, Svedenhag 1995*).

The fixed concentration concepts were however criticized as valid-but-with-limitations. The individual anaerobic threshold was then described by (*Stegmann et al. 1981*). However, Heck et al. (*1985*) in a comprehensive article defended the $4 \text{ mmol} \cdot \text{L}^{-1}$ concept.

As the focus in study I was to compare threshold velocities during treadmill running with and without 30 s rests, it was judged reasonable to use the frequently reported OBLA or fixed $4 \text{ mmol} \cdot \text{L}^{-1}$ protocol (*Sjödín and Jacobs 1981*).

The outcome of study I was that measuring lactate in blood during treadmill running may be performed with and without 30 s of rest without affecting running velocity or HR at 2, 3 and $4 \text{ mmol} \cdot \text{L}^{-1}$. It is speculated that the result would be the same if other work modes such as ergometer rowing, cycling and kayaking or other threshold concepts with and without breaks were compared. The 4-5 x 4 min work loads including breaks was thereafter applied repeatedly in Study III on treadmill and track to establish OBLA velocity.

A part of the OBLA concept is that approximately $4 \text{ mmol} \cdot \text{L}^{-1}$ in peripheral blood mirrors a concentration sustainable in steady state during continuous work. Higher work loads will consequently prompt blood lactate accumulation. This aspect of OBLA was clarified and supported by Heck et al. (*1985*). They used a 28-min protocol where runners performed at velocities corresponding to $4.0 \text{ mmol} \cdot \text{L}^{-1}$ as well as higher velocities derived from the basic incremental tests. With this protocol they defined the term MaxLass as being the highest steady-state lactate with maximally $1 \text{ mmol} \cdot \text{L}^{-1}$ increase during the final 20 minutes. They found in their study 4.02 ± 0.7 , range 3.05 - $5.5 \text{ mmol} \cdot \text{L}^{-1}$.

This concept was also focused on in study III (and pre-study IV, Appendix). The $4 \text{ mmol} \cdot \text{L}^{-1}$ velocity was established on both treadmill and on track and tested during 30-min-steady-state running on treadmill and track. To account for air resistance (*Pugh 1970*), 95% of the $4 \text{ mmol} \cdot \text{L}^{-1}$ velocity was used. No significant differences were found in blood lactate between treadmill and track incremental testing or in treadmill and track steady-state running (see Figure 3b, main study II and Figure 1 in Appendix). It can consequently be concluded that incremental tests may be established on both surfaces and that the $4 \text{ mmol} \cdot \text{L}^{-1}$ concept holds true in this study.

5.2 Evaluation of a portable VO_2 system during ergometer biking (Study II).

For approximately a century the Douglas bag method has been used in both laboratory and in the field to measure work capacity and energy demands in different sports (*Hollmann 1997*). Under field conditions there are however some problems associated with carrying and changing the bags. To address this shortcoming, portable metabolic devices (PMD) for field use have been developed during the last decades (*Macfarlane 2001*). Their use, however, has been frequently questioned concerning reliability and validity (*Hodges et al. 2005*).

In preparation for later field measurements we evaluated a new PMD over a wide range of VO_2 using a mechanically braked pendulum ergometer bike in Study II. This arrangement offers the most standardized and handy conditions possible, still using physiological/biological validation (*Casaburi et al. 2003*). The criterion method was a carefully controlled new Douglas bag system. Two versions of the PMD were evaluated. The first measured VO_2 significantly too high in the submaximal range (2-14%) and too low in the maximal range (4.1%), where V_E was also too low at 8.4%. Reliability was, however high and as good as for the DB method. With the updated version of the PMD, (new firm ware and software) measurements of VO_2 were equal to those with the DB at all work rate levels, while V_E was still significantly low at the highest level at 4.1%. The possible reason for the remaining too low V_E is discussed elsewhere. Validation results from laboratory conditions during ergometer biking are not always transferrable to more field-like conditions, which remained to be investigated.

5.3 Running economy on treadmill and indoor track determined with portable and/or Douglas bag equipments (Study III).

With results from the previous validation study (Study II) of the portable device provided a robust foundation for continued measurements during treadmill running and the more field-like track running. Compared to Study II the PMD was more challenged in study III as the equipment was carried on the back. This resulted in more movement and a test of the telemetric transmission of data. The major aim here was to investigate eventual differences in running economy on treadmill and track. The significantly higher VO_2 and V_E on track compared to treadmill, 6% and 8% respectively, confirmed earlier results representing the air resistance difference (*Pugh 1970*). Now, with the PMD, no calculation related to running velocity and size of the runner and compared to track running is needed as it is already included in the running economy measurement. The runners had no complaints about running with the PMD on their backs and or breathing through the turbine attached to the face mask.

The second aim of the study, investigating the reliability of the PMD compared to DB during treadmill running, did not show such good agreement as during ergometer cycling. The difference between DB and PMD during treadmill running was significant, with 5-6% higher

VO₂ for the PMD. During the maximal tests PMD measured 5.5% too low vs. DB, which was not found in the previous ergometer bicycle validation with the second-generation PMD.

Reasons for reduced agreement PMD vs. DB during running were not clarified, but may be connected to the more pronounced movement of the equipment on the runner's back compared with that in ergometer biking.

5.4 Measurements of vertical displacement in treadmill running. A methodological comparison (Study IV).

The possibility to easily measure V_{disp} of the CoM during running gives running economy a wider dimension as vertical movements cost energy and preferably should be reduced to a minimum (*Williams and Cavanagh, 1987*). The methods validated here, position transducer (PT) and accelerometers (AM) measurements are based on simplicity (single-point measurements) and were compared to the gold standard, an optoelectrical system with 36 reflectors attached to the athletes.

The high agreement between PT V_{disp} and CoM V_{disp} (0-15 mm) makes the PT practical for fast recordings of V_{disp} during treadmill running. The AM V_{disp} included in the study showed somewhat lower agreement to the criterion method, especially at the highest running velocities, 5.0–6.1 m · s⁻¹.

It was obvious that V_{disp} decreases with higher running velocities (mean ~75 mm at 6.1 m · s⁻¹) and it may be increasingly difficult to further reduce them. However, the individual V_{disp} -velocity graphs showed great discrepancies in lower velocities as well as at the highest. For runners with a V_{disp} of 80 mm and higher at 6.1 m · s⁻¹, the prospect to improve RE by means of a V_{disp} reduction seems promising.

Regarding future measurements on indoor and outdoor tracks, the measurements will need to rely on improved methods based on accelerometers.

5.5 A new method for recording the temporal stride pattern during treadmill running (Study V).

Valid and reliable measurements of the temporal pattern of the stride during running (here treadmill running) are of a great importance relating to analysis of running economy. In this area force plate (FP) measurements represent the gold standard, although the equipment is rather expensive. Moreover, running over one or series of force plates on the ground may involve problems such as reaching the correct speed and hitting the FP without unnatural adjustments of the stride (*Diss 2001, Marigold 2008, Reynolds and Day 2005*). Successful designs of treadmill force plates have been reported (*Kram et al. 1998*) and may be one method, albeit still expensive.

