Characteristic of Some Physiological Parameters Based on Bicycle and Treadmill Exercise Testing

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Abstract – **In this paper examines procedure for modelling of cardiac output and oxygen consumption as response to cardiopulmonary exercise on a treadmill or bicycle ergometer. The results are presented on 2 athletes - football player and country ski runner which undergone a several stress tests over some years. The work shows the development of parameters and their modelling by means of static and dynamic models. The results should be used also for modelling of some other physiological parameters. Measurements were performed under laboratory conditions which allowed measurable dosing of the load for the bicycle ergometer and speed and slope for the treadmill ergometer and well measurable responses on this exercises e.g. heart rate, ventilation and oxygen consumption.**

Keywords – **Bicycle ergometer, Cardiac output, Heart rate, Kinetic models, Oxygen consumption, Treadmill ergometer.**

I. INTRODUCTION

Cardiopulmonary exercise testing (CPET) on ergometer (bicycle or treadmill) 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 [1-4]. 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. CPET 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. CPET 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 some type of ergometer [5, 6]. In the laboratory, more than 5000 examinations on bicycle or treadmill ergometer, both in athletes and patients have been performed over 30 years, while some the subjects have been re-tested, allowing to follow their fitness level evolution over several years. In Fig. 1, the photo shows CPET examination on a bicycle and treadmill ergometer in a laboratory where heart rate, electrocardiography (ECG), ventilation, blood pressure, oxygen consumption and carbon dioxide output was measured. From loads and measured parameters the mathematical model of VO_2 was derived [7-9]. Also from load and measured VO_2 the cardiac output *CO* was estimated and its mathematical models were derived. Bicycle work is quantified in watts [W] or in (kpm/min; 1 W = ~ 6 kpm/min). Treadmill load is quantified in speed [km/h] and slope [%].This work describes static and kinetic models of selected parameters based on repeated tests performed on the bicycle and treadmill ergometer over several years in 2 athletes.

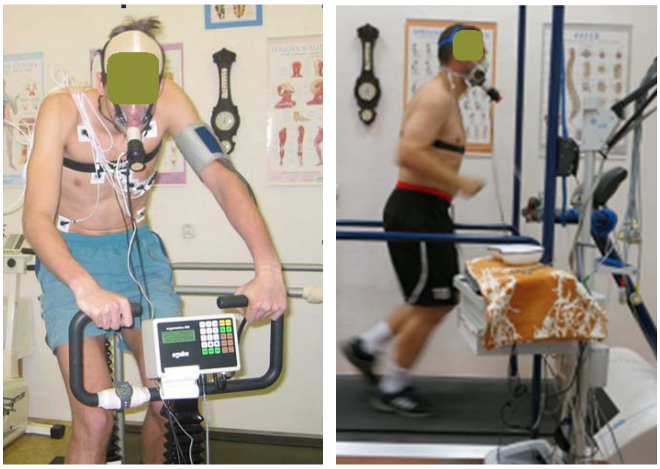

Fig. 1. Photos of the subjects performing cardiopulmonary exercise testing on a bicycle ergometer (left) and treadmill ergometer (right) in a surgery where ECG, heart rate, ventilation, blood pressure, oxygen consumption and carbon dioxide output are measured

II. MATERIAL AND METHODS

The static dependence and kinetic of VO_2 consumption and *CO* as a response on load are important physiological parameters for the determination of functional health status and muscle energetic function during physical exercise. The experiments confirm that oxygen consumption is mainly controlled by intramuscular factor related metabolic system. The data evaluations 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. The *CO* can't be directly measured during CPET, but it can be non-invasively estimated from VO_2 consumption. To achieve this,

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an appropriate load profile must be used, because VO_{2max} must be reached during examination. The CO estimation is based on VO_2 measuring (calculated from ventilation and oxygen uptake) and then derived according the formula [10, 11]:

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

The time evolution of load for bicycle ergometer is shown in Fig. 2..The time evolution for treadmill speed and grade is shown in Fig. 3. This or similar exercise profile was used in all examinations.

