A Real Time Vibrotactile Biofeedback System for Optimizing Athlete Training

Mohamad Eid, Umair Saad, and Usama Afzal
Multimedia Communications Research Laboratory – MCRLab
New York University Abu Dhabi, United Arab Emirates
[mohamad.eid, ua264, us299]@nyu.edu

Abstract *– In sports applications, the use of real time performance monitoring and biofeedback is vital for optimized training, technique improvements and minimized risk of injuries. This paper presents an efficient mechanism to allow athletes to utilize biofeedback and vibrotactile feedback to regulate their exercise intensity to optimize their performance. ECG sensor (heart rate) and force sensors are utilized to measure the intensity of the exercise. The proposed system uses Karvonen equation to calculate the predicted maximum heart rate (HRmax) of an individual. Once the HRmax is calculated, vibrotactile feedback is provided to the athlete in order to stay within a lactate threshold; i.e. athlete's body prevents the accumulation of lactic acid in the body hence preventing fatigue. Along with keeping track of the Target Heart Rate Range, the proposed system keeps track of the amount of calories burnt by an athlete during an exercise session hence ensuring that the intended amount of calories are burnt at the right heart rate in order to increase the overall efficiency of the workout. Preliminary performance analysis has shown the effectiveness of the system to maintain a desirable intensity of exercising for optimal training using vibrotactile feedback as opposed to other forms of existing feedback and no feedback.*

Keywords *– Real Time Athlete Training, Biofeedback; Force Sensors; Vibrotactile Actuators; Energy Expenditure.*

I. INTRODUCTION

Preventing diseases, controlling chronic degenerative diseases and promoting health are few of major concerns of sports medicine. Based on the historical development, sports medicine can be divided into four sub-categories where medical management of the athletes is one of the primary sub-categories [1]. In order to obtain optimal training effects and avoid overtraining for athletes, it is essential to monitor the intensity and frequency of their exercise. Frequency and duration of the exercise can rather easily be measured using biofeedback sensory technologies and used to calculate the intensity of the exercise [2].

Table 1 shows a list of indicators that have been used to estimate the intensity of the exercise to provide optimal training [3]. In an ideal situation, all indicators should be used to calculate an index for the intensity of the exercise however this may be impractical and costly. Furthermore, some indicators are more important than others. For example, although speed and heart rate are both indicators of exercise intensity, heart rate is a better indicator than speed since environmental and physiological factors have a larger impact on speed compared to heart rate. Factors such as wind, air temperature, air density, humidity and terrain may affect speed, and hence affect the intensity estimation [3].

Table 1: Different indicators of exercise intensity [3]

Speed	Heart rate
VO2	% Maximal heart rate
% VO2 max	% Heart rate reserve
Power	% Lactate threshold
Energy expenditure	% Ventilatory threshold
Perceived exertion	Maximal lactate steady state
Multiples of resting metabolic rate (MET)	

A crucial point of attention for athletes today is to regulate their heartbeat and intensity of exercise. Athletes often use instruments to monitor their heartbeat [4]. However there is no tool available to athletes that allow them to monitor their heartbeat without significantly diverting their attention from their exercise routine. The current solutions require the athlete to look at their heartbeat on a display, and they are left to figure whether they should respond to the number, i.e., whether they should exercise more intensely, with the same intensity, or less intensely [5-7]. Moreover, the current solutions are not ideal because different athletes have different requirements of intensity in their exercise programs, and athletes definitely should not be left to interpret the meaning of the heartbeat just as a patient should not take his own vitals. Furthermore, it is unreasonable to have a trainer beside the athlete all the time to interpret the numbers. Another major limitation to the existing solutions is that only heartbeat is used to determine the intensity of the exercise.

The subject of this paper is to evaluate the effectiveness of using biofeedback to regulate exercise intensity in order to maximize performance of athletes. In order to do this, an array of force sensors and an ECG belt sensor are used to measure the exercise intensity. A leg band vibrotactile device is developed to instruct the athlete to adapt (increase and/or decrease) the exercise intensity to meet their exercising goals and without being distracted from the main task of exercising. After building a prototype for the system, it is used to test athletes' performance with/without the vibrotactile feedback system to demonstrate the proposed system.

