A Biofeedback Interactive Boxing System for Optimal Performance

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ABSTRACT

Abstract – **In this paper, we introduce a system that links an individual's heart rate and muscle reaction time through performance boxing. In order to do so, the system utilizes force sensors, LED lights and a simple ECG belt. The system aims at making the individual exercise at a specific heart rate – the heart rate that results in an optimal performance as well as an effective work out. Though there have been several works that have looked into making boxing more interactive for the user, this system focuses on developing a boxing routine that would be specific to an individual. This is achieved by using the individual's heart rate and recovery rate.**

Keywords – Biofeedback; Interactive Multimedia; Boxing Training; FSR Force Sensors; Adaptive Sports Training

I. INTRODUCTION

Fitness boxing is a physical exercise that mimics ordinary boxing technique using point gloves or punch bags. One of the oldest training methods in boxing is shadow boxing where the boxer trains with a boxing bag rather than a real competitor. Shadow boxing training improves coordination and quickness nevertheless requires expertise to ascertain time utilized and training intensity; people sometimes sustain injuries by exercising excessively and find it difficult to benefit from training [1]. Furthermore, monotonous exercise makes the training experience boring, and if the degree of difficulty is not set properly, people cannot perform effectively and efficiently. Therefore, fitness machines with automatic controls based on physiological and psychological feedback are being developed to optimize training and with gaming elements to encourage regular exercising [2].

Meanwhile, the availability, cost, pervasiveness of sensory technologies have enabled the integration of biofeedback into fitness practices. Biofeedback is the process of providing information about the physiological and/or psychological state of a human user [3]. One or more sensory devices are used to measure certain parameters and are fed back to the subject via display means (visual and/or auditory).

The present study proposes an interactive boxing bag in which heart rate is measured in real time while the boxer is training and the boxing sequence (the sequence of targets to punch as well as the speed and intensity of the punches) is actively adjusted based on the heart rate, thus allowing the boxer to perform sufficient amounts of exercise and experience a sense of accomplishment.

The developed prototype consists of two main pieces of equipment – the heart rate monitor and the standing punching bag. The heart rate monitor is strapped across the chest of the boxer. The standing punching bag has pressure sensors installed at various locations. The locations correspond to traditional punching combinations. There will be LED lights that show the user where he or she needs to punch in order to follow the combination. The LED lights and the pressure sensors will be linked such that once a threshold punching force is reached the next light in the sequence will glow in a different color than if the punch was not strong enough. The punching force threshold can be customized depending on the needs of the boxer. The proposed system incorporates feedback in an indirect and seamless manner into the workout to minimize distraction while exercising.

The heart rate of the boxer determines how fast and complex the combinations should be. Firstly, there is a warm-up period, during which the heart rate will increase to a certain level. During this period, the complexity and speed of the combinations increases gradually. Once the boxer's heart rate reaches 70% to 80% (known as the target zone) of his or her maximum heart rate, the complexity and speed of the combinations reach their maximum and stay constant as long as the boxer's heart rate is within the target zone. The combinations programmed at this point will be aimed at maintaining the boxer's heart rate at 70% to 80% of his or her maximum.

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 method and elaborate the various components of the system. Section 4 presents implementation details and hardware used in the prototype. Section 5 describes the performance evaluation and user feedback. Finally, in section 5 we summarize the paper findings and provide perspectives for potential future work.

II. RELATED WORK

In the past few years, researchers have devoted increasing attention to find ways of making boxing an interactive sport for a single user [4-8]. Interactivity has been a method of choice of many gaming and exercise devices in order to increase customizability and efficient learning or training.

The authors in [4] looked into ways of tracking human arm motions. The developed boxing system involved two robots – one controlled by the user and the other controlled by an automatic motion planner. The user's arm movements were tracked by three-dimensional position sensors attached to the wrists and elbows and are replicated by a graphical human boxer. The robot boxer was controlled by a motion planned that computed both defensive and offensive arm movements responding to the human boxer's movements. The the development of edutainment concerning Thai martial arts and self-defense in order to give both knowledge and entertainment at the same time is presented in [9]. The authors used a technique to capture the motion of two individuals who demonstrate 30 postures of Thai marital arts and self-defense and wore outfits with markers of 42 spots on all their bodies. The data obtained was then used to model the activity in an animated environment. The work in [10] compared the motions of the user to an already saved motion within the system. Rather than training, the scope of this work was to teach boxing techniques.

