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Using extension method for health analysis system of a fitness device

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ABSTRACT

This paper used foot-operated fitness equipment, a power generation system and a biomedical measurement system to construct a fitness system for fitness exercise, energy storage and diagnosing the user's movement conditions. The diagnostic mode is that the rotation speed and output power of pedal-dynamo are converted into the mileage and calorie consumption of the user's pedaling movement. Second, the biomedical measurement module can diagnose the user's movement health status timely according to the heartbeat signals and the consumed calories while the user is in exercise. The diagnostic data were integrated using touch tablet PC and LabVIEW software for the image controlled man-machine interface. The user can observe the real-time motion state through the virtual instrument interface. The built-in program can diagnose the health status, and count the total generation and movement process after exercise.

1. Introduction

Energy saving and carbon reduction has become a worldwide trend, and many countries are seeking for alternative energy sources to reduce damages to the Earth. Green energy and environmental concerns have become the main consideration in science and technology industries. As LOHAS (Lifestyle of Health and Sustainability) becomes a popular lifestyle of modern people, many people are choosing a consumption pattern that embraces the health of oneself, family, and even the Earth. Renewable energy, green building, organic food, and austerity life are examples of LOHAS.

Cycling is a popular recreational sport in modern society. However, as limited to weather and traffic factors, the indoor foot-operated fitness equipment is a popular sports mode. The users can challenge their physical limits, and observe their pedaling speed, time, and heart rate at any time on the fitness equipment. Besides exercise, the fitness equipment can be used to improve cardio-pulmonary function effectively, and strengthen leg muscles, consume body fat and improve physical constitution. It is especially applicable to physically handicapped, weak people, and patients in rehabilitation.

As the fitness equipments on the market use belt or magnetic control (Long, Zhang, Jin, Ying, & Zhang, 2009; Zhang, 2008) to consume the users' calories to reduce weight, the energy of movement from burning body fat has not yet been properly used. The check-up examination function of modern treadmills has been studied (Steven, Wang, & Branko, 2005), but this function of vertical fitness equipments still needs to be developed. Therefore, a green, environment-friendly and self-power generation mode is designed by integrating the green energy-environmental protection with check-up examination, the physical property of converting mechanical energy into electric energy can be used circularly, and the power generation system of the foot-operated fitness equipment can be properly used to generate power. The electric energy can be recovered and supplied for the interactive heart rate health examination fitness equipment to evaluate the user's body motion state. The heart rate can be identified by the R wave in cardiogram (Rangayyan, 2001), or can be used for different loads, such as public lighting and recreational household appliances. Combined with the concept and innovation of modern technological products, an additional tablet PC is fixed to the front platform of the fitness equipment to display the signals measured by the fitness equipment, so that the users can know their health status easily by touching the interface of tablet PC.

2. System structure

The main system structure is consisted of mechanical, electric power and signal systems. The mechanical system contains a 27-gear shifting system selecting pedaling degree freely. The power system contains a dynamo using electric and electronic technical voltage stabilization and charge control functions to accumulate energy in the battery for various loads. The principle of power generation is that the pedaling drives the gear accelerator and the chain to run the dynamo. After the voltage stabilization of charge controller, the battery is charged, and then converted by converter into commercial power for public lighting and recreational

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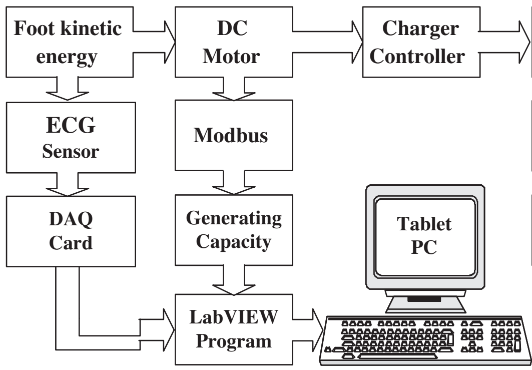

Fig. 1. System structure.

appliances, such as decorative lamps for trees in parks, public street lamps, and household appliances.

The signal system uses Electrocardiogram (ECG) sensor. The USB6009 DAQ card and Modbus signal communication interface are used to capture the user's pedaling voltage and current signals from the input end of charge controller and the output end of dynamo. The tablet PC displays the user's general health condition by using LabVIEW program, including mileage, heartbeat, consumed calories and BMI test, so as to complete a system for check-up examination. The overall system structure of the combined interactive physical fitness equipment is shown in Fig. 1.

