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Self Biofeedback Control of Oxygen Consumption (Vo_2) during Cycling Exercise: Based on its Real Time Estimate

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Abstract— **The aim of this paper is to develop the self biofeedback (SBF) control of oxygen consumption (Vo_2) during cycling exercise. The developed system uses an estimator that can predict Vo_2 in real time by using the measurements of heart rate (HR), respiratory rate (RespR) and frequency of exercising activity, this terms is known as Exercise Rate (ER). The biofeedback command is given to the exercising subject in terms of the desired action required by the subject to achieve the targeted Vo_2 $(Vo_{2target})$ profile. The desired action is determined by the SBF system based on the current estimates of Vo_2 and is communicated to the exercising subject by flashing an indicator on the computer screen. The results obtained in this study demonstrate that the estimator developed for cycling exercise is capable of estimating Vo_2 in real time. The developed system is tested on six healthy male subjects. The obtained results show that the SBF system performs well with the average steady state error in terms of Root Mean Square Error (RMSE) of 1 ml/min/Kg during low intensity exercise and with RMSE of 1.6426 ml/min/Kg during high intensity exercise.**

I. INTRODUCTION

Optimal intensity is considered as the most fundamental variable for a number of reasons [1], [2]. It directly impacts on the physical fitness and is responsible for maintaining a healthy life style. Exercise intensity is defined in terms of various physiological variables. These variables are oxygen consumption (Vo_2), heart rate (HR), rating of perceived exertion, lactate threshold, and critical power [1]. Amongst these physiological variables, the HR is non-invasive and can be measured easily [3], [4], [5]. However, values of HR are include non-metabolic factors [6], [7]. Despite the fact, that measurement of Vo_2 is expensive and is also impractical to use this measure during exercise. However, it is a more accurate measure of exercise intensity [8]. Therefore, attempts have been made to develop more practical methods of Vo_2 estimation by using the non-invasive physiological variables[9], [10], [11]. Previously, we developed the methodology for Vo_2 estimation, which is useful for designing the self biofeedback (SBF) control of Vo_2 during cycling [9].

The SBF control of any physiological variable is based on individual perception to achieve the targeted profile. The SBF control of HR during walking exercise was developed in paper [12]. Analysis of the proposed SBF control of HR shows that the HR was directly proportional to the stride and pitch rates. These rates are considered as frequency of exercise and are currently known as ER [13].

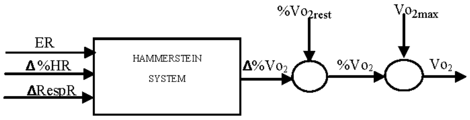

Fig. 1. Block diagram of Vo_2 estimator

The aim of this paper is to implement and analyze the SBF control of Vo_2 during cycling exercise. In order to avoid unwieldy and expensive measurement of Vo_2, the proposed system uses an estimator to predict Vo_2. Previously, we developed an estimator of Vo_2 in paper [9]. Which estimates Vo_2 by using non-invasive and easily measurable quantities such as HR, RespR and ER. This estimation technique is improved by introducing the change in percentage of oxygen consumption from the resting to the exercising phase, with respect to the maximal oxygen consumption (Vo_{2max}) i.e., $\Delta\%Vo_2$. This quantity is responsible for determining variations among subject that is based on physical fitness. Which makes the estimation of Vo_2 more robust toward the individual and are subject to variations based on physical fitness. The developed estimator is validated on six healthy male subjects during cycling exercise. $\Delta\%Vo_2$ is estimated by using ER, the change in percentage of maximum heart rate (HR_{max}) from the resting to the exercising phase i.e., $\Delta\%HR_{max}$ and change in respiratory rate $(\Delta RespR)$ from the resting phase to the exercising phase. The Hammerstein system [14] is used as an estimator of $\Delta\%Vo_2$. The proposed estimator is implemented in real time and is used in the development of the SBF control of Vo_2 during cycling exercise. Results show that the developed Vo_2 estimator is capable of estimating Vo_2 in real time and all six subjects are achieved the target Vo_2 profile by using SBF system.

II. ESTIMATION METHODOLOGY FOR Vo_2

During cycling exercise, it is interesting to note that the cyclic movement is responsible for producing the change in HR, Vo_2, and RespR from their respective baseline measurements. This cyclic movement is represented as frequency of exercise and is defined as exercise rate (ER) [13]. The major goal of this paper is to design a Vo_2 estimator that can accurately predicted the dynamic and steady state behavior of Vo_2