The remainder of the paper is organized as follows: section 2 describes related work and highlights the scope of this paper. In section 3, we present the architecture of the proposed system and the design details. Section 4 presents implementation details and hardware usage. Section 5 describes the performance evaluation in terms of intensity adaptation. Finally, in section 5 we summarize the paper findings and provide perspectives for future work.

978-1-4799-0849-3/13/$31.00 ©2013 IEEE

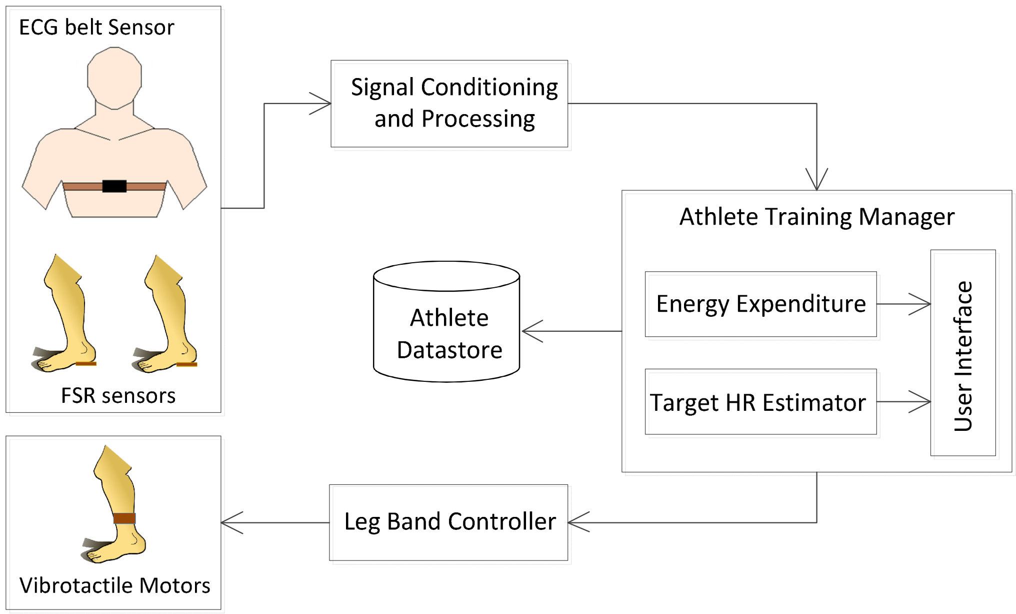

Figure 1: The software architecture for the real time athlete training system.

II. RELATED WORK

There are several devices in the market and prototypes in the research community that aid an athlete to exercise more efficiently but they are limited to audio-visual feedback hence there is a need for a more effective feedback mechanism. We are proposing a real time optimizing system with vibrotactile feedback to minimize athlete distraction from training.

SenseWear-Pro2-Armband developed by the Body-Media Company is an armband that includes skin temperature sensor, skin surface temperature sensor, accelerometer, thermal diffusion sensor and galvanic skin reaction sensor [8]. It is one of the many techniques used to record data. Once the data is recorded and saved by the armband, it is viewed on the computer using InnerView Wearer Software in terms of skin temperature, calorie consumption and amount of physical activities [1]. Another popular device used to capture similar data is called Vital Jacket (VJ) from BioDevices S.A. Vital Jacket (VJ) [9].

Although the presence of several sensors recording values for different indicators may provide more accurate estimates of the exercise intensity, the inability to obtain biofeedback on field reduces the effectiveness of these sensory technologies [10]. A more suitable sensor for regulating exercise intensity combines the most indicators to estimate exercise intensity, is wearable on field and is cost effective. Bodymedia Sensewear is an example of an unobtrusive activity-monitoring device. It utilizes a heat flux sensor, galvanic skin response (GSR) sensor, skin temperature sensor, near- body temperature sensor, and a two-axis accelerometer to gather data related to energy expenditure [11]. Once the readings are stored in the device, they can be mapped to calorie consumption based on specific software algorithms. However, this device must be worn on the upper arm for 24 hours every day; it has the potential to disrupt user's sleeping and interfere with clothing [11].

Several companies around the globe have already realized the importance of instantaneous biofeedback on individuals' performance during an exercise. Nike's Nike+Sportband provides instantaneous visual feedback through a wristband of the heart rate, calories burnt, and the speed and the distance travelled during a run [12]. All of the up-mentioned works do not support any haptic feedback that does not hinder the focus of the athlete on performing the training exercise itself. Our system provides real-time tactile feedback for optimizing training performance.