2.1. Mechanical system structure

The mechanical structure consists of a body and a transmission mechanism. The body mechanism is consisted of ① frame, ② rotating axle, ③ a pair of cranks and ④ pedals; the rotating axle can penetrate through the body rotationally and is mounted with cranks on both sides, so the rotating axle has additional free rotating pedals for the user to pedal; ⑤ the transmission mechanism is combined with the rotating axle and the arbor respectively, so that the rotating axle can drive the arbor to rotate; the transmission mechanism consists of ⑥ driving fluted disc, ⑦ arbor fluted disc, ⑧ gear set; the gear set consists of variable-speed shaft, connecting gear, complex-velocity shifting fluted disc, driving chain, connecting chain, output chain, and all the transmission mechanisms are connected by coupling ends. This mechanism can be used to regulate the speed shifting system, allowing the user to regulate the speed and power freely. Finally, the interlocking chain drives the power system of pedals. Fig. 2 shows the mechanical system structure.

Fig. 3. Fitness system structure.

We put the tablet PC in front of the fitness system configuration, the rear of system supplies load by storage power, we design limit switch on the handle part, it mainly lets users increase the interaction with the system, we are not only doing exercises but also using the limit switch of fitness system configuration to make LED lights work; We assemble physiological measurement system under the tablet PC, when users use this system, it can pull the signal measurement line to measure heart rate. Fig. 3 shows the fitness system structure.

2.2. Power system structure

The power system structure of the physical fitness equipment is consisted of battery, gear shift, dynamo and charge controller placed in the power generation system. The pedals drive the change gear, and the change gear accelerator turns the dynamo. The charge controller stabilizes the unadjusted DC voltage of dynamo and charges the accumulator. The power system structure is shown in Fig. 4.

2.3. Signal system structure

The signal system monitors physiologic signals and the internal voltage and current values of power generation box, including heartbeat, power generation output voltage, output current, total

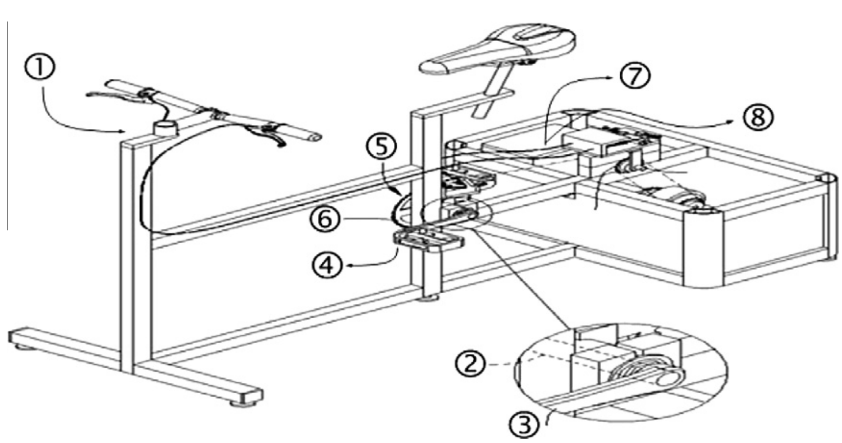

Fig. 2. Mechanical system structure of fitness equipment.

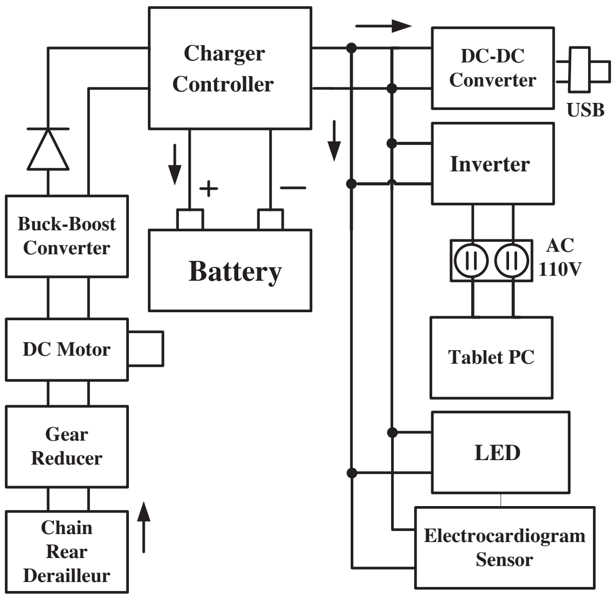

Fig. 4. Power system structure.

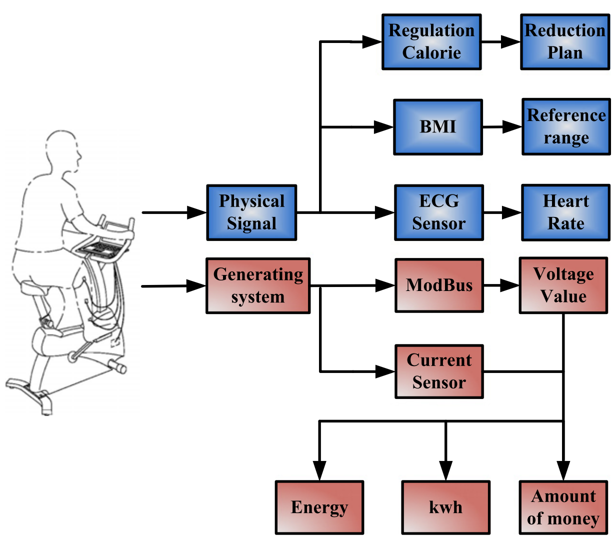

Fig. 5. Signal process structure.

output power, and pedaling speed. The signals are captured and detected by sensor and measurer, and they are designed in the monitoring program LabVIEW using the original theoretical equations, and displayed by tablet PC. The signal system flow structure is shown in Fig. 5.