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TABLE I

SUBJECTS: PHYSICAL CHARACTERISTICS

Subject	Age yrs	Mass Kg	Height cm	HR_{max} bpm	Vo_{2max} $\frac{ml}{min-Kg}$	Vo_{2rest} $\frac{ml}{min-Kg}$
S1	28	60	160	192	39.77	3.541
S2	29	60	164	191	39.57	3.662
S3	31	78	177	189	35.55	3.536
S4	25	63	167	195	31.42	2.765
S5	24	61	172	196	39.50	3.082
S6	23	95	177	197	35.16	3.241
Mean	26.3	69.5	169.5	193.33	33.37	3.402
Std±	2.65	14.263	7.01	3.14	4.0151	0.341

TABLE II

ESTIMATED HAMMERSTEIN MODEL PARAMETERS DURING CYCLING EXERCISE

	Cycling
ARX Estimator PRBS Datasets	$y(t)=\frac{B}{A}u(t)+e(t)$
$A(z)$	$1-1.349z^{-1}+0.7379z^{-2}-0.2106z^{-3}$
$B1(z)$	$0.1084z^{-2}-0.006307z^{-3}+0.01486z^{-4}$
$B2(z)$	$0.001481q^{-1}-0.001687q^{-2}$
$B3(z)$	$0.02519q^{-3}$
Estimated coefficient for Input Nonlinearity $f(u)$	
Sigmoid Coeff for ER	
No's Of Units	4
Regressor Mean	0.3583
Non Linear Subspace	1
Linear Subspace	1
Linear Coeff	-0.0231
Dilation	[368.64 368.64 3.19 15.21]
Translation	[132.08 132.08 −0.17 −7.66]
Output Coeff	$[0.02\ 0.02\ 0.12\ 0.04]^T$
Output Offset	−0.0573
Piecewise Linear for $\Delta RespR$	
No's of Units	3
Breakpoints	5.4216 10.7831 16.2103 0.1205 0.1292 0.1544
Piecewise Linear for $\Delta\%HR_{max}$	
No's of Units	3
Breakpoints	0.1133 0.1702 0.5731 −0.0032 0.0147 0.0288
Linear Block G(Z) Hammerstein System	$y(z)=\frac{B}{F}w(z)+e(z)$
$B_1(z)$	$z^{-2}-0.4828z^{-3}+0.322z^{-4}$
$B_2(z)$	$z^{-1}-0.7866z^{-2}-0.2077z^{-3}$
$B_3(z)$	z^{-3}
$F_1(z)$	$1-1.091z^{-1}+0.545z^{-2}-0.2335z^{-3}+0.01524z^{-4}$
$F_2(z)$	$1-1.033z^{-1}+0.3887z^{-2}-0.3396z^{-3}$
$F_3(z)$	$1-0.3598z^{-1}+0.1091z^{-2}-0.09779z^{-3}$

in real time. The proposed Vo_2 estimator used ER, $\Delta RespR$, and $\Delta\%HR_{max}$ as the inputs and Vo_2 as the output. The block diagram of the proposed estimator is shown in Fig.1. $\Delta\%Vo_2$ is found as an important variable for Vo_2 estimation. This quantity is responsible for determining variations among subject that is based on physical fitness. Therefore, Vo_2 estimator predict the $\Delta\%Vo_2$ by using Hammerstein system, as shown in Fig.1. The inputs of the hammerstein system are obtained by performing the mathematical manipulation of HR_{max}, Vo_{2rest}, Vo_{2max} and $\Delta RespR$. Among these values HR_{max}, Vo_{2rest} and Vo_{2max} are computed by using the physical characteristics of the exercising individual and resting value of HR. $\Delta RespR$ is determined by using resting value of RespR. The Vo_{rest} is determined by using the Harris Benedict Equation in papers [15], [16], [17]. The formulation of the Harris Benedict Equation for Vo_{2rest} was defined in terms of individual fitness. This formulation can cater to the individual and is subject to variation based on physical fitness and it was given in ml/min [15], [17]. Based on this formula, the Vo_{2rest} was determined for all exercising individuals and is tabulated in Table-I.

The Vo_{2max} is determined by using a simple formula, which was developed in paper [18]. This formula calculate Vo_{2max} by using the resting heart rate (HR_{rest}) and HR_{max}, computed Vo_{2max} for all subjects is tabulated in Table-I.