III. SYSTEM ARCHITECTURE AND DESIGN

The software architecture for the proposed real-time athlete training system is shown in Figure 1. The system reads physiological data (namely the heart rate and feet movement forces) to determine the intensity of training and provide feedback via the leg band device on whether to increase, decrease, or maintain the same training intensity. The architecture components are explained in further details below.

A. Sensory Module

The sensory module is composed of an ECG belt sensor that captures the heart signal to determine the heart rate and an array of Force Sensitive Resistor (FSR) sensors. The FSR sensors change their resistance according to the amount of force pressure applied on them. We deployed five pressure sensors positioned at important contact points identified on the lower surface of the shoes. This allows us to measure the user movements (gait) and eventually the energy expenditure (with the aid of a time clock). The signal conditioning and processing module filters the signals and converts the data into a uniform format that is comprehensible by the Athlete Training Manager.

B. Athlete Training Manager

The Athlete Training manager has three main tasks: (1) implementing an energy expenditure algorithm for computing the calories consumed by the athlete, (2) compute the target heart rate range using the Target HR Estimator, and (3) providing a graphical user interface to the user (the athlete, a trainer, or a third party) who can set training goals in order to personalize training. Furthermore, the Athlete Training manager communicates with the Athlete Datastore that implements a database to store the athlete's training data as well as the athlete's user profile.

The data obtained from the ECG and FSR sensors is used to calculate Maximum Heart Rate (HR_{max}), Lactate Threshold, Heart Rate Reserve (HRR) and amount of calories burnt. Values of all these variables are then processed to indicate the intensity of the exercise.

HR_{max} is the highest heart rate that an individual can achieve during exercise without facing any physical complications such as breathlessness or severe headaches. HR_{max} depends on the age of an individual. HRR reserve is the difference between the HR_{max} and the RHR (Resting Heart Rate). Resting Heart rate is the beats per minute (bpm) while an individual is at complete rest. RHR is often measured while an individual is asleep and almost always lies within the range 60-80 bpm. Lactate Threshold is said to be the intensity of the exercise for which lactic acid starts to accumulate in the blood stream.

Although there are several methods of calculating the Maximum Heart Rate using the age, in this paper we will use Karvonen Equation [13]. The Karvonen method is the oldest and the most trusted method of calculating Maximum Heart Rate as it is used by several training centers around the world.

The Maximum Heart Rate is used to determine the Target Heart Range at which an athlete should perform a particular exercise and maintain no more than 4 mmol/l lactate in the bloodstream [14]. In case the athlete trains above the Target Heart Range, the level of lactic acid in the bloodstream will increase at rate faster than the rate at which it is removed; hence it will cause fatigue and tiredness. In case the athlete trains below the Target Heart Range, the exercise will not be optimal.

Therefore, it is clearly visible that if an exercise is performed within the Target Heart Range, the levels of lactic acid in the blood first rises beyond the 4 mmol/l level at first but then falls periodically to the desired lactic acid value. This ensures that the athlete is not exhausted, can train for longer time periods and burn the desired amount of calories. The Target Heart Rate Range is computed as shown in Figure 2.

```
MHR (HRmax) in women = (226 –Age)
MHR (HRmax) in men = (220 – Age)
RHR = Heart Rate at Rest
HRR (Hear Rate Reserve)= MHR – RHR
% Intensity = (%age of HRmax)

Target Heart Rate =
{[(MHR-RHR) x %intensity] + RHR}

Target Heart Rate Upper (THRU) =
(Target Heart Rate + 5) %

Target Heart Rate Lower (THRL) =
(Target Heart Rate - 5) %

if(HR < THRL)
      Increase intensity command
else if (HR > THRU)
      Decrease intensity command
```

Figure 2: Target Heart Rate Range algorithm (Seiler, 2006)

C. Leg Band Controller

The Leg Band Controller is composed of a microprocessor that receives commands from the Athlete Training manager and generates actuation signals that control the vibrotactile motors. The actuation circuit is composed of three vibrotactile motors that are arranged vertically and actuated in a sequence (upward indicating that the user should increase intensity and downward when the user should decrease exercise intensity) to provide real-time feedback.