In our study a tight web of infrared light (IR₄₀) was beamed over the treadmill surface so that stance and flight phases of the stride could be registered. Foot contact time measured with IR on the treadmill correlated highly with measurements using a contact shoe (CS), which in turn correlated well with the FP in overground running. The IR device on the treadmill eliminates the use of cables connected to the runners; also, the desired velocity may be kept with precision for long time and without aiming at defined landing areas on the treadmill.

The somewhat longer stance phase (11.5 ± 8.4 ms) with IR₄₀ vs. contact shoe (and FP) was systematic in the whole velocity range measured.

The importance of measuring stance-phase duration is based on its close relation to total and net vertical impulse (TVI and NVI) which in turn correlates to running economy. Reduced stance-phase duration (TVI, NVI) result in lower VO₂ (*Heise and Martin 2001*), and better running economy. In addition, Paavolainen et al. (*1999*) showed that short stance phase correlates well with running economy and performance time in elite orienteers during 5-km track running. Shorter stance duration and good running economy was also recently confirmed by Nummela et al. (*2007*).

6 FUTURE DIRECTIONS

6.1 Field measurements of VO_2 with PMD

The measured validity and reliability of the PMD opens the way for field measurements in several sports. However, remaining uncertainties about outdoor measurements with the influence of humidity, temperature and altitude, should be addressed in future validations. Specific questions to answer in applied sports physiology are for example how well different ergometers in laboratory measurements correlate to real sports activities (competition and training). Rowing and kayaking ergometers may be compared with on-water registrations using the PMD. As the PMD was evaluated over a wide range of work loads, it may also be used in the occupational area and in the clinic.

Different portable devices have been on the market for decades, and a promising level of reliability and validity is reached for the specific device used in the present work. However, additional development of hardware, software and functionality is still needed.

6.2 Vertical displacement in laboratory and on the track

V_{disp} measurement may be further refined by investigating subdivisions of the total V_{disp} (air phase, and downward compliance during foot contact). Methods for registration, effect on running economy and individual pattern may be interesting topics to investigate; another would be how V_{disp} fractions (during flight phase and support phase) change with velocity. As mentioned earlier, measuring V_{disp} with the position transducer is only possible in the laboratory. For track and field measurements the accelerometer (AM) based method needs improvement for better accuracy. Additionally it appears possible to capture and transmit AM data online by connecting to the PMD. This would be most favorable when it comes to measuring one important sub factor for RE.

In a separate study, using the same opto electrical system data as in study IV, it was shown that a minimal marker set (10 instead of 36) for the estimation of CoM represents a good trade-off between simplicity and accuracy in future studies like this (*Halvorsen et al. 2009*).

6.3 Temporal pattern of stride with IR_{40}

Stance phase duration is regarded as one of the few variables (together with V_{disp}) that strongly relate to a good running economy (*Nummela et al. 2007*). The IR_{40} equipment can be permanently mounted on the TM and a combination of simultaneous registrations of VO_2 , V_{disp} and stance phase duration may be of great value for future extended running economy measurements.

6.4 Online monitoring of running economy?

Finding valid and reliable methods for measuring sub factors of importance for RE, improves the conditions for reaching better running economy. The use of visual and auditory real-time feed back of V_{disp} and stride length during treadmill running will be tested and evaluated on well- trained runners. As a continuation to the presented studies visual and auditory computer-based methods have been developed for manipulating V_{disp} and stride length. Preliminary, not completely-evaluated results are at hand. Interest will be focused on whether both acute and long-term changes are possible and whether possible effects will result in measurable and remaining running economy improvement on both treadmill and track.

7 CONCLUSIONS

- The calculated threshold velocity and HR at $4\text{mmol} \cdot \text{L}^{-1}$ was not different when a 30 s interruption for blood sampling was used compared to sampling at the end of each four-min period during continuous running. The sampling-standing-still phase was more convenient and less risky for both athlete and test leader.
- Reliable and stable measurements of oxygen uptake can be performed during running with the PMD device.
- Running economy by means of submaximal oxygen uptake during steady state running is $\sim 6.5\%$ lower during track running compared to treadmill running, which most probably is related to differences in air resistance. Lactate threshold tests give similar results performed on treadmill and indoor track.
- Changes and differences in V_{disp} of CoM may be correctly measured with a single-point recording using a position transducer.
- The temporal pattern during stride analysis can be accurately measured on treadmill using an infrared device giving a dense 40-beam web when mounted on the treadmill.

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My colleagues and friends at the Elite Sports Centre at Bosön for a never-ending support,

My greatly-loved wife Ninni and our children, who over the years have been chasing me along the woodland tracks as well as in the progress of this thesis,

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10 APPENDIX, PRE-STUDIES

Four of the five main studies were preceded by pilot studies and based on years of development work. As the pre-studies include relevant findings, are being frequently implemented but are not presented in the main studies, it may be of interest to review them. They also cast light on the research procedure.

10.1 PRE-STUDY I: Lactate threshold tests on treadmill and/or on overground running?

Gullstrand L, Sjödin B, Svedenhag J.

Lactate threshold tests in running have long been a standard tool for evaluating and monitoring training in most sports institutes. It is performed on a treadmill using a variety of protocols regarding duration and number of repetitions, as well as concerning evaluation method after finishing the test (*Heck et al. 1985*).

In this pre-study (as in main study IV) a fixed $4 \text{ mmol} \cdot \text{L}^{-1}$ concept was used to calculate suitable optimal training velocity according to Sjödin and Jacobs, (*1981*). We noticed however that well-trained runners occasionally experienced the calculated velocity as too intensive during track training.

The pre-study therefore sought to compare velocity (v), heart rate (HR) and perceived exertion (RPE) at $4 \text{ mmol} \cdot \text{L}^{-1}$ lactate in blood (Hla_4), derived from incremental treadmill (at level grade) and 200 m indoor track tests. Further, 30 min runs were performed on a level treadmill and indoor track at 95% of the Hla_4 velocity to see whether Hla , HR and RPE were reproduced at the end. Nine well-trained middle-distance runners participated.

No significant differences were detected in v (15.9 to $15.8 \text{ km} \cdot \text{h}^{-1}$), HR (both modes $187 \text{ beats} \cdot \text{min}^{-1}$) or RPE (13 to 12 in legs, 13 to 13 in breathing) at Hla_4 from threshold tests on treadmill and track, respectively. At the end of the 30-min runs on both surfaces, no significant differences were found in Hla (4.5 ± 0.9 to $4.9 \pm 1.4 \text{ mmol} \cdot \text{L}^{-1}$), HR (190 ± 5 to $190 \pm 5 \text{ beats} \cdot \text{min}^{-1}$) and RPE in legs and breathing (14 to 14 and 14 to 15). (Figure 1).

It was concluded that lactate threshold tests based on $4 \text{ mmol} \cdot \text{L}^{-1}$ can be performed either on treadmill or track with a similar outcome for this category of runners. It was further concluded that 30-min runs at 95% of the Hla_4 velocity will lead to similar values in all variables on a treadmill and a 200-m indoor track and that $4 \pm 1 \text{ mmol} \cdot \text{L}^{-1}$ was reproduced in both running modes.

