Models for Oxygen Consumption and Cardiac Output as Response to Treadmill Exercise

Milan Stork
Department of Applied Electronics and Telecommunications/RICE
University of West Bohemia
Plzen, Czech Republic
stork@kae.zcu.cz

Jaroslav Novak
Department of Sports Medicine
Medical Faculty in Plzen
Charles University in Prague
Plzen, Czech Republic
novakj@lfp.cuni.cz

***Abstract* – This paper examines procedure for static and dynamic modeling of oxygen consumption (*VO_2*) and cardiac output (*CO*) as response to cardiopulmonary exercise on a treadmill ergometer. It should be noted that the derivation of the subject dynamic model was more difficult due to the intermittent load caused by the measurement of lactate. The results are presented on athlete (top football player) who has undergone a total of 10 stress tests over 6 years. The work shows the development of parameters and their modeling by static and dynamic models. The resulting models are generally applicable and the presented procedures can of course also be used for modeling of other physiological parameters. Measurements were performed under laboratory conditions which allowed measurable dosing of the speed and slope of the treadmill and well measurable responses on this load.**

Keywords - cardiac output; heart rate; oxygen consumption; static model; dynamic model; lactate measuring

I. INTRODUCTION

Cardiopulmonary exercise testing on treadmill ergometer (CPETT) provides assessment of the integrative exercise responses involving the pulmonary, cardiovascular, neuro-psychological, and skeletal muscle systems, which are not adequately reflected through the measurement of individual organs system function [1, 2, 3]. Under exercise some diseases can exhibit much sooner. The testing is provided on treadmill with increasing speed and elevation. Data gained from non-invasive treadmill examination, enable derive dynamic physiological models. These models permit the evaluation of both submaximal and peak exercise responses, providing the doctor with relevant information for different clinical decisions. CPETT is increasingly being used in a wide spectrum of clinical applications for the evaluation of undiagnosed exercise intolerance and for the objective determination of functional capacity and impairment. Its use in patient management is increasing with the understanding that resting pulmonary and cardiac function testing cannot reliably predict exercise performance and functional capacity and that overall health status correlates better with exercise tolerance than with resting measurements. CPETT involves measurements of heart rate (*HR*) oxygen uptake (VO_2), carbon dioxide (VCO_2) expenditure and pulmonary ventilation during a step-vice increased physical workload up to the maximum (or symptom-limited level in patients) on treadmill ergometer. In the laboratory, more than 2000 examinations on treadmill, both in athletes and patients have been performed over 20 years, while some the subjects have been re-tested, allowing to follow their health status cardio-pulmonary fitness level over several years. In Fig. 1, the photo shows CPETT examination on a treadmill ergometer in a laboratory where heart rate, electrocardiography (ECG), ventilation, blood pressure, oxygen consumption and carbon dioxide output was measured. From load and measured parameters the mathematical model of VO_2 was derived. Also from load and measured VO_2 parameters the *CO* was estimated and it's mathematical model was derived [4, 5]. This paper describes the development and models of selected parameters based on 10 tests performed on a treadmill ergometer carry out on same subject (top football player) over 6 years.

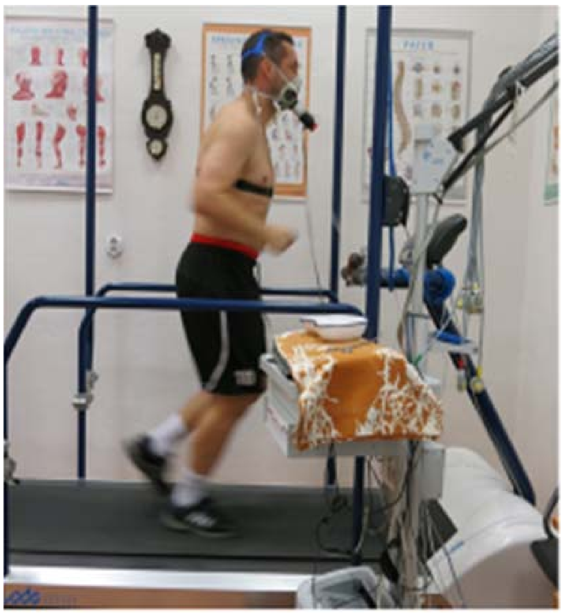

Figure 1. Photo of the subject performing spiroergometry examination on a treadmill ergometer in a surgery where heart rate, ventilation, blood pressure, oxygen consumption, carbon dioxide output and lactate threshold are measured