$$\%Vo_2=\frac{Vo_2}{Vo_{2max}},\Delta\%Vo_2=\%Vo_2-\%Vo_{2rest} \tag{1}$$

During exercise, deviation in Vo_2 from its resting phase is changed with the intensity. The maximum change is occurred, when $Vo_2=Vo_{2max}$. Therefore, $\Delta\%Vo_2$ was used as a generalization factor amongst subjects for Vo_2 estimation and it is given in Eq.1. Similarly, the change in percentage of HR_{max} from resting to exercising phase $(\Delta\%HR_{max})$ is also increased with the Vo_2. The maximum change in $\Delta\%HR_{max}$ is achieved, when $Vo_2=Vo_{2max}$. The prior knowledge about Vo_{2rest}, HR_{max} and Vo_{2max} of the individual were found useful factors to cater the physical variations among subjects. The different ER or a intensity level produces different deviation in HR, Vo_2, and RespR, while subject is engaged in exercise. Therefore, ER is also introduced as input of the estimator. RespR is used as a distinguisher between the metabolic and non-metabolic in HR, which lead to inaccurate estimation of Vo_2. Therefore, the measurement of the RespR is used as an input of the Vo_2 estimator during cycling exercise. Thus, the relationship between inputs (HR, ER, RespR) and output (Vo_2) is identified by using hammerstein system. This system is consist of two blocks, a static input nonlinearity followed by a linear dynamic system. The static nonlinearity f(u) and linear dynamic G(z) of the Hammerstein systems were identified from the experimental data, which was obtained from the six healthy subjects during cycling exercise. Their physical characteristics are given in Table-I. The detailed experimental procedure was described in paper [9].

A. Estimation of $\Delta\%Vo_2$

The hammerstein model is adopted for $\Delta\%Vo_2$ estimation. This model is a nonlinear system, which requires a good starting value to converge quickly to a global minimum [19]. Initialization of the Hammerstein system during cycling exercise was carried out by estimating the arx model that was achieved from the data sets of the PRBS input signal. The

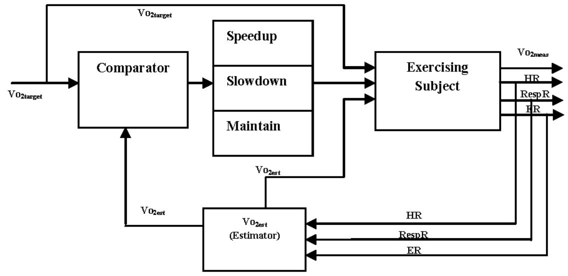

Fig. 2. Block diagram of the Self Biofeedback Control of Vo_2

model inputs are ER, $\Delta\%HR_{max}$ and $\Delta RespR$ and the model output is $\Delta\%Vo_2$. Minimum Description Length (MDL) and Akaike Information Criterion (AIC) were used for selection of the arx structure. The polynomials of the arx models for cycling is given in Table-II. This initial model was assigned in the Hammerstein system as initial guess of the linear block. The input nonlinearity vector of f(u) was assigned as sigmoid-net for ER input. This f(u) vector were assigned as piecewise linear for HR and RespR. The order of nonlinearities for each inputs signal were selected based on the fitness of $\Delta\%Vo_2$. The maximum fitness was achieved by selecting the nonlinearity order of (4,3,3) for ER, $\Delta RespR$ and $\Delta\%HR_{max}$. The nonlinear and linear dynamic block of the Hammerstein structure were estimated by using the Matlab command PEM. The details of the input nonlinearity vector(f(u)) for ER, RespR and $\Delta\%HR_{max}$ and also linear dynamics of the Hammerstein system are illustrated in Table-II.

III. REAL TIME IMPLEMENTATION OF THE SELF BIOFEEDBACK SYSTEM FOR THE REGULATION OF Vo_2

This section provides the details of implementation of the SBF control of Vo_2 during cycling exercise. Fig.2 shows the block diagram of the designed SBF system. The biofeedback control of Vo_2 generates an alarm by flashing an indicator on the computer station. This indicator displays the desired action, which is required by the subject to achieve $Vo_{2target}$. It also displays the Vo_{2est} and $Vo_{2target}$,so that the subject decides the precision of action by himself. The command of action is decided by the SBF system is based on Vo_{2est} and $Vo_{2target}$. The switching of the control command is described in Eq.2.

$$U(n) = \begin{cases} Speedup & \text{if } Vo_{2est} < 0.95Vo_{2target} \\ Maintain & \text{if } 0.95Vo_{2target} \leq Vo_{2est} \leq 1.05Vo_{2est} \\ Slowdown & \text{if } Vo_{2est} > 1.05Vo_{2target} \end{cases} \tag{2}$$

The controlling commands are *Speedup*, *Slowdown* and *Maintain*. These commands are indicated with the help of their respective indicator on the computer station (CS). The SBF system decides which command of action is required to be turned on. The implementation of the SBF was required an accurate measurement of the sensory data for the estimation of Vo_2. The sensors were deployed on the exercising subjects and connected to the CS. Details of the measurement sensors required for the measurement of ER, HR, RespR and Vo_2 are found in our previous paper [9]. Received data was decoded and used for Vo_2 estimation in real time. During resting phase 5 minutes recordings of HR and RespR were used to determine the baseline measures of these quantities. The obtained resting values were used for calculating the Vo_{2max}, Vo_{2rest}, $\Delta\%HR$, and $\Delta RespR$. The SBF system was implemented in real time with the help of the National Instrument (NI) Labview software, which was installed in the CS. Received sensory data was filtered and used for the mathematical calculations for the prediction of Vo_2. Based on the predicted output of $Vo2$, the SBF system decides the action that is required to be performed by the subject. The indicator of the required action is switched on in front of the exercising subject. The developed SBF system was validated on the six healthy subjects that were elected for designing the Vo_2 estimator.