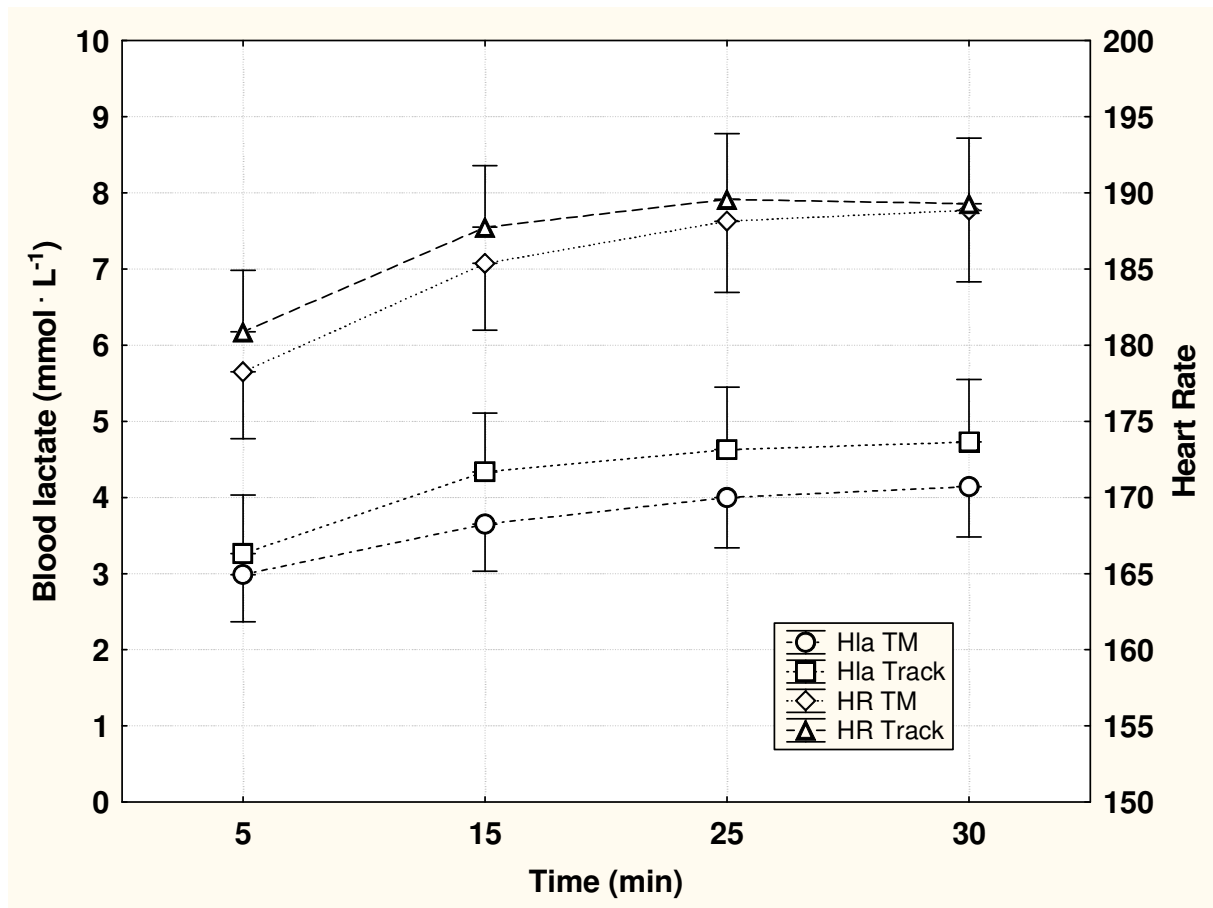


Figure 1. Blood lactate and heart rate development during 30 min running at 95% of the $4 \text{ mmol} \cdot \text{L}^{-1}$ velocity on treadmill and 200 m indoor track (means and 95% Conf. Intervals). No significant differences were detected at any time point between the two running modes in heart rate or blood lactate. At 25 and 30 min, heart rate was significantly higher than at to 5 min on both track and treadmill (Pre-study I).

Effect on main study III:

The protocol from the pilot study was repeated in the main study concerning establishment of lactate thresholds from treadmill and track and the 30-min runs on treadmill and track at 95% of the $4 \text{ mmol} \cdot \text{L}^{-1}$ velocity. Another experience from the pre-study was that control and monitoring of speed during 200 m track running could be accomplished with great accuracy and was consequently used in the main study.

Both studies show that heart rate and running velocity with $4 \text{ mmol} \cdot \text{L}^{-1}$ was the same for treadmill and track. After 30-min running, heart rate was the same in both studies and blood lactate was somewhat higher ($+ 0.5 \text{ mmol} \cdot \text{L}^{-1}$) after track running compared to treadmill, however not significantly in any of the studies.

It was concluded that the used protocols were realistic and confirmed literature data (*Heck et al. 1985*). Results from the pre-studies were also verified in the main studies giving robust foundations for conclusions.

The study offered no an answer to the runners' impression that track training at the threshold sometimes was too demanding, but it was speculated that a portable device measuring VO_2 (as later used in main-study III) could further illuminate this.

10.2 PRE-STUDY II: Vertical and lateral movements related to running economy during treadmill running.

Gullstrand L, Nilsson J, Lindholm T, Ansnes J. (2000) Svensk Idrottsforskning, 2:25-30.

The aim of pre-study II was to investigate the relations between VO_2 and vertical and mediolateral displacement during TM running at submaximal velocities (11, 13, 15 $\text{km} \cdot \text{h}^{-1}$). Ten well-trained male athletes (five mid-distance runners and five from other sports) participated. A skin-marker between the fifth costae and the sacral bone represented an approximation of the body centre of mass. Vertical and mediolateral displacements (V_{disp} and $M\text{-}L_{\text{disp}}$) of the marker were videofilmed at 30 frames/s, digitized and later analysed with an APAS motion analysis system. Step frequency and length were calculated with the signal from a pressure sensor mounted under the TM. VO_2 was measured on-line (Oxycon-4, Mijnhardt, Holland) during five-min periods on level TM and served as a measure for calculated RE. Blood samples were collected after each five-min period for blood lactate analysis and VO_2 max was determined during a 5-8 minute incremental test.

Maximal oxygen uptake and aerobic running capacity. Table 1 shows some basic data about the participants. VO_2 max for the elite runners as a sub group was as a mean over $70 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, which was significantly higher compared to the mean value including participants from other sports with $60.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. The same significant difference could be seen between the two groups when O_2 was related to as a function of body weight^{-0.75} according to Bergh et al. (1991) and Svedenhag [(1995) ($\text{mL} \cdot \text{kg}^{-0.75} \cdot \text{min}^{-1}$). In table 2 the relative O_2 uptake (% of VO_2 max = aerobic running capacity) is given for each participant. In all 3 velocities there is a significant difference in fractional O_2 utilisation between runners and non-runners (45 vs. 64, 53 vs. 73 and 63 vs. 81 % respectively). In the runners group the relatively low O_2 uptake was accompanied by low blood lactate values (all below $3.0 \text{ mmol} \cdot \text{L}^{-1}$), whereas most in the non runners group had more than $4 \text{ mmol} \cdot \text{L}^{-1}$.