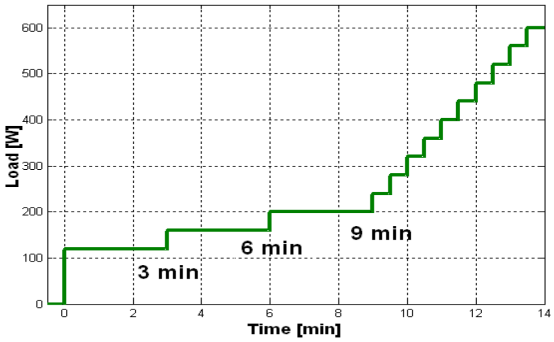

Fig. 2. Load profile for bicycle examination. Whole load can be separated into 3 step loads (120, 160 and 200 W) and one linearly increasing load up to maximal load

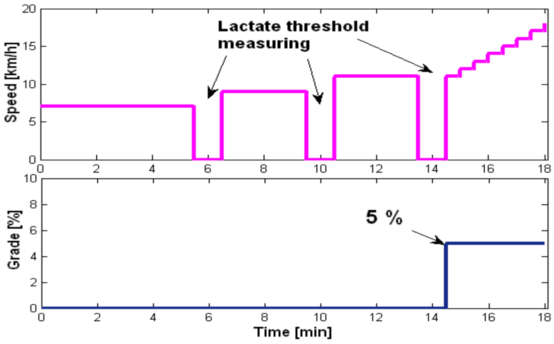

Fig. 3. Exercise profile used for treadmill exercise (speed and grade). Workload speed profile is interrupted for lactate threshold measuring. Load profile can be separated into 3 step loads (7, 9 and 11 km/h) with interrupts and ramp load up to maximal load

Basic parameters of athletes for 10 test applied over several years are: **Cross - country skier:** Age=18 to 24; BMI: mean=22.9 SD=1.74; He: mean=184 SD=5; We: mean=77.7 SD=9.4; L_M: mean=499 SD=64; VO_{2MAX}: mean= 5.88 SD=0.77

Football player: Age=25 to 31; BMI: mean=24.9 SD=0.52; He: mean=179 SD=0.2; We: mean=80 SD=1.7; S_{PM}: mean=18 SD=0; VO_{2MAX}: mean= 5.11 SD=0.15. Where BMI=Body Mass Index [kg/m^2], He=Height [cm], We=Weight [kg], L_M=Maximal load [W], S_{PM}: Maximal speed [km/h], VO_{2MAX}=Maximal oxygen uptake [l/min] and SD is Standard deviation.

III. RESULTS

In this first part of modeling, the static dependences of physiological parameters: VO_2, CO and HR on the load in the form of regression relationships are first derived from the 10 measured examinations. The linear regression equation of the dependence of VO_2 on the load is

$$VO_2 = 0.0103 \cdot Load + 0.6 \quad \text{[l/min, W]} \quad (2)$$

The examinations data from which the regression relationship was derived are shown in Fig. 4.

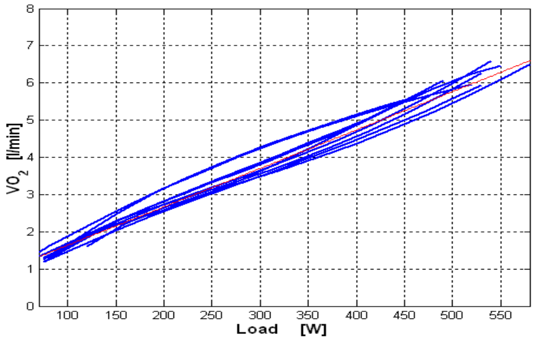

Fig. 4. VO_2 as function of load measured on bicycle ergometer

Similarly, the relationship for CO dependence on load applies (based on nonlinear regression equation)

$$\begin{aligned} CO &= 1.788 \cdot 10^{-7} \cdot (Load)^3 \\ &-2.307 \cdot 10^{-4} \cdot (Load)^2 \\ &+0.1216 \cdot Load + 8.4 \end{aligned} \quad \text{[l/min, W]} \quad (3)$$

The regression formula (3) was derived from data, see Fig. 5.

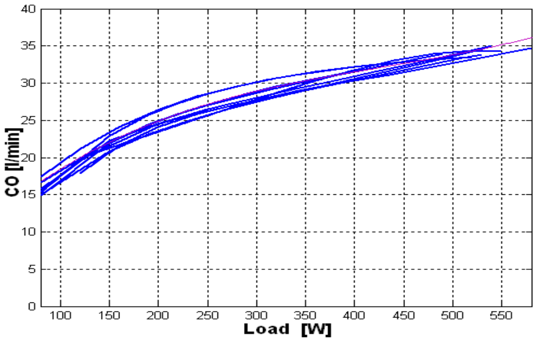

Fig. 5. CO as function of load (for bicycle ergometer)

The nonlinear regression equation of HR dependence on the load is

$$\begin{aligned} HR &= 3.32 \cdot 10^{-4} \cdot (Load)^2 \\ &+0.39 \cdot Load + 67.3 \end{aligned} \quad \text{[beat/min, W]} \quad (4)$$

Similarly, regression equations of VO_2, CO and HR dependence on speed of a treadmill ergometer are derived. Therefore linear regression equation for VO_2 is

$$VO_2 = 0.328 \cdot Speed - 0.626 \quad \text{[l/min, km/h]} \quad (5)$$

The examinations data from which the regression relationship was derived are shown in Fig. 6.