TABLE III

STEADY STATE ERROR (RMSE1/RMSE2) AND TRANSIENT TIME (TS/T_{HL}) DURING LOW AND HIGH INTENSITY EXERCISE

	Cycling			
Subject	RMSE1 (ml/min/Kg)	RMSE2 (ml/min/Kg)	TS (secs)	T_{HL} (secs)
S1	3.84	1.6445	120	100
S2	1.7573	1.7033	100	130
S3	1.2495	0.90	250	120
S4	1.366	1.268	100	120
S5	0.6187	0.3086	260	180
S6	1.0235	0.8966	280	120
Mean	1.6425	1.1202	185	128.333

IV. REAL-TIME EXPERIMENTAL RESULT

In this section, we describe the results and performance of SBF control of Vo_2 based on its realtime estimates during cycling exercise. The Vo_2 estimator were identified from the data sets that were obtained from experimental study. This experimental study were carried out on six healthy male subjects during cycling exercise. The performance of the identified Vo_2 estimators was assessed in terms of root mean square error (RMSE). The average RMSE are 0.8772, 0.9162, 1.0119 and 0.9388 in ml/min/Kg at the ER of 36 pedals/minute, 48 pedal/minute, 60 pedal/minute and 72 pedal/minute, respectively.The performance of the SBF control of Vo_2 is dependant on the accurate estimation of Vo_2. Results illustrate that the proposed Vo_2 estimator in Fig.1 is capable to estimate Vo_2 during the low and high intensity exercise. In real time, developed estimator gives average $RMSE =$ 0.9825 ml/min/Kg, while controlling Vo_2 of exercising individual. Which indicates that the estimated values of Vo_2 were closed to the measurement of Vo_2. The developed *SBF* system was validated on 6 healthy male subjects. The quantitative measures for SBF system were

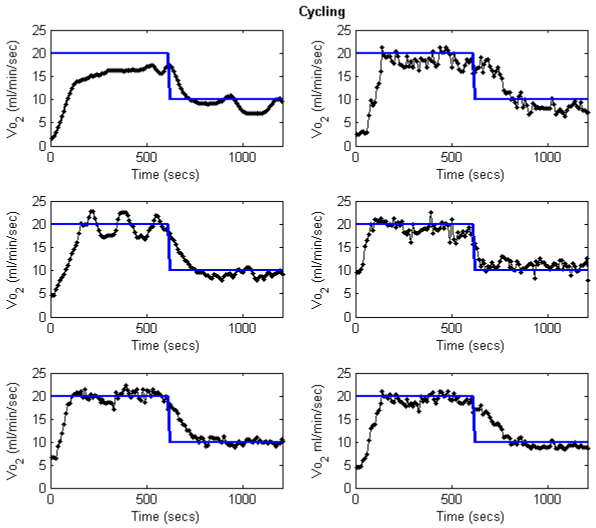

Fig. 3. $Vo_{2target}$ (Solid line) and Vo_{2est} (dotted line) during cycling

defined in terms steady state error (SSE) and transient response i.e.,TS and T_{HL}. T_S is transient time during onset high intensity exercise. These transient responses are significantly varied amongst the subjects as shown in Table-III. Which show that the proposed control strategy is subject dependant in terms of transient response. Values Vo_{2est} for all exercising individuals are shown in Fig.3. Which indicates that all subjects were achieved $Vo_{2target}$ to some extent during the high and low intensity of cycling exercise. The average $RMSE1 = 1$ ml/min/Kg and $RMSE2 = 1.6426$ ml/min/Kg in Table-III indicate that the SBF control for Vo_2 was performed well during low intensity exercise in comparison to high intensity exercise.

V. CONCLUSIONS

The TS during high intensity and T_{HL} during low intensity exercise were varied amongst subjects. Furthermore, significant difference is noticed in regulating the Vo_2 during low and high intensity exercise. The average RMSE1 is greater than the average RMSE2 for all subjects. This indicates that all subjects performed well during low intensity exercise. We can conclude that the steady state Vo_2 control using the SBF system is only possible with low intensity exercise. The dynamic response of Vo_2 is varied amongst the subjects, whether we consider low or high intensity exercise. Which results in the fact that the Vo_2 transient response is not effectively controlled by the SBF system. Based on these observation, the SBF control of Vo_2 is only useful for low intensity exercise in which humans can easily justify with their body movement to achieve the target profile. In our future research, we will improve the quality of estimation and control using robust control and state estimation techniques; see e.g. [20], [21], [22].

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