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II. Material and Methods

Time evaluation of VO_2 consumption and CO are important physiological parameters for the determination of functional health status and muscle energetic during physical exercise. The experiments confirm that oxygen consumption is mainly controlled by intramuscular factor related metabolic system. The experiments also confirm a high correlation between CO and VO_2. The VO_2 consumption is considered as the most accurate criterion of the cardiorespiratory fitness. It can't be directly measured during CPETT. Noninvasive estimation of CO is based on VO_2 measuring and then calculated according the formula [6, 7]:

$$CO(VO_2) = \frac{100 \cdot VO_2}{\left(5.721 + 0.1047 \dfrac{100 \cdot VO_2}{VO_{2MAX}}\right)} \quad \text{[l/min]} \quad (1)$$

For use this equation it is needed to measure VO_{2max}. To achieve this, an appropriate load profile must be used. The treadmill speed and grade is shown in Fig. 2. This exercise profile was used in all 10 examinations. During the examination, the run was interrupted 3 times to measure the Lt - lactate threshold. Treadmill speed is set to zero during Lt measuring. Speed can be separated into 3 step speeds and almost linearly increasing speed. Initially, a speed of 7 km/h is applied for approx. 5 minutes, then a speed of 9 and 11 km/h for 3 min. Then the speed is increased by 1 km/h every 30 s with grade 5%. During the exercise the HR, VO_2 and other parameters are measured as response to speed. The VO_2 and maximal measured value VO_{2MAX} is then put in eq. (1) to estimate CO. The subject tested in this study was male top football player, tested sometimes 1 or 2 times per year in the laboratory during complex preventive sports-medical examination. VO_{2max} and several other functional parameters provide important information about prerequisites for achieving high sport performance.

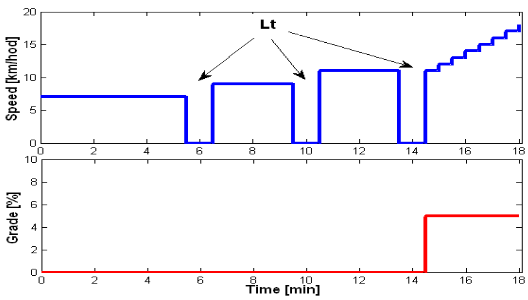

Figure 2. Exercise profile used in all 10 examinations. Workload speed profile (top) and treadmill grade (bottom). Lt-lactate threshol measuring. Speed is set to zero during lactate threshold measuring. Total load can be separated into 3 step loads and ramp load

In Tab. I the basic parameters of tested subject (examination No., age, BMI – body mass index, height, weight, maximal speed and maximal VO_{2MAX}) are presented. For load simulation with lactate threshold interrupts, the speed can be decomposed into 3 different ramp pulses of speeds (step and negative delayed step) and ramp with linearly increasing speed, all is displayed in Fig. 3

TABLE I. Examination, Age, BMI, Height, Weight, Maximal Speed S_{PM} and Max. Oxygen Consumption VO_{2MAX} of Tested Male Subject

Ex	Age	BMI	He	We	Sp_M	VO_{2MAX}
1	25	24.3	179	77.8	18	5
2	26	24.3	179	77.8	18	5.1
3	26.5	24.1	179.5	77.5	18	4.9
4	27	25.1	179.5	80.8	18	5.1
5	27.5	24.9	179	79.9	18	4.9
6	28	25	179.5	80.5	18	5.3
7	28.5	25.4	179.5	82	18	5.2
8	29	24.8	179.5	79.9	18	5.3
9	30	25.4	179	81.3	18	5.1
10	31	25.6	179	82	18	5.2

For load simulation with lactate threshold interrupts, the speed can be decomposed into 3 different ramp pulses of speeds (step and negative delayed step) and ramp with linearly increasing speed, all is displayed in Fig. 3. This approach is used for derivation of dynamic model.