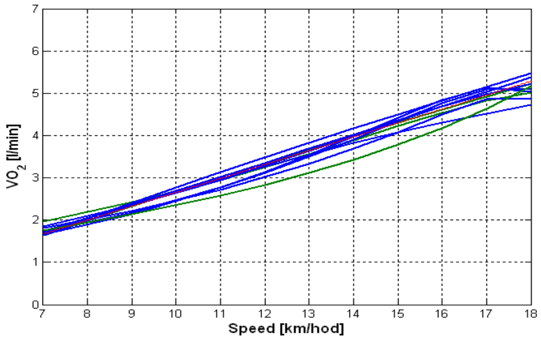

Fig. 6. VO_2 as function of speed measured on treadmill ergometer

Nonlinear regression function for *CO* is (derived from data, Fig. 7)

$$\begin{aligned} CO = &- 0.0542 \cdot (Speed)^2 \\ &+2.68 \cdot Speed + 1.39 \end{aligned} \quad \text{[l/min, W]} \quad (6)$$

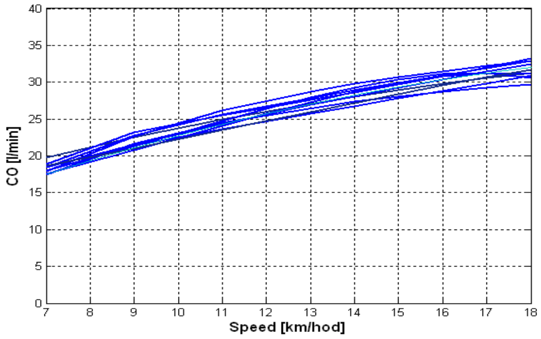

Fig. 7. *CO* as function of speed (for treadmill ergometer)

The nonlinear regression equation of *HR* dependence on the speed is

$$\begin{aligned} HR = &- 0.0361 \cdot (Speed)^3 + \\ &1.09 \cdot (Speed)^2 - 3.63 \cdot Speed + 106 \end{aligned} \quad \text{[beat/min, km/h]} \quad (7)$$

The next section presents the results of dynamic VO_2 models as a function of load and time. First, a model for a bicycle ergometer is tested, where there is no load interruption during the lactate measurement. The second (more complex) is model for treadmill ergometer where speed is interrupted when the lactate thresholds are measured. The models can be searched as first-order systems with different time constants, gains and with internal delay. Input function (without ramp) is

$$\begin{aligned} u(t) = &K_1 \left(1(t) - 1(t - D_{1,2})\right) \\ &+ K_2 \left(1(t - D_{2,1}) - 1(t - D_{2,2})\right) + \\ &K_{n-1} \left(1(t - D_{n-1,1}) - 1(t - D_{n-1,2})\right) + K_n \cdot 1(t - D_{n,1}) \end{aligned} \quad (8)$$

where $1(t\text{-}D)$ is unit step with delay D. $1(t\text{-}D)=0$ for $t\text{-}D \le 0$.

Usually the traditional approach for model identification is not used because small sample set of exercise intensities. The Laplace transform of the first order models with different gains and time constants (which are used for modelling) is

$$\begin{aligned} Y(s) = &\left(exp\left(-D_{1,1}s\right) - exp\left(-D_{1,2}s\right)\right) \frac{K_1}{s\left(\tau_1 s + 1\right)} \\ &+ \left(exp\left(-D_{2,1}s\right) - exp\left(-D_{2,2}s\right)\right) \frac{K_2}{s\left(\tau_2 s + 1\right)} + \\ &\cdots \left(exp\left(-D_{n-1,1}s\right) - exp\left(-D_{n-1,2}s\right)\right) \frac{K_{n-1}}{s\left(\tau_{n-1} s + 1\right)} \\ &+ exp\left(-D_{n,1}s\right) \frac{K_n}{s\left(\tau_n s + 1\right)} \end{aligned} \quad (9)$$

The inverse Laplace transform of *Y(s)* is

$$\begin{aligned} y(t) = &K_1 \left(1\left(t - D_{1,1}\right) \left[1 - exp\left(\frac{t - D_{1,1}}{\tau_1} \right) \right] \right) \\ &- K_1 \left(1\left(t - D_{1,2}\right) \left[1 - exp\left(\frac{t - D_{1,2}}{\tau_2} \right) \right] \right) \\ &\cdots + K_n \left(1\left(t - D_{n,1}\right) \left[1 - exp\left(\frac{t - D_{n,1}}{\tau_n} \right) \right] \right) \end{aligned} \quad (10)$$

The example of such simplified system response is shown in Fig. 8 (X-axis is from 0 to15 min).