3. System signal measuring means

The physical performance signal detection of the foot-operated fitness equipment refers to converting the heartbeat frequency measured by the system and the direct voltage and current of generator into data. The heartbeat is measured by the ECG sensor which measures physiologic signals.

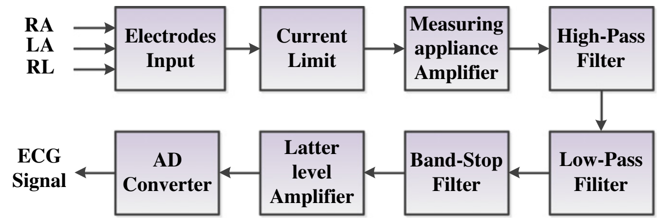

Fig. 7. Electrocardiogram signal capture process.

The regular and obvious waveform is formed of QRS amplitude. In this waveform, the wave peak is R wave, and the number of heartbeats is identified according to the amplitude of this peak. Fig. 6 is the typical ECG.

In Fig. 7, the electrode input part is single channel part, including RA (right arm), LA (left arm), and RL (right leg) measurement. The electrode pads are silver chloride dielectric material patch, for reducing different skin impedance matches. There is additional high resistance $1\,M \sim 3\,Mohm$ between electrode input and instrument amplifier to limit the current, for the purpose of protecting human body and preventing the inrush current of measurement module in uncertain conditions. The instrument amplifier is implemented by AD620 circuit (Wang, Liu, & Hong, 2010), and the amplification is $20 \sim 50$ times. In order to prevent the component from reaching electric saturation, the magnification of this component is designed as adjustable. The schematic of circuit design is shown in Fig. 8.

Generally, the measurement range of normal ECG is $0.1 \sim 100$ HZ. However, the high pass and low pass filters adopt second-order active filter. The major difference to passive filter is that there is an additional operational amplifier in the circuit. Therefore, it has gain effect, and the filter will not lose signals. The high pass filter is shown in Fig. 8. The range is set as $0.01 \sim 0.05$ Hz in order to obstruct the DC potential behind instrument amplifier, including human DC potential. The second-order active filter is shown in Fig. 9. The range is set as $120 \sim 150$ Hz, for filtering the high frequency noise out of the circuit, and leaving the range of $0.01 \sim 150$ Hz (Huayu Cloud Technologies, 2011). The cut-off frequency (fc) and gain control can be calculated by the resistance and capacitance values in circuit, as shown in Eq. (1).

$$f_c = \frac{1}{2\pi RC} \tag{1}$$

3.1. ECG signal measuring means

The heart functions as autonomic blood pump, the blood conveying process is shown in Fig. 9. The cardiac muscle is operated by the sinoatrial node (SA node), also known as cardiac rhythm point. It is a special nervous muscle fiber tissue in the upper wall of right atrium, there are 60–100 depolarizations per minute on average (Huayu Cloud Technologies, 2011).

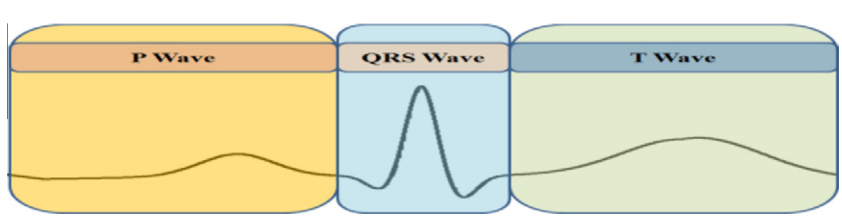

Fig. 6. Typical ECG.

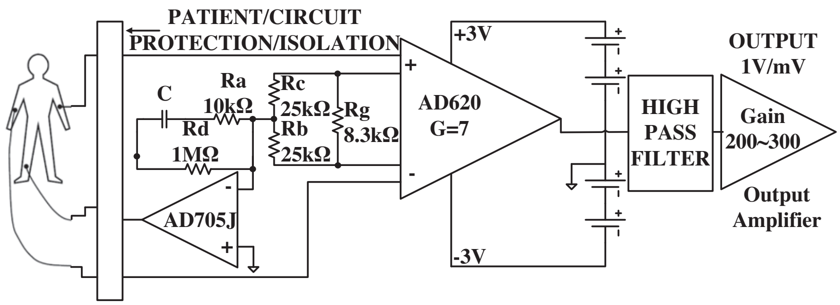

Fig. 8. Schematic of instrument amplifier circuit.