Step length, step frequency, $M\text{-}L_{\text{disp}}$ and V_{disp} related to velocity. The step length increased significantly related to velocity while step frequency remained relatively constant in all velocities (Figure 2), There was a significant correlation between step length and velocity (0.92, $p < 0.05$). The $M\text{-}L_{\text{disp}}$ related to leg-length did not show any significant change vs. velocity. Nor did net V_{disp} related to velocity show any statistical difference. However, there was a reduction in the mean value of the V_{disp} for the non-runners at $15 \text{ km} \cdot \text{h}^{-1}$ while the runners increased somewhat at the same velocity (Figure 3).

O_2 consumption related to velocity. For all participants there was a linear correlation between running velocity and VO_2 ($r=0.92$) and VO_2 % of VO_2 max (Figures 4 and 5 respectively), which was significantly higher for the non-runners vs. runners in all velocities. ANOVA showed significant differences between all speeds and both groups.

O_2 consumption related $M\text{-}L_{\text{disp}}$ and V_{disp} . No significant relation was found between O_2 and $M\text{-}L_{\text{disp}}$ in any of the velocities. In Fig. 6 the relation between O_2 and V_{disp} is normalised for leg length at 11, 13 and $15 \text{ km} \cdot \text{h}^{-1}$. The correlations were 0.72, 0.72 and 0.53 respectively and were significant for 11 and $13 \text{ km} \cdot \text{h}^{-1}$.

It was concluded that V_{disp} seem to be of importance for RE and should be tested as an indicator for RE together with VO_2 .

Table 1. Characteristics of the participants. (Means and \pm SD).

Partici- pant	Mass (kg)	Heigth (cm)	Age (yrs)	VO₂ max (mL·kg⁻¹·min⁻¹)	VO₂ max (mL·kg^{-0.75}·min⁻¹)	Sport
1	79	194	25	76.7	230	MD running
2	67	178	20	70.7	202	MD running
3	72	183	24	71.7	209	MD running
4	68	182	23	71.0	204	MD running
5	71	185	23	73.6	214	MD running
6	79	188	25	57.8	172	Badminton
7	62	178	28	52.4	147	Ice hockey
8	100	193	24	57.2	181	Martial arts
9	76	180	26	69.6	206	Badminton
10	83	180	31	64.2	194	Wrestling
Mean	75.7	184	25	66.2	196	
SD	10.7	58	3	8.7	27	

MD running – Mid-distance running

Table 2. Relative contributions (%) of VO₂ max at the different running velocities. (Means and \pm SD).

Participant	11 km·h⁻¹	13 km·h⁻¹	15 km·h⁻¹	Sport
1	47	56	66	MD running
2	47	55	65	MD running
3	42	49	60	MD running
4	46	54	62	MD running
5	45	52	61	MD running
Mean (SD)	45.4 (2.1)	53.2 (2.8)	62.8 (2.6)	
6	67	77	87	Badminton
7	73	81	88	Ice hockey
8	70	79	86	Martial arts
9	57	63	72	Badminton
10	53	64	73	Wrestling
Mean (SD)	64.0 (8.6)	72.8 (8.6)	81.2 (8.0)	

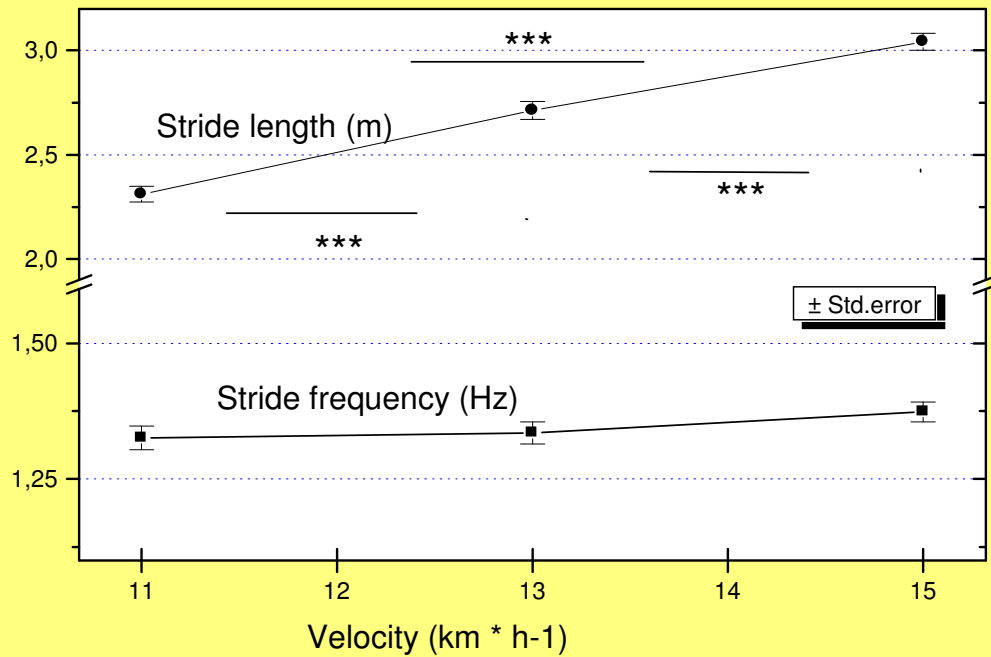


Figure 2. The relation between step length and step frequency vs. velocity for all participants. Mean values \pm SE. Asterisks denote significant differences.

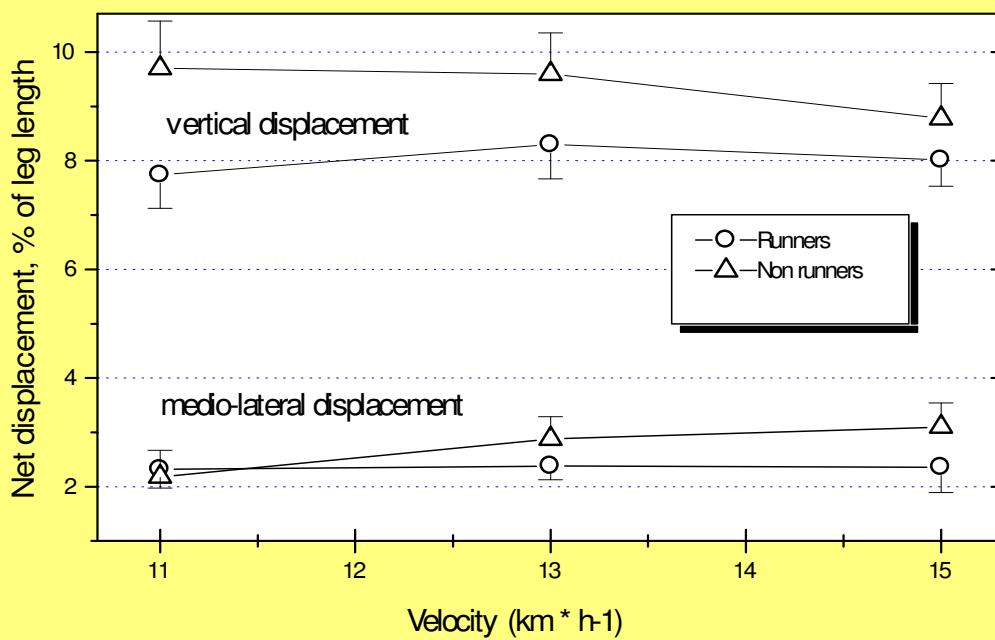


Figure 3. Vertical and medio-lateral displacement in % of leg length for both groups.