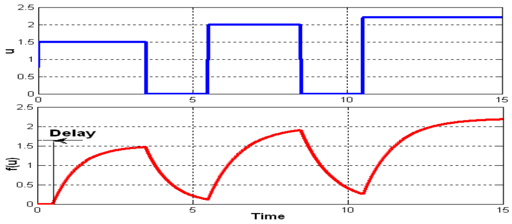

Fig. 8. Example of load (top) and response of first order system with delay, different gains and different time constants

The results of kinetic modelling of VO2 for bicycle and treadmill ergometers are displayed in Fig. 9 (for bicycle) and in Fig. 10 (for treadmill with interrupts). The measured and estimated values are shown.

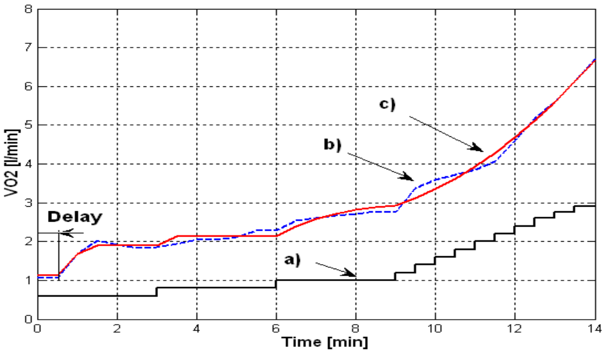

Fig. 9. VO_2 kinetic measured on treadmill ergometer, a) Load/200, b) Measured values (dash, blue), c) Model response (solid, red)

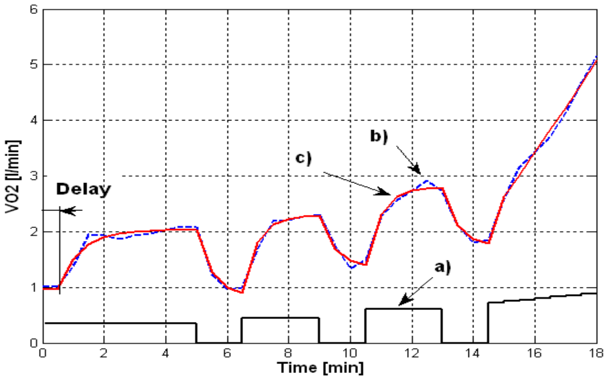

Fig. 10. VO_2 kinetic measured on bicycle ergometer, with interrupts for lactate threshold measuring, a) Speed/20, b) Measured values (dash, blue), c) Model response (solid, red)

The time delay, gains and time constants for kinetic models were finding by optimization methods from measured data. It was found that 2 different time constants are sufficient, longer at the beginning of the examination, shorter after warm up (τ_1=43; τ_2 =27 [s]). Time delay was ~28 [s]. The same method was used also for *CO* model. The universal circuit diagram which can be used for simulation is shown in Fig, 11. A copy of the oscilloscope screen is shown in Figure 12.

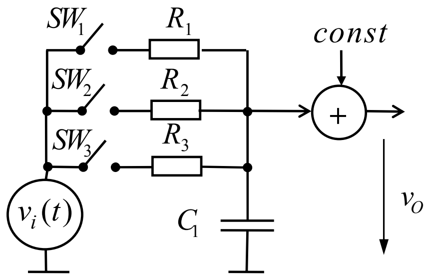

Fig. 11. The circuit diagram for simulations of parameters VO_2 and *CO*. SW – switch. Circuit parameters for VO_2 model are R_1=0.36 MΩ; R_2=0.72 MΩ; C_1=2 μF (1300 times faster than reality)

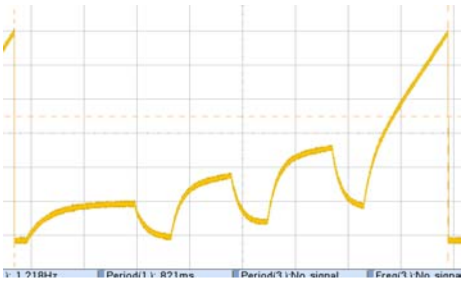

Fig. 12. The copy of the oscilloscope screen VO_2 kinetic on bicycle ergometer - simulation by means of electrical circuit

IV. CONCLUSION

In this work, the possibilities of static and dynamic modeling of some physiological parameters were based on the results of stress examinations. These models can be used to compare the level of training of athletes, the development of parameters during training, training dosage, but also for assessment of patients condition.

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