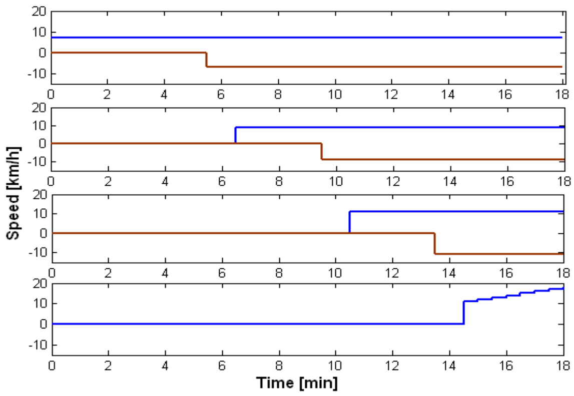

Figure 3. The treadmill speed can be separated into 3 step delayed speeds and negative sign of delayed speed and one step with linearly increasing speed

III. Static Models

In this chapter the static models for $VO_2=f(Speed)$; $CO=f(Speed)$ and $VO_2=f(HR)$ are derived. The all 10 examination are shown in Fig. 4, 5 and 6 (data values during the time of lactate measurement was not used for model estimation). It can be seen that dependencies of $VO_2=f(Speed)$ and $CO=f(Speed)$ are almost linear, but $VO_2=f(HR)$ must be approximated by third order regression polynomial function. The coefficients for $VO_2=f(Speed)$ and $CO=f(Speed)$ approximations are presented in Tab. II.

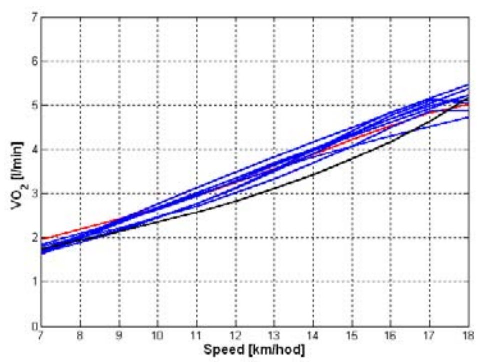

Figure 4. VO_2 as function of speed for all 10 examinations is displayed

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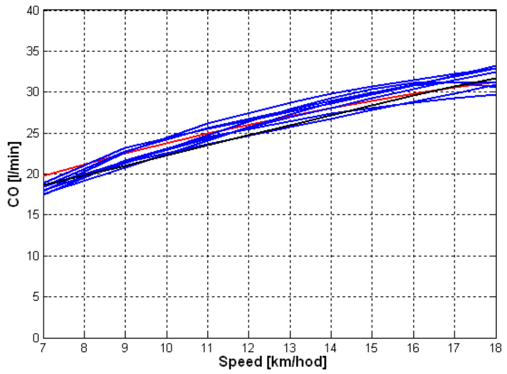

Figure 5. *CO* as function of speed for all 10 examinations is shown

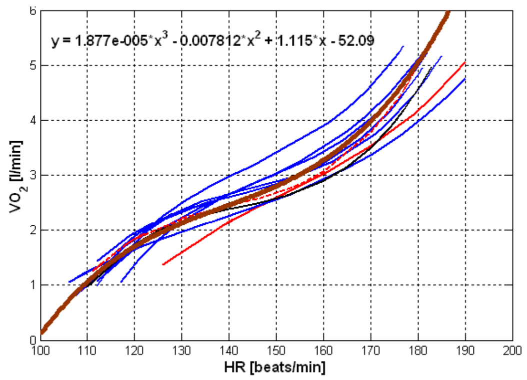

Figure 6. VO_2 as function of *HR*. for all 10 examination is presented. Nonlinear regression equation is placed in upper part. The bold brown curve corresponds to this equation

TABLE II. COEFFICIENTS OF LINEAR APPROXIMATION OF VO_2 AND *CO* OF MALE SUBJECT

	VO2(speed)		CO(speed)		
Ex	k_1	c_1	k_2	c_2	VO_{2MAX}
1	0.28	-0.07	1.1	13	5
2	0.33	-0.63	1.4	9.1	5.1
3	0.29	-0.32	1.1	11	4.9
4	0.33	-0.78	1.4	8.2	5.1
5	0.3	-0.45	1.4	8.1	4.9
6	0.35	-0.74	1.5	8.8	5.3
7	0.33	-0.59	1.4	9.8	5.2
8	0.31	-0.37	1.3	10	5.3
9	0.32	-0.6	1.3	9.4	5.1
10	0.27	-0.26	1.2	10	5.2