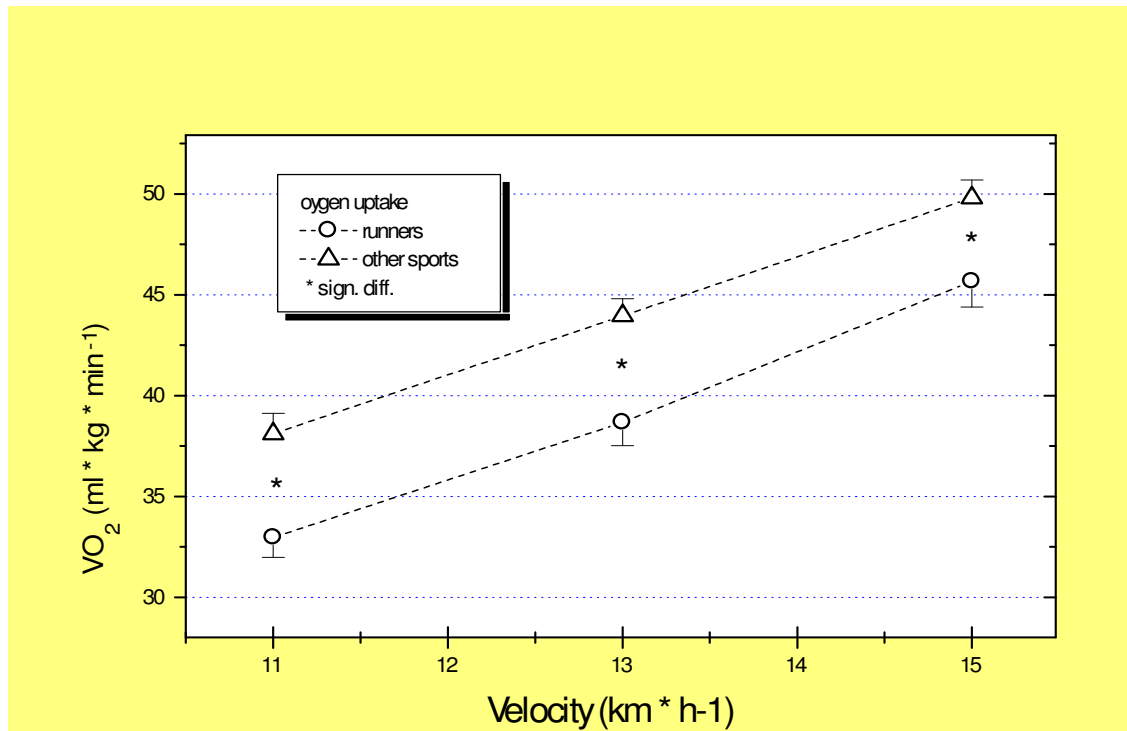


Figure 4. Oxygen uptake for the two groups at three velocities. Significant differences were detected at all velocities.

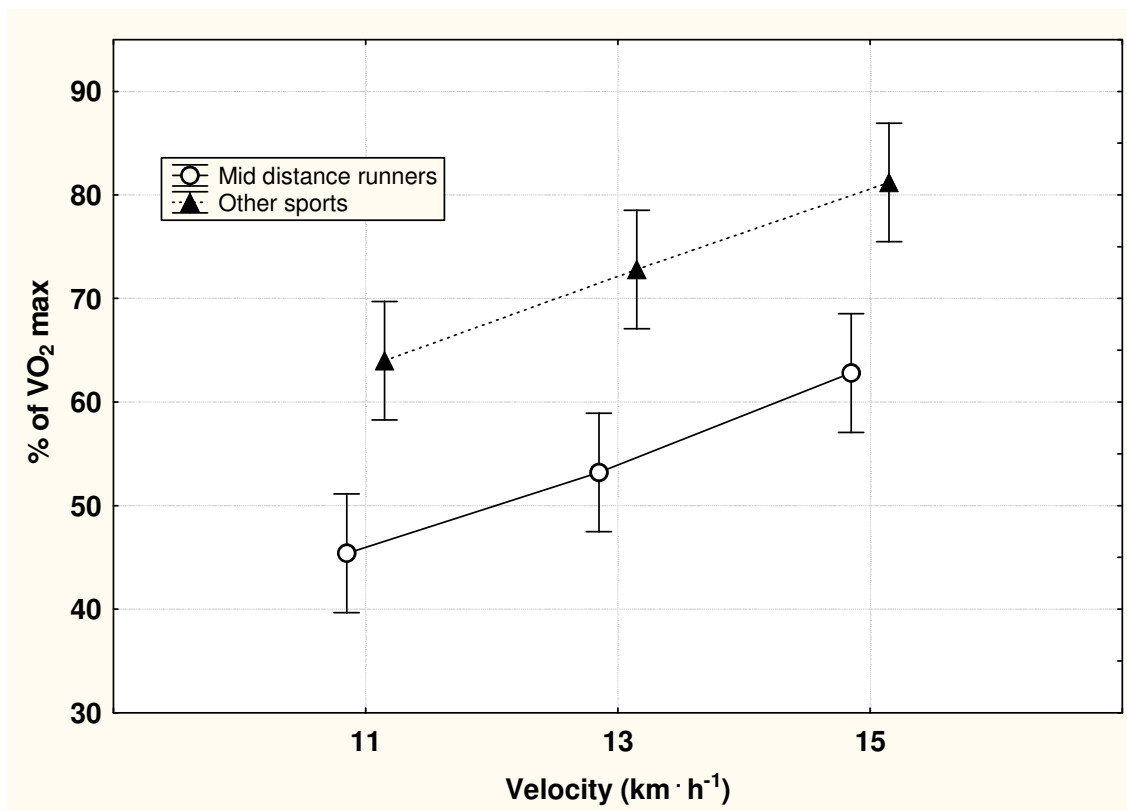


Figure 5. Aerobic running capacity expressed as % of VO_2 max during given submaximal and steady-state velocities (according to Sjödin, Svedenhag, 1985).