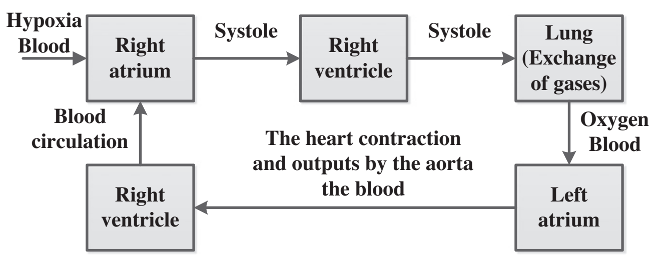

Fig. 9. Schematic of blood conveying by heart.

3.2. Calorie and heartbeat measurement

In terms of energy conversion, the energy generated by the user obtained after integration can be converted into the calories consumed by the user according to 1 calorie equaling to 4.2 Joule energy in physics. When the diet calories have been controlled within $1200 \sim 1500$ calories, the daily calorie consumption is about $500 \sim 600$ calories, and fat accumulation can be avoided. If the input power Pin is the output power of charge controller, deduced from Eq. (2), and integrated as Eq. (3), the obtained energy is the applied work, and the unit is joule. The η is the conversion efficiency of the power generation system box which is about 76%.

$$P_{in} = \frac{P_{out}}{\eta} \tag{2}$$

$$W = \int_0^T P_{in} dt \tag{3}$$

When the ECG module detects QRS peak, the DAQ signal acquisition card captures the signal, the sampling frequency is set as 1 kHz, and the number of cycles is captured. The obtained value minus the value captured last time, multiplied by 1 ms, and the result is the time of each QRS peak. It is converted into frequency per minute by Eq. (4), and then the heart rate is obtained.

$$f_{(hz)} = \frac{1000}{t_{(ms)}} \times 60 \tag{4}$$

According to research results, there must be 3–5 times of exercise per week in order to maintain good cardiopulmonary fitness and muscular endurance. The heart rate should reach 60%–90% of maximum heart rate each time, and the duration and intensity should be 20–60 min. American Heart Association suggests that the most effective exercise items for heart are aerobic exercise lasting long or using large muscle groups, e.g. cycling. The exercise intervals are shown in Table 1, generally, 220 minus actual age is the limit of personal heartbeat per minute as proposed by ACSM (American College of Sports Medicine., 2010).

Table 1
Heart rate exercise intensity management HR-max%.

Maximum heart rate	Exercise goal
$50\% \sim 60\%$	Keep fit
$60\% \sim 70\%$	Body weight control
$70\% \sim 80\%$	Aerobic boundary
$80\% \sim 100\%$	Physical performance for competition

3.3. Man-machine interface design

The interface module of LabVIEW panel is as shown in Fig. 10. All the user test data are displayed on the interface board, and are classified into 5 major types, which are signal interface, kinetic heartbeat analysis, pedaling power data, data record and pedaling result analysis.

In the computer monitor signal interface in Fig. 11, the user is required to enter the data in the white and yellow fields for identifying health. In other monitoring interfaces, the program identifies and analyzes values automatically, so that the user can know his states in exercise. In order to convert the user's physical performance into energy, the output values of generator inside the power generation box are designed as monitoring interface, as shown in Fig. 11.

According to ACSM, the heart rate standard varies with age, the users at different ages have different heartbeat conditions during exercise. Fig. 12 shows the user's electrocardiogram, and the heartbeat state is displayed on meters. Whether the user's heartbeat state is as that shown in Table 3 can be known clearly.

Finally, the user can know the exact analytic results of pedaling as shown in Fig. 13. The calorie consumption analysis enables the user to know the consumption goal of his kinestate within a period of time as a health reference to know his exercise schedule. After pedaling, the user can obtain the riding goal and data of the day from the pedaling result interface, as shown in Fig. 13.

4. Extension identification

The extension theory was proposed by Prof. Tsai Wen in 1983. The theory uses objects, characteristics and corresponding magnitude to handle contradictory problems for extension set and incompatibility problem in order to develop a new domain (Wang & Ho, 2005). The elementary theory of extension is that the matter-element, extension set theory, and the matter-element concept are used to solve contradictory noncompatibility problem. The matter-element is consisted of three elements, including object, characteristic and magnitude. The extension set uses extension model to handle the problems that the traditional mathematics and fuzzy mathematics cannot handle (Chao, Ho, & Wang, 2008; Wang, Chao, Huang, & Tsai, 2011; Wang, Tseng, Chen, & Chao, 2009).