The linear equations for VO_2=*f(Speed)* and *CO=f(Speed)* are

$$VO_2 = k_1 \cdot speed + c_1 \quad \text{[l/min, km/h]} \quad (2)$$

$$CO = k_2 \cdot speed + c_2 \quad \text{[l/min, km/h]} \quad (3)$$

Mean k_1=0.31, mean c_1= -0.48, std k_1=0.026, std c_1= 0.23. Mean k_2=1.31, mean c_2=9.7, std k_2=0.14, std c_2=-1.45 (std = standard deviation).

IV. DYNAMIC MODELS

In this part, the dynamic mathematical models of VO_2=*f(speed)* and *CO=f(speed)* are derived from the measured values. All model parameters were derived by optimization. It is important to note that examinations are interrupted (treadmill speed is zero) for lactate threshold measuring, see Fig. 2.

Because treadmill is stopped (during Lt measuring), the value of *HR*, VO_2 and other parameters decay. Therefore more complex mathematical models should be used. In this case, it was necessary to use a dynamic model [8, 9, 10]. Universal dynamic model for $Y=f(S_P, t)$ is

$$\begin{aligned} Y &= H(t-D_1)K_1\left(1-\exp\left(\frac{t-D_1}{\tau_1}\right)\right)\cdot S_{P1} \\ &+H(t-D_2)K_2\left(1-\exp\left(\frac{t-D_2}{\tau_2}\right)\right)\cdot(-S_{P1}) \\ &+H(t-D_3)K_3\left(1-\exp\left(\frac{t-D_3}{\tau_2}\right)\right)\cdot S_{P2} \\ &+H(t-D_4)K_4\left(1-\exp\left(\frac{t-D_4}{\tau_2}\right)\right)\cdot(-S_{P2}) \\ &+H(t-D_5)K_5\left(1-\exp\left(\frac{t-D_5}{\tau_2}\right)\right)\cdot S_{P3} \\ &+H(t-D_6)K_6\left(1-\exp\left(\frac{t-D_6}{\tau_2}\right)\right)\cdot(-S_{P3}) \\ &+H(t-D_7)K_7\left(1-\exp\left(\frac{t-D_7}{\tau_2}\right)\right)\cdot S_{P4} \\ &+H(t-D_8)K_8(t-D_8)\cdot S_{P4} \end{aligned} \quad (4)$$

where *Y* is VO_2 or *CO* and *H(.)* is Heaviside function

$$H(t-D)=\begin{cases} 1, & t>D \\ 0, & t\le D \end{cases} \quad (5)$$

where *D* is time delay. Results are shown in Fig. 7 and Fig. 8. The Fig. 7, 8 shows time evolution of measured parameter (VO_2, *CO*, dashed lines) and the resulting approximation obtained from a mathematical model [11, 12, 13]. The progress of the error is shown at the bottom of the figure. Correlation coefficients and root mean square errors (RMSE) are also calculated. The dynamical model can be expressed by an electrical circuit with resistors, capacitors, amplifiers and a summing circuit, see Fig. 9. It should be noted that 2 different time constants τ_1 and τ_2 were found in the model. At the beginning of the test, the time constant is greater, and then it is smaller and remains the same. Notice: Also the time constants were found by optimization.

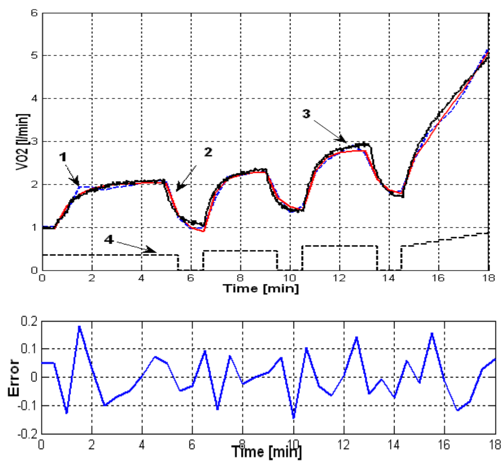

Figure 7. Comparison of measured data and model for VO_2 (top).1-Measured values, 2-Result of dynamical model, 3-Result of *RC* model, 4-Speed/20. Error between measured values and simulations (bottom).Correlation coeff.= 0.997, RMSE = 0.08