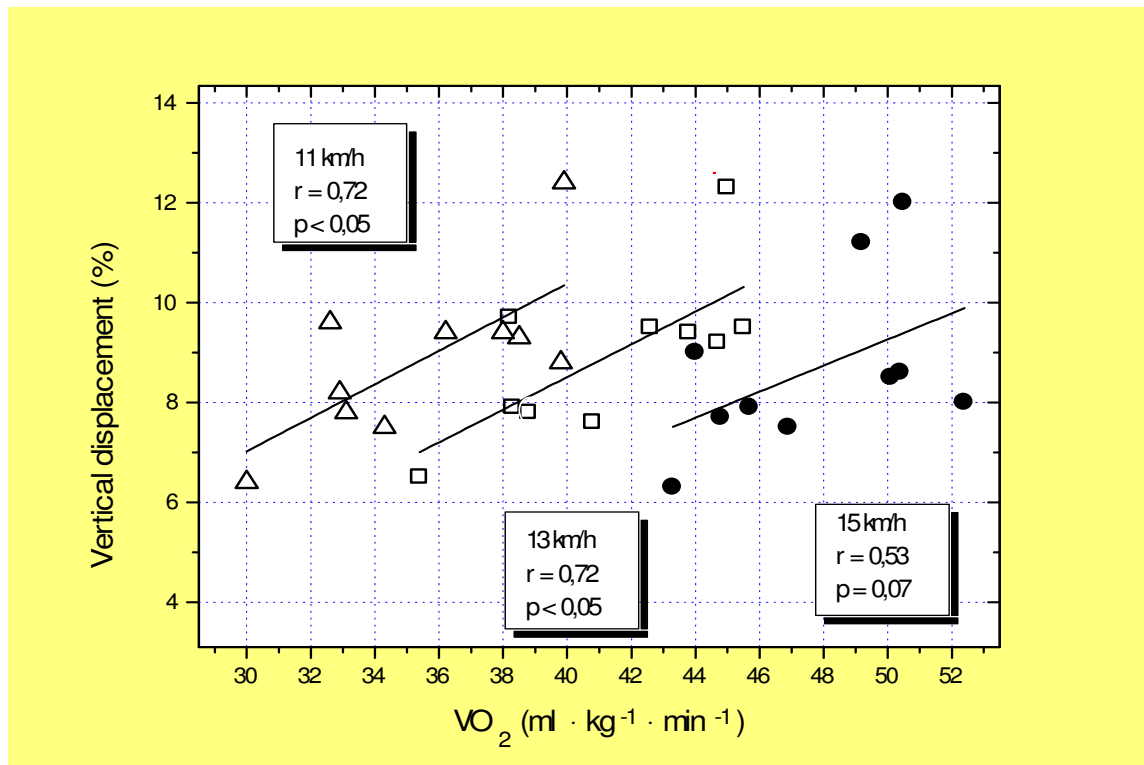


Figure 6. Relations between net vertical displacement and VO_2 at 11, 13 and 15 $km \cdot h^{-1}$. Significant correlations were found at 11 and 13 $km \cdot h^{-1}$.

Effect on pre-study III and the main studies IV and V:

As no correlations of importance were detected between running economy and mediolateral movements during treadmill running, only measurements of vertical movement were included in the ensuing studies. APAS-based measurements and movement analysis were time consuming and therefore a position transducer was introduced to measure vertical displacement.

The measurement method for calculation of step frequency and step length (signal from a pressure sensor mounted under the TM) seemed to be imprecise and was replaced by the infrared light device over the treadmill surface.

10.3 PRE-STUDY III: Vertical displacement measurements during treadmill running, a method comparison.

Gullstrand L, Nilsson J, Halvorsen K.

Before the present Study IV, trials were performed on how to measure V_{disp} during treadmill running. The video filming and digitizing with the APAS system used earlier as a criterion method for an estimated CoM was here replaced with the ProReflex optoelectronic system.

The new and easy-to-handle device to be tested was a spring-loaded position transducer (PT) mounted in the ceiling above the runner on the treadmill. The wire length variation was related to a linear voltage change and may be used as a very precise tool for distance registration and consequently for measuring V_{disp} during treadmill running.

The wire was connected to the runner's waist with a strap at the height of the crista iliaca anterior superior and on the back at sacrum level. This single-point approximation of the CoM was compared, with the ProReflex system to a) another single point marker attached to the strap and b) four skin markers attached to the runner's lower back. Data were collected at 500 Hz and analysed with the Data Studio software (Pasco Scientific, CA, USA).

Four active people from different sports, all used to treadmill running, participated and ran for about 40 seconds at 10 to 18 $\text{km} \cdot \text{h}^{-1}$ or at even higher velocities. Figure 7 show that the three modes of registration measurements give similar values with less than 5 mm difference except for mid-distance runner B.

Individual V_{disp} patterns were detected over the velocity range. In common for all participants was a more or less pronounced reduction of V_{disp} with increasing velocity. Irrespective of sport or degree of training, three participants (A, C and D) ended at a similar V_{disp} with 75 to 80 mm at the highest velocities.

The V_{disp} difference in the graphs showing the two mid-distance runners were interesting as their personal best times on 3000m were very similar: B had a relatively high average V_{disp} over the velocity range, while C presented an even and low average V_{disp} at all velocities.

It is reasonable to speculate that participant C was running more economically, especially as he weighted 10 kg less than B. However, VO_2 was not measured on that occasion. This example indicates that V_{disp} measurements may be used as an analyzing tool or direct feedback to runners seeking to improve their running economy. Thus while running at 20 $\text{km} \cdot \text{h}^{-1}$ a 20 mm V_{disp} reduction would be reasonable for runner B to achieve.

The close V_{disp} relationship between the modes in this pre-study led to the more developed and extensive validation study IV, in addition including accelerometers. In Figure 8 unpublished graphs from the main study give further support for the individual V_{disp} patterns and how V_{disp} decreases with increasing velocities.

Both pre-studies and study IV show a decreasing V_{disp} with higher running velocities. This may explain the pre-study II finding that no significant correlation was found between O_2 uptake and V_{disp} in 15 $\text{km} \cdot \text{h}^{-1}$ but at the two lower velocities.

It was concluded that the PT and the ProReflex V_{disp} corresponded well and that V_{disp} measurements revealed interesting individual patterns. Further, the reduced V_{disp} at the higher velocities will make it more challenging to use as an important single factor in running economy. This fact suggest that RE should be measured individually at the highest possible running velocity, still in steady state, and not at 15 (*Sjödin and Svedenhag, 1985*) or 16 $\text{km} \cdot \text{h}^{-1}$ (*Foster and Lucia, 2007*) for well-trained distance runners.