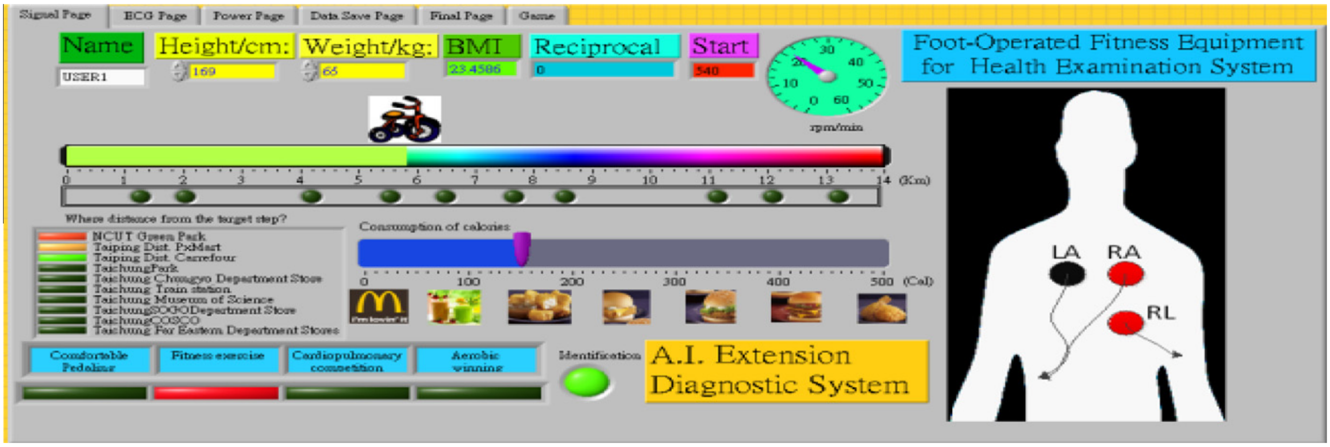

Fig. 10. Main interface of monitoring program.

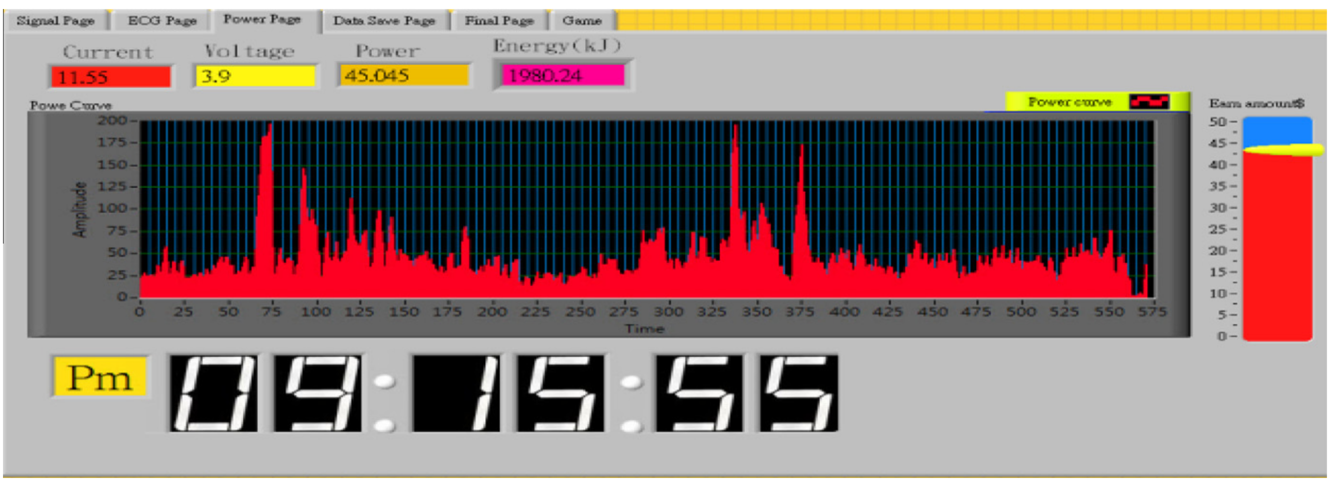

Fig. 11. Pedaling data interface.