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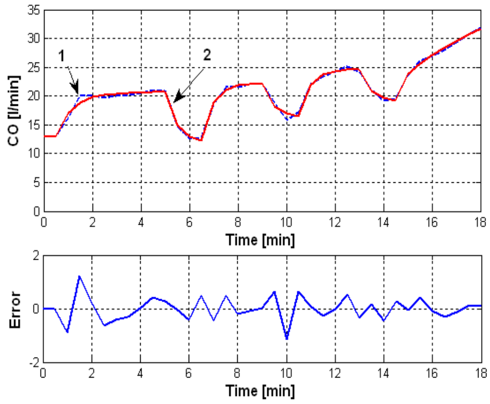

Figure 8. Comparison of measured data and model for *CO* (top). 1- Measured values, 2 - Result of dynamical model. Error between measured values and simulations (bottom).Correlation coeff.= 0.996, RMSE = 0.45

Parameters of eq. (4) for VO_2 model are: k_i=[0.153 0.17 0.16 0.1 0.13 0.096 0.11 0.03]; τ_1=0.72; τ_2=0.48; D_i=[0.5 5 6.5 9 10.5 13 14.5 15.5]; :

Parameters of eq. (4) for *CO* model are: k_i= [1.1 1.2 1.13 0.66 0.76 0.51 0.57 0.054]; τ_1=0.68; τ_2=0.46; D_i=[0.5 5 6.5 9 10.5 13 14.5 15.5];

It should be noted that a time transformation was used for the simulation. 1 minute corresponds to 1 sec during simulation, the simulation is 60 times faster. The individual time delays are controlled by a microcontroller which also controls the amplification of the amplifiers. Using the software it is possible to change the circuit model for e.g. VO_2 or for *CO*, *HR* and other physiological parameters. Result of VO_2 model as electrical circuit is shown in Fig. 9, model as electronic system is presented in Fig. 10.

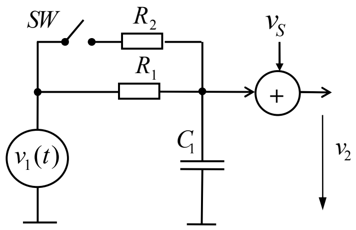

Figure 9. Electrical circuit for simulations of dynamical model of (VO_2, *CO* etc.). Two different time constants are realized by switch and parallel connection of resistors R_1 and R_2; R_1=0.72 MΩ; R_2=1.44 MΩ; C_1=1 μF

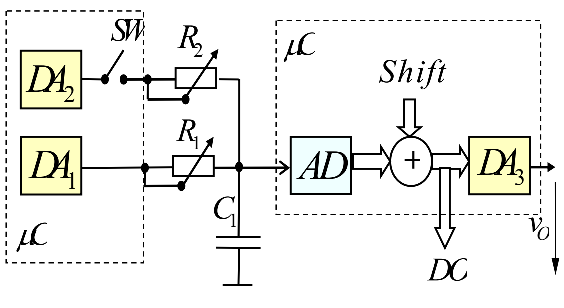

Figure 10. The block diagram for simulations of parameters VO_2 and *CO* based on μC-microcontroller. *DA* – digital/analog converter, *AD* – analog/digital vonverter, *SW* – switch. Circuit parameters for VO_2 model are R_1=0.72 MΩ; R_2=1.44 MΩ; C_1=1 μF

V. Conclusion

In this work, static and dynamic mathematical models of VO_2 and *CO* were derived in dependence on running speed. A static model of the dependence of VO_2 on *HR* was also derived. The models were derived for a top football player based on 10 examinations on treadmill ergometer. Moreover examinations were interrupted for lactate threshold measuring. The results show that first order models with time delay, with variable gain and only 2 time constants can be used. The first, longer time constant τ_1 is at the beginning of the test, the second τ_2, shorter time constant for the rest of the test. The results show that mathematical models well represent real measurements. Models were derived from real data using optimization methods.Clearly show functional stability in a well-trained athlete at all levels throughout his career with an almost constant values.

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