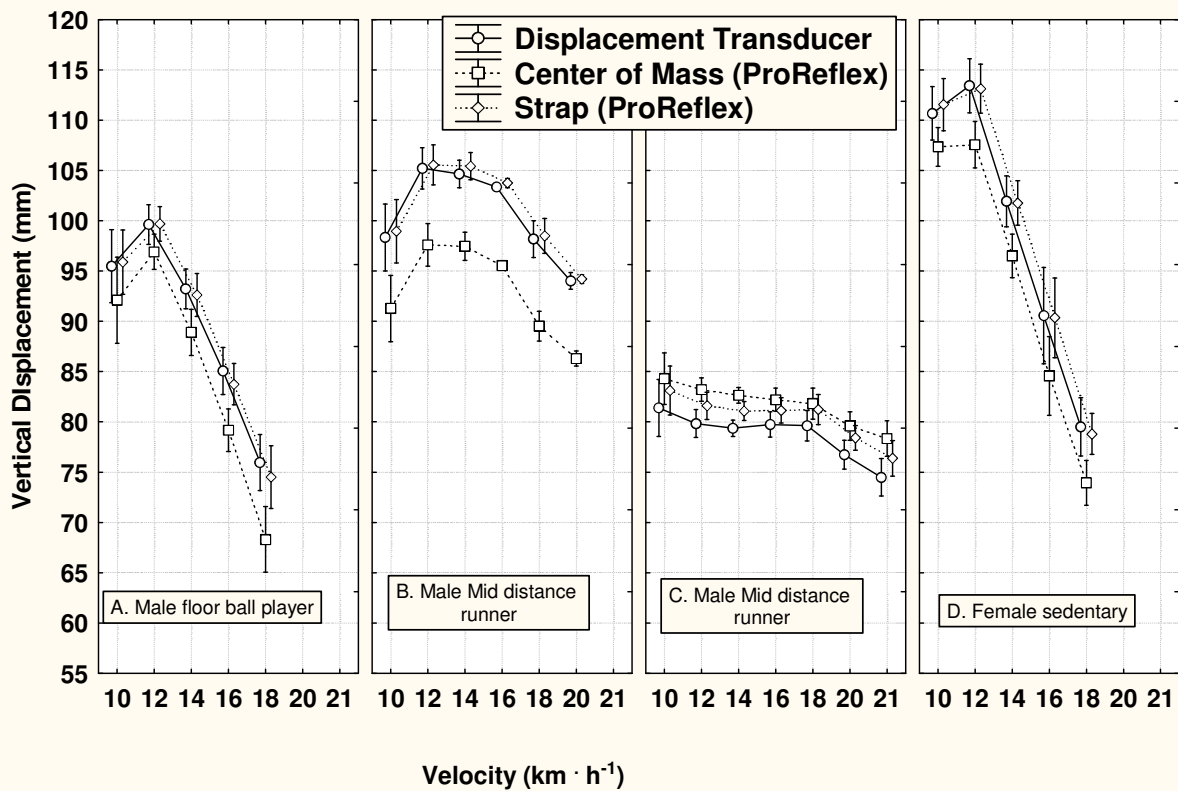


Figure 7. Means and 95% confidence intervals for V_{disp} measured with three modes and in different velocities during TM running.

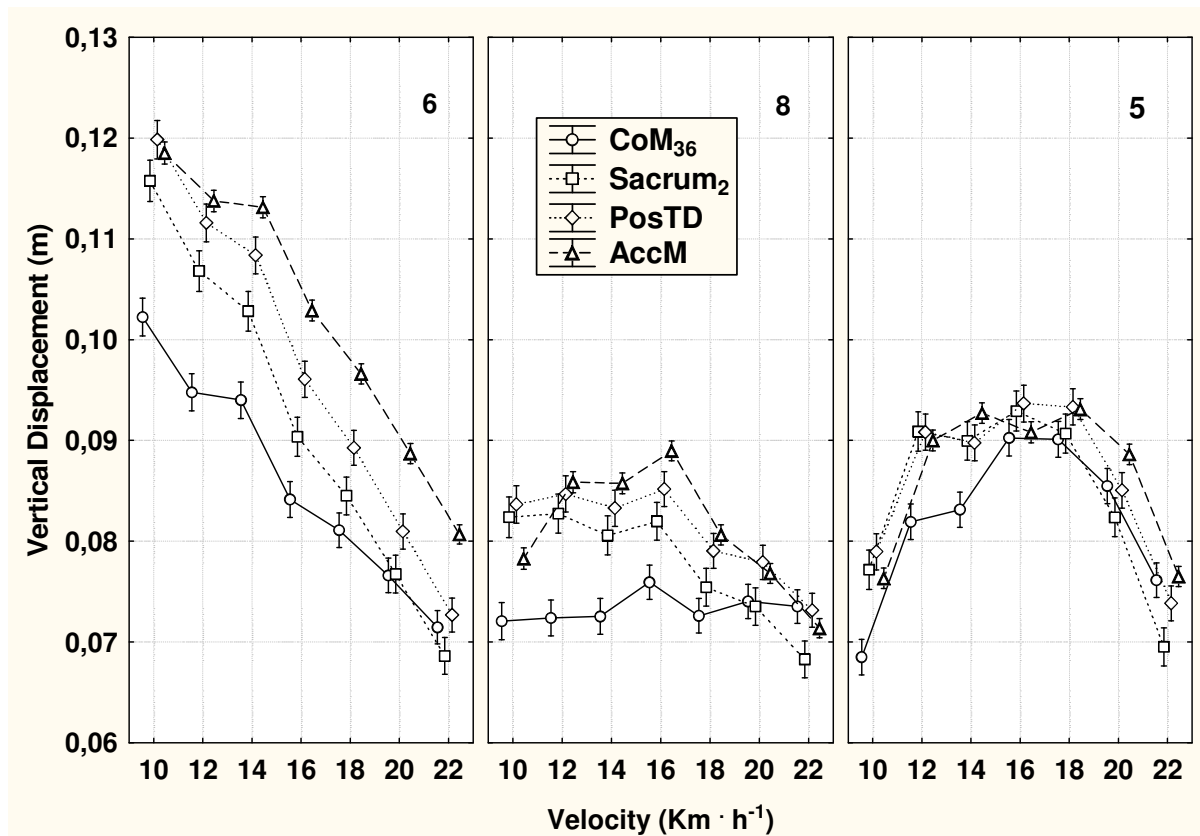


Figure 8. Means and 95% confidence intervals for V_{disp} measured with four modes in three runners. Note the variety of V_{disp} characteristics related to velocity. Runners 6 and 8 were international level orienteers and 5 a national level soccer player. V_{disp} is calculated from 36 (CoM_{36}) and two reflectors ($Sacrum_2$). PosTD and AccM are one-point V_{disp} of position transducer and accelerometer, respectively (from Study IV).

Effect on main study IV:

For calculating CoM V_{disp} a one-and four-point reference model measured with the ProReflex optoelectrical system and the position transducer showed interesting and promising results. However, for a more precise validation of the position transducer CoM V_{disp} , it was decided to use a 13-segment model based on 36 reflectors in Study IV.

10.4 PRE-STUDY IV: Stride registrations with infrared radiation devices and validation against force plates and contact shoe during overground and treadmill running.

Gullstrand L, Nilsson J.