D. Athlete Datastore

The Athlete Datastore is a database that stores the training user profile, training goals and settings, and performance data. Examples of user's profile information include, but not limited to, type of exercising, age, gender, amount of calories to be burnt, and training goals.

IV. SYSTEM IMPLEMENTATION

Figure 3 showcases the system implementation along with a labeling of the key hardware pieces. For the prototype, we used a commercial gel insole and attached to it the following components:

- 5 FSRs of 0.5" sensing area diameter located on key contact points onto the lower surface of the shoes,
- Zephyr Bioharness ECG wearable sensor [15] that captures the heart signal with a sampling frequency of 250Hz. The sensor is shaped like a belt that is worn on the torso. All data collected by the sensor are sent via a Bluetooth link to a nearby computing unit (such as desktop or mobile device),

- An Arduino UNO/Processing device with Bluetooth module,
- A Linvor Bluetooth modem [16] with 9600 baud rate located on the side,
- 3.3 V power supply from a rechargeable Cell battery located underneath the heel,
- Two charging inlets located on the side (used to recharge the cell battery)

All sensors are connected to the Arduino UNO microprocessor which reads their analog signal and converts it to digital form. A piece of software executing on the Arduino microprocessor runs the power module logic and orders the sending of sensory data on the wireless link.

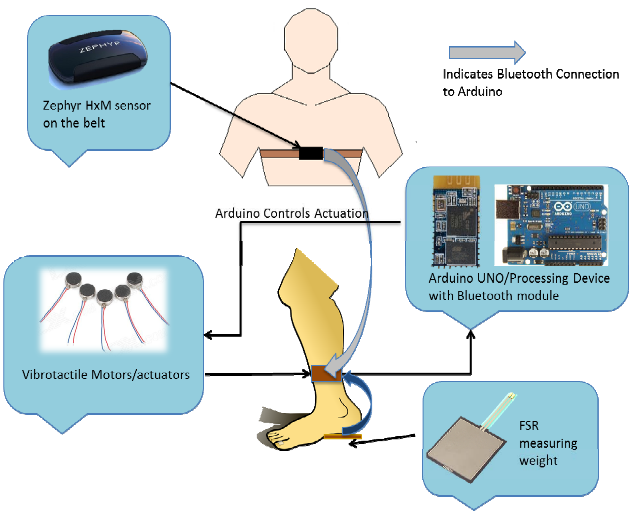

Figure 3: System implementation

V. PERFORMANCE EVALUATION

In order to test the efficiency of the proposed system, we carried out a performance evaluation. Ten test subjects participated in the experiment; one of the test subjects is a 21 years old male student who weighs 70kg as his data is presented in this paper. Each subject was asked to run on a treadmill three times—wearing our device, wearing the Nike+Sportband and wearing no device—to burn approximately 265 kcal. The subjects were also asked to run on the treadmill on a constant speed of 7miles/hr. It took on average approximately 18 minutes for them to burn 265kcal; considering that the expended calories were calculated using the following method [17]:

Energy Expenditure (kcal) = 1.05 * METS *duration (hour) * weight (kg)

Where METS (Metabolic Equivalent Task) is a value taken from the standard METS table [18] (is equal to 12 considering that the subjects were running at 7miles/hr in our case). The subjects were given a rest of at least 5 hours each between the 1st, 2nd and 3rd runs on the treadmill.

Firstly, the subject being represented in this paper was not wearing our device and was asked to steadily increase the running speed on the treadmill from 0 – 7mile/hr and then keep it constant for the 18 minutes exercise duration. His heart rate was sampled every 30 seconds during the exercise session and the intensity of the exercise for this duration was also calculated using his heart rate; the results were plotted against time as shown in Figure 4. During the exercise, his maximum heart rate recorded was equal to 184 beats/min and his maximum exercise intensity recorded was approximately equal to 87%. The treadmill was stopped once the subject completely burnt 265kcal but his heart rate was continuously sampled for the next 12 minutes every 30 seconds; assuming that 12 minutes after the exercise was enough time for the heart rate of the subject to fall back to the Rest Heart Rate. For the 2nd and 3rd runs the procedure remained the same but the subject was wearing the feedback devices. The exercise intensity graph of all three runs is represented in Figure 4.