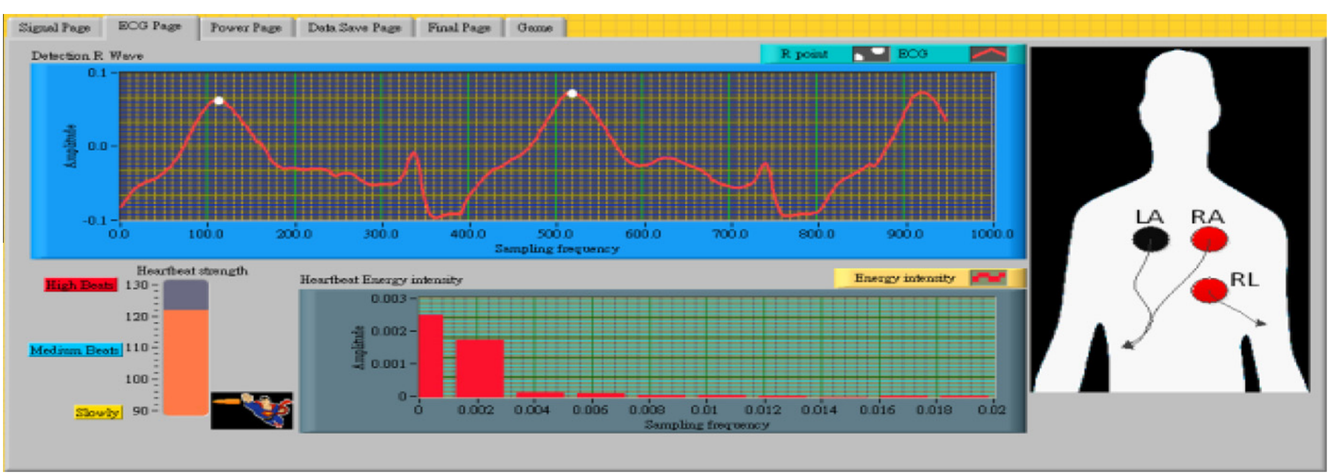

Fig. 12. Kinetic heartbeat analysis interface.

4.1. Extension theory

In the extension theory, the combination of three major elements describing objects is called matter-element, defined as the name of object R is N, characteristic C and magnitude V are called matter-element, the matter-element describing objects is:

$$R = (N, C, V) \tag{5}$$

In Eq. (5), when the elements of matter-element change and the internal structure of object changes, the matter-element changes accordingly. Therefore, the concept originated from that the matter-element is the response describing the variability of objects.

Table 3
Classical domain for various physical conditions.

$$R_1 = \begin{bmatrix} N_1 & c_1 & \langle 70,95\rangle \\ & c_2 & \langle 60,80\rangle \\ & c_3 & \langle 10,18\rangle \\ & c_4 & \langle 0,200\rangle \end{bmatrix} \quad R_2 = \begin{bmatrix} N_2 & c_1 & \langle 95,110\rangle \\ & c_2 & \langle 100,110\rangle \\ & c_3 & \langle 20,24\rangle \\ & c_4 & \langle 200,400\rangle \end{bmatrix}$$

$$R_3 = \begin{bmatrix} N_3 & c_1 & \langle 110,125\rangle \\ & c_2 & \langle 90,100\rangle \\ & c_3 & \langle 25,29\rangle \\ & c_4 & \langle 400,600\rangle \end{bmatrix} \quad R_4 = \begin{bmatrix} N_4 & c_1 & \langle 125,140\rangle \\ & c_2 & \langle 70,80\rangle \\ & c_3 & \langle 25,30\rangle \\ & c_4 & \langle 600,800\rangle \end{bmatrix}$$

However, an object often has multiple characteristics, so the characteristic vector can be expressed as $C = [c1\ c2 \ldots cn]T$, and the magnitude vector can be expressed as $V = [v1\ v2 \ldots vn]$T, then the multi-dimensional matter-element is expressed as:

$$R = (N, C, V) = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{6}$$

The joint field $X_j = \langle w, z\rangle$ and classical domain $X_i = \langle x, y\rangle$ of extension theory are two intervals in real number field $\langle -\infty, \infty\rangle$. The interval X_i is of $X_j \subset X_i$ in interval X_j. If a is one point in real number field, the correlation function is defined as Eqs. (8) to (9).

$$P(a, X_i, X_j)\begin{cases} \rho(a, X_j) - \rho(a, X_i), & a \notin X_i \\ -1, & a \in X_i \end{cases} \tag{7}$$

where

$$\rho(a, X_i) = \left|a - \frac{x+y}{2}\right| - \frac{y-x}{2} \tag{8}$$

$$\rho(a, X_j) = \left|a - \frac{w+z}{2}\right| - \frac{z-w}{2} \tag{9}$$

$P(a, X_i, X_j)$ is the relevance of a to X_i and X_j. The correlation function is shown in Fig. 14.

4.2. Physical performance identification proposed in this study

When the user applies different forces to the pedals, the output voltage and current of dynamo inside the power generation system change accordingly. The normal pedaling revolution is about 90 rpm, and the human limit is 100 ~ 110 rpm, as shown in Table

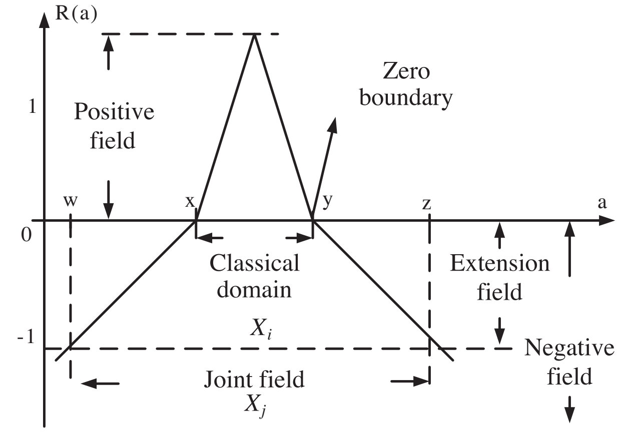

Fig. 14. Schematic of extension correlation function.