The idea of using infra red radiation beams over the TM and overground surfaces was preceded by a number of experiments. The first version of the IR device consisted of four emitters and 4 receivers giving a web of 16 beams and producing a distinct on and off signal when one single IR beam was disconnected and all were reconnected. The first validation trials were performed with an AMTI force plate as criterion method during stepping on the spot and overground running, on a straightway at different velocities. For collection (at 500 Hz), storing and later analyzing the support phase duration a Pasco Interface and Science Workshop, software (Pasco Scientific, CA, USA) was used.

One finding was that the mean value stance phase duration with the IR₁₆ was practically identical to that measured with the FP. This was unexpected and should not be the case as the beams 10 mm above the force plate would be disconnected before the FP surface was struck.

A reasonable explanation is that the 16-web version had gaps where the first part of shoe could land and influence the FP before the beams were cut off. The same artefact could arise during “toe-off” where the tip of the shoe could still be on though it had already permitted reconnection of the IR beams (Fig.10).

Later, the IR₁₆ device was improved with 10 emitters and 4 receivers giving a tighter web with 40 beams (IR₄₀). The problems with the shoe hitting gaps during “heel-down” and “toe-off” phases during registration of the stance phase duration was then solved (Fig. 9).

Subsequently the mean duration of the stance phase in running with different velocities was systematically about 0.02 s longer with the IR₄₀ than with the force plate.

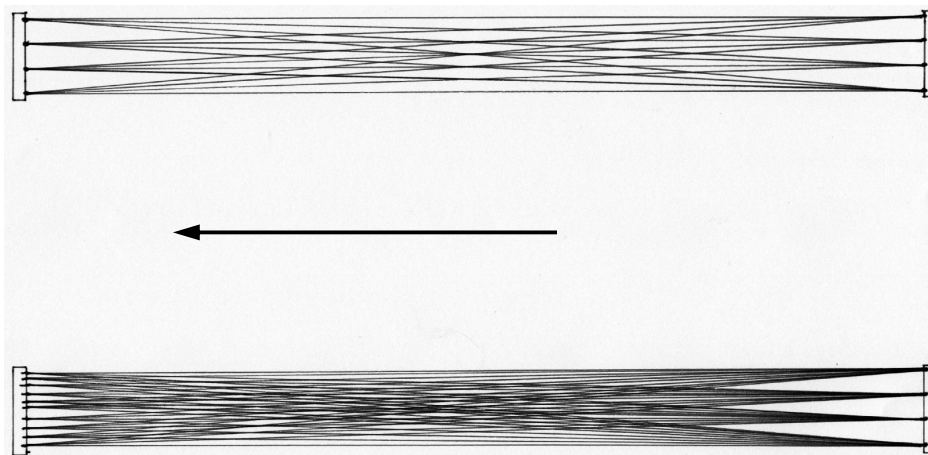


Figure 9. Plot of web patterns in the two IR devices. Note the regular gaps in the upper IR₁₆ version whereas in the IR₄₀ version the gaps are drastically reduced. The IR₁₆ device had four emitters and four receivers and the IR₄₀ ten emitters (mounted at irregular distances) and four receivers. Scaling is correctly based on 240 mm width and 2400mm length. Arrow indicates running direction and approximate step length.

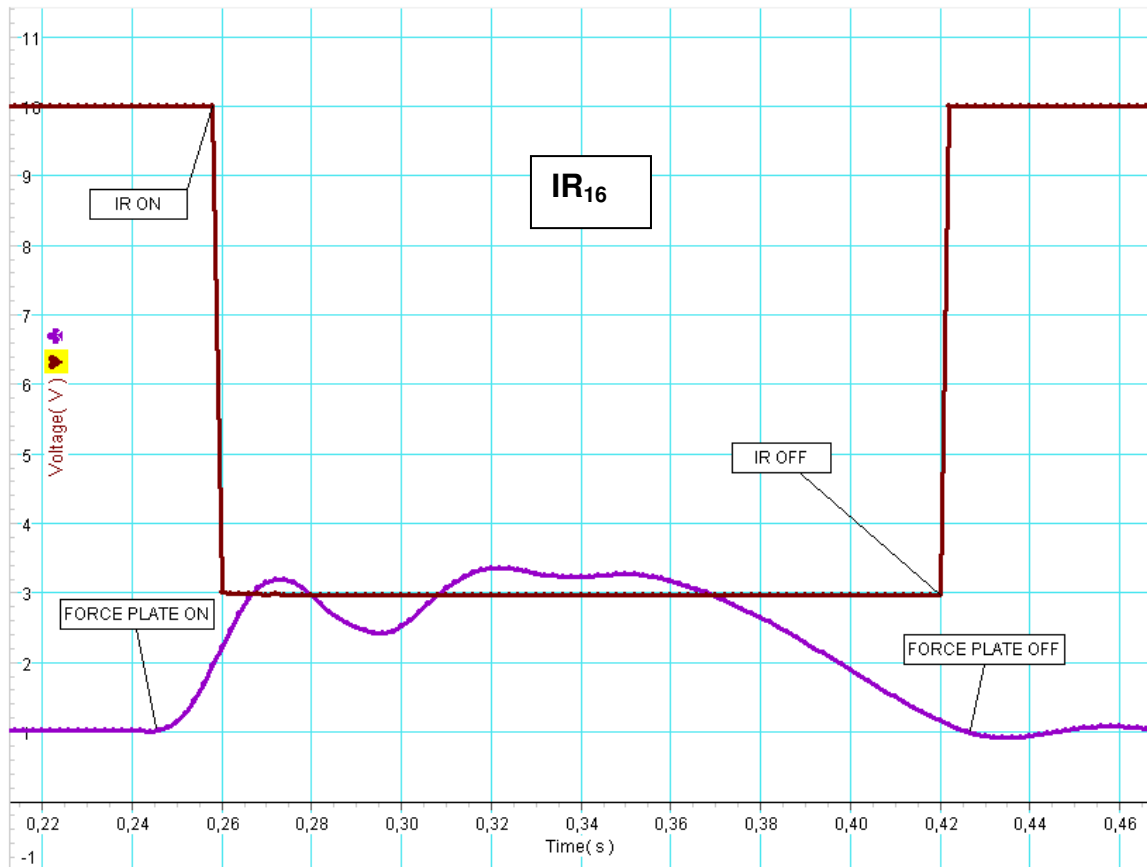


Figure 10. Original error registration of the stance phase duration with the IR₁₆ device during running at 6.0 m · s⁻¹. An unrealistically later IR touch-down, and an earlier IR toe-off compared to FP is seen. Sampling rate was 500 Hz.

Effect on main study V:

As it was concluded that the closer correlation between IR₁₆ vs. FP than between IR₄₀ vs. FP was due to error measurements, the IR₄₀ device was chosen as more reliable for the main study V and future measurements on the treadmill.

10.5 VELOCITY CONVERSION TABLE

Table 5. Transformation of velocities used in this thesis

$\text{km} \cdot \text{h}^{-1}$	$\text{min} \cdot \text{km}^{-1}$	$\text{m} \cdot \text{s}^{-1}$
10	6:00	2.8
12	5:00	3.3
14	4:17	3.9
16	3:45	4.4
18	3:20	5.0
20	3:00	5.6
21	2:51	5.8
22	2:43	6.1