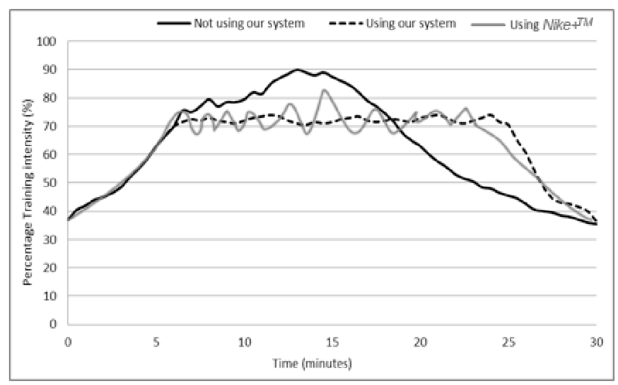

Figure 4: Heart Rate of the subject without wearing our device during the 30mins after starting the exercise

The difference between all three runs on the treadmill is quite apparent as shown in Figure 4. It is visible that the subject was greatly aided by the Vibrotactile feedback of our device to ensure that he burns the desired amount of calories while exercising in the Target Heart Range (Target Heart Range was defined as the interval [70%, 75%]). Note that the exercising intensity was bounded by the desired Target Heart Range interval throughout the exercise session. This demonstrates the ability of the user to exercise at a desirable range of target heart rate using our device. Compared to the Nike+Sportband, our device was able to provide more efficient feedback for the subject in order to regulate the exercise intensity in the desired range. There are more fluctuations when the exercise is being regulated with the Nike+Sportband, clearly showing the relative inefficiency of the visual feedback to the subject.

Two performance observations are discussed here. First, since the subject was notified through the Vibrotactile feedback whenever he was out of the Target Heart Range, it was seen that this lead to a slight change in the method of the exercise by the subject. It was seen that the subject was taking bigger steps on the treadmill and breathing more efficiently in order to ensure that despite running at 7miles/hr, his heart rate stays within the Target Heart Range. Upon asking, the subject also said that he felt less tired after running with our device. Compared to the Nike+Sportband the change in the method of the exercise after feedback was greater in magnitude. The subject was not being provided with continuous regulatory feedback because the subject is not constantly looking at the wristband while running on the treadmill. Whenever the subject looked at the band for the feedback, he had to take a relatively drastic action to fall back into the target heart range that led to a less smooth run on the treadmill.

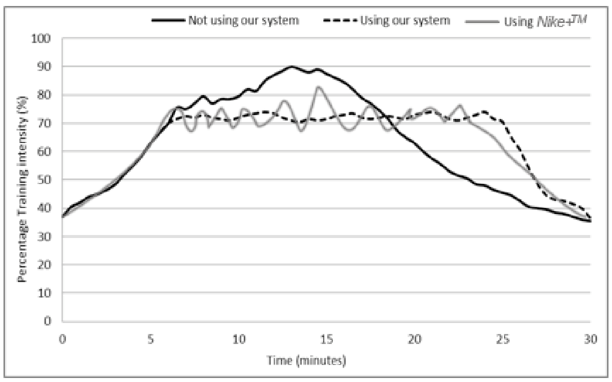

Figure 5: Intensity of the exercise of the subject during the 30mins with wearing our device

Secondly, since the subject's heart rate was not as high as during the first run, it took him less time to get back to Rest Heart Rate. It is also essential to note that for most time of the exercise while wearing our device, the intensity of the exercise stayed between 70 – 75% instead of getting as high as 90% compared to the first run. With the Nike+Sportband the intensity of the exercise was also regulated to some extent but again not as efficiently with our device; the exercise intensity fluctuated between 67% – 83%. It can clearly be seen that some kind of feedback ensures better regulation of exercise, but also that vibrotactile feedback is more efficient than devices that are already exist in the market and provide visual feedback. Therefore, the proposed system is highly efficient in optimizing athlete's exercise using biofeedback. Figure 5 shows another session with the same user, with similar conclusions.

VI. CONCLUSION

In this paper, we proposed a real time mechanism using biofeedback and vibrotactile feedback to regulate the exercise intensity for athletes in order to optimize their performance. The performance evaluation confirmed that if an athlete trains with biofeedback in the form of vibrotactile feedback to maintain the heart rate in the target lactate threshold their performance is improved, their recovery from exercise is quicker, and the desired calories are burnt in the optimal way. The goal is that an athlete's body will become used to exercising in the target lactate threshold, such that eventually the athlete would not need biofeedback to maintain his heart rate in the target range, and instead the body would naturally keep the heart rate in the desired range, improving the athlete's performance. The data for the remaining nine subjects also led to similar conclusions and was consistent with the data of the presented subject in this paper.