Table 2
Rhythmic pedaling revolution.

Revolution range	Rhythmic pedaling grade
60 ~ 80 rpm	D Level
80 ~ 90 rpm	C Level
90 ~ 100 rpm	B Level
100 ~ 110 rpm	A Level

2. The revolution range is divided into 4 grades. The pedaling revolution varies with the grade. The maximum revolution aims at American cyclist Lance Armstrong who has won the Tour of France three times (Shie, January 2008). The heart rate range is based on the HR max 220 specified by ACSM (American College of Sports Medicine, 2010), and the exercise intensity management in Table 3 is used to set the classical domain range, the matter-element joint field is shown in Eq. (14).

$$R = \begin{bmatrix} \text{Fitness Level} & HR & \langle 60,220\rangle \\ & rpm & \langle 10,140\rangle \\ & Vol & \langle 0,40\rangle \\ & Cal. & \langle 0,1200\rangle \end{bmatrix} \tag{10}$$

The matter-elements in physical performance identification are N1 = comfortable pedaling, N2 = fitness exercise, N3 = cardiopulmonary competition and N4 = aerobic winning; C1 = exercise heart

Fig. 13. Test result interface.

rate, C2 = revolution, C3 = dynamo output voltage in pedaling, C4 = consumed calories in pedaling. The classical domains of various matter-elements are shown in Table 3.

4.3. Physical performance identification procedure

The procedure of physical performance identification using extension is described below:

Step 1: Set up ranges of signal characteristics that can be collected from human body as the matter-element joint field model, as shown in Eq. (10).

Step 2: Collect the characteristics of matter-elements or test various data, and set four kinds of classical domain, as shown in Table 3.
Step 3: Calculate the correlation function values between matter-elements to be measured and classical matter-element, as shown in Eqs. (7)–(9).
Step 4: Select weights W1, W2, W3 and W4 of various physical performance degrees, each is 0.25.
Step 5: Calculate the degree of association among various physical performance degrees, as shown in Eq. (11).

$$\lambda_i = \sum_{j=1}^{4} w_{ij} P_{ij} \tag{11}$$

Step 6: Normally correct relevance among various physical performances, as shown in Eqs. (12) and (13).

$$\lambda_i' = \frac{2\lambda_i - \lambda_{min} - \lambda_{max}}{\lambda_{max} - \lambda_{min}} \tag{12}$$

$$\lambda_{max} = \max_{1 \le j \le 4}\{\lambda_i\}, \quad \lambda_{min} = \min_{1 \le j \le 4}\{\lambda_i\} \tag{13}$$

Step 7: Identify the user's physical performance degree in exercise, till the test time is up.
Step 8: The next user starts with Step 2, otherwise end it.

5. Actual measurement results

Finally, when multiple users use the equipment, the data are displayed on the communication interface of tablet PC as waveforms of electrocardiogram and compared. The data of 10-minute pedaling are displayed, the users consume about 80 calories per minute on average, and the power delivery varies with the pedaling speed. The positive wave peak value R wave in electrocardiogram is used as the unit of heart rate.

5.1. ECG comparison

Fig. 15 shows the condition curve of user's heartbeat per minute. There cannot be intense movement during exercise, the user should keep in general standard cycling posture as possible. However, the measured ECG waveforms of different subjects are different, but the R wave peak is obvious in signals.
Fig. 15 shows the measured ECG of User 2. It is found that the peak R value is higher than that of User 1 in Fig. 16. This is because the exercise duration is longer than User 1's, the point is whether the subject's R wave has obvious frequency hopping.

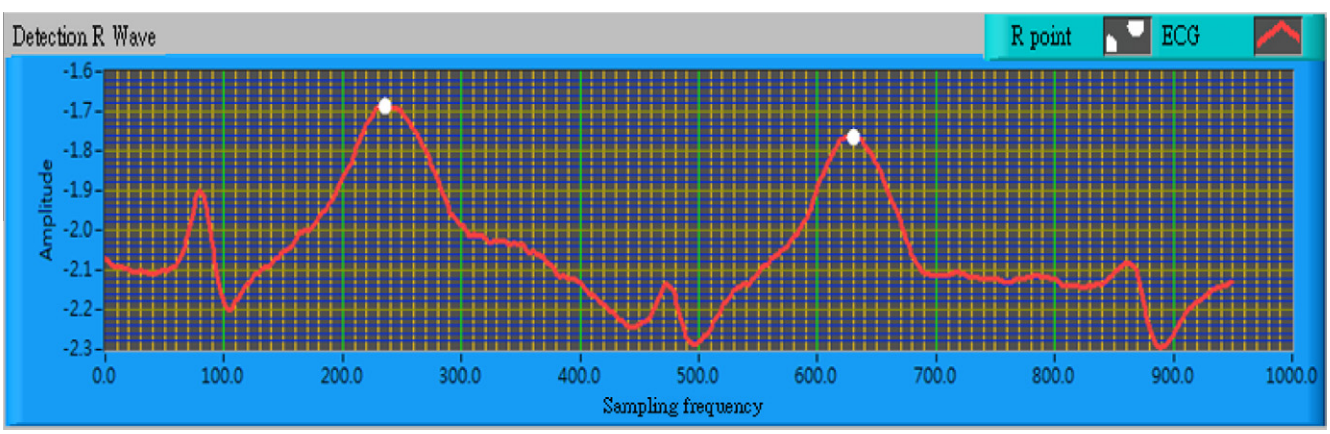

Fig. 15. Measured electrocardiogram of user 1.

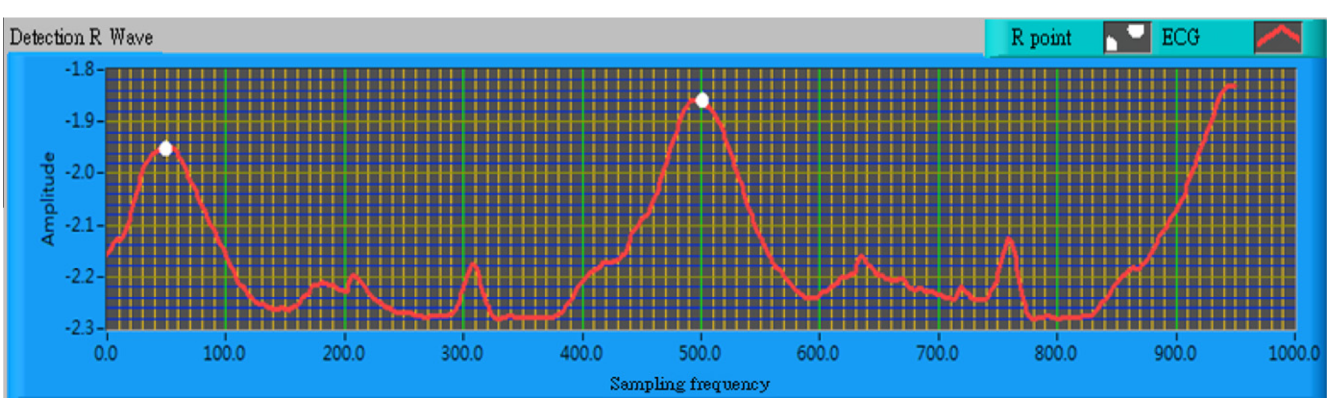

Fig. 16. Measured electrocardiogram of user 2.

Table 4
Test data.

Data of 10-minute pedaling of subjects	Average heart rhythm (min)	121	116	124
	Distance (km)	4.46	3.11	4.25
	Mean calorie consumption (cal)	89.92	83.34	78.51
	Energy(kj)	22.660	21.128	21.243
	Average power (watt)	142.9	73.6	213.7
	Daily calorie consumption (kcal)	1890	1578	2226
	Kinestate analysis	Fitness exercise	Fitness exercise	Cardiopulmonary competition

5.2. Comparison of measured data results

This study tested 15 users, and each test lasted 10 minutes. Finally, 3 data with significant differences were selected for analysis. The physical performance identification procedure was used to identify the heartbeat conditions and classify them into comfortable pedaling, fitness exercise, cardiopulmonary competition and aerobic winning. The tablet PC was used for data storage and transmission interface. When the users pedaled the fitness equipment, the DAQ card transmitted and displayed and stored data in the tablet PC. Table 4 shows that Subject 3 has the highest average power among all subjects, and consumes most calories, meaning that the user applied more force than the other three subjects. The four subjects rode similar distances in the same time, the average distance was 3.94 km. However, they had different average powers as they applied different forces to the pedals. The subjects generated very low power. For example, the average power of subject 1 is 142.9 W, it means that he needs 7 h to generate 1 kWh on average. If the BMI physical fitness analysis is used to identify the health of four subjects, the system will analyze the range of this kinestate according to the heart rhythm. The calorie consumption enables the subjects to aim at daily target to keep fit, even to lose weight.

6. Conclusions

The originality and inspiration of this study came from the integration of technology and LOHAS health. The energy consumed by cycling exercise can be converted into power for household appliances, and the tablet PC at the front end of foot-operated fitness equipment is used as a physical health examination platform, so that the users can enter profiles before exercise. The data of different users can be recorded, and the energy consumed in exercise can be converted by program into physical fitness data. In addition, the users can preset daily amount of exercise and use the designed ECG sensing circuit, so as to know the heart health status during exercise. The computer-based monitoring realizes the combination of fitness and human body.

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