Note: The data for the remaining nine subjects will be provided if needed.

REFERENCES

[1] S.B. Lee, J.H. Hong, and T.S. Lee, "Analysis of Physical Activities in Wu-Shu Training," 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp.632,635, 22-26 Aug. 2007.

[2] C. Franco, A. Fleury, P.Y. Gumery, B. Diot, J. Demongeot, and N. Vuillerme, "iBalance-ABF: A Smartphone-Based Audio-Biofeedback Balance System," IEEE Transactions on Biomedical Engineering, vol.60, no.1, pp.211,215, 2013.

[3] A. Jeukendrup and A. VanDiemen, "Heart rate monitoring during training and competition in cyclists", Journal of Sports Sciences, 16 Suppl:S91-9, 1998.

[4] X. Yong, B. Tingting, B. Chunhua, and M. Qianli, "Design of the Athlete's Electrocardiogram Monitoring and Evaluation System Based on Wireless Sensor Network", 2011 First International Workshop on Complexity and Data Mining (IWCDM), pp.60,63, 24-28 Sept. 2011.

[5] A.E. Aubert, D. Ramaekers, Y. Cuche, R. Lysens, H. Ector, and F. Van de Werf, "Effect of long term physical training on heart rate variability", Computers in Cardiology, pp.17,20, 8-11 Sept. 1996.

[6] B. Ilie, "Portable equipment for monitoring human functional parameters," 2010 9th Roedunet International Conference (RoEduNet), pp.299-302, 24-26 June 2010.

[7] S. Korsakas, A. Vainoras, V. Miskinis, R. Ruseckas, V. Jurkonis, R. Jurkoniene, K. Berskiene, L. Siupsinskas, and V. Marozas, "Electrocardiosignals and motion signals telemonitoring and analysis system for sportsmen", 2005 Computers in Cardiology, pp.363-366, 25-28 Sept. 2005.

[8] BodyMedia SenseWear System official Website: http://sensewear.bodymedia.com/ (accessed June 10, 2013).

[9] Vague Terrain Official Website: http://vagueterrain.net/journal18/biodevices/01 (accessed June 10, 2013).

[10] Y. Can, J. Pallauf, B.V.K.V.Kumar, and M.T. Coimbra, "Customizing the training dataset to an individual for improved heartbeat recognition performance in long-term ECG signals", 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp.3322-3325, 2011.

[11] R. Nanami, Y. Kawahawa, and T. Asami, "A Calorie Count Application for a Mobile Phone Based on METS Value", 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, pp.583-584, 2008.

[12] Nike + SportBand official website: http://nikeplus.nike.com/plus/products/sport_band/, accessed June 11, 2013.
[13] L. Sornanathan and I. Khalil, "Fitness monitoring system based on heart rate and SpO2 level", 10th IEEE International Conference on Information Technology and Applications in Biomedicine (ITAB), pp.1-5, 2010.
[14] W. Kindermann, G. Simon and J. Keul, 'The significance of the Aerobic-anaerobic Transition for the Determination of Work Load Intensities During Endurance Training', European Journal of Applied Physiology, Vol. 42, No. 1, pages: 25-34, 1979.
[15] Zephyr, BioHarness BT [online] Available: http://www.zephyr-technology.com/bioharness-bt, accessed June 11, 2013.
[16] Bluetooth Module, http://www.bluetooth.com/pages/Bluetooth-Smart-Devices.aspx, last accessed: June 11, 2013.
[17] H. Jung, Y.D. Lee, and D.U. Jeong, "A novel method for energy expenditure using multisensor based activity monitoring", International Conference on Computer Sciences and Convergence Information Technology (ICCIT), pp.103,106, 2011.
[18] M. Jette, K. Sidney, and G. Blumchent, "Metabolic Equivalents (METS) in Exercise Testing, Exercise Prescription, and Evaluation of Functional Capacity", Clin. Cardiol. ,vol. 13, pp. 555-565, 1990.