Another interesting work to help referees when it came to determining the number of punches to be awards to a particular boxer is presented in [5]. Interactivity then comes with a system adapting to challenge the user at the correct performance level. For instance, the authors in [6] built an effective artificial intelligence solution for a 3D boxing simulation game [6]. A customizable feature in which the level is determined by the user is also proposed. The agent being played against has human abilities such as learning, making mistakes and developing strategies against the user.

There has also been research into the relationship between heart rate and maximizing aerobic fitness training. For example, 'Interactive Exercise Monitoring System and Method' explored the combination of initial physical assessment and heart-rate monitoring during exercise [7]. The initial physical assessment created a "heart-rate curve" and this curve indicated where the user needed to maintain his or her heart-rate. Another instance is Peter Gregory Gorman who in 2001 used an ECG belt which wirelessly transmitted an encoded signal to a receiver-display unit [8]. This was not specifically designed for boxing, but for general fitness enhancing exercise.

Our proposed system will incorporate parts of the above-mentioned projects. However the project is highly focused on developing a specific individual's fitness in performance boxing, through indirect feedback which subtly guides the user to work out efficiently. We propose to use the boxer's heart rate to automatically determine the intensity of the boxing regimen. Secondly, the output is in the form of simple LED lights and consequently, focuses the boxer's attention on performing to the best of his/her ability, rather than looking at a separate output display.

III. System Implementation

Figure 1 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:

- *ECG Belt:* The ECG belt will wrap around the torso, the bottom of the ribs, of the user. The ECG will monitor the heart-rate of the user and therefore, plays a critical role in the combination of punches that the user will have to follow. Zephyr Bioharness ECG wearable sensor [11] is been used with a sampling frequency of 250Hz. All data collected by the sensor are sent via a Bluetooth link to a nearby computing unit (such as desktop or mobile device),

- *Round Force Sensitive Resistors:* These sensors measure the ability of the user to deliver the required punches. The sensors are given a threshold value, which is programmed into the Arduino. The sensor detects and measures the force and sends it to the Arduino, which will then either allow the system to move to the next location or change the color of the lights.

- *Arduino UNO [12]*: The Arduino runs the program that determines the sequence of punches. The Arduino UNO sends signals to the LED lights and determines the color of the light which serves as indications to the user as to where to punch on the punching bag and how hard to the punch.

- *Punching Bag:* The punching bag is a 30 cm x 60 cm stationary object that has the sensors and LED lights attached to it. The circuitry of the system is places at the back of the punching bag. The LED lights and sensors have been positioned such that the user would not find the LED light as an obstacle.

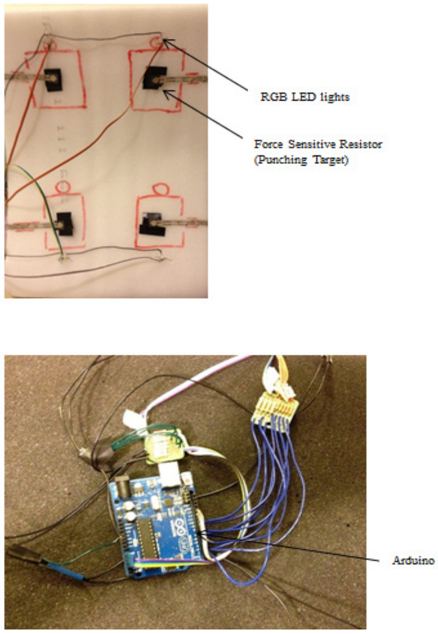

Fig. 1. Above: Location of sensors and LED lights; Below: Circuitry used in the system with Arduino

- *Laptop:* The laptop runs the programs and enables the flow of information from one program to another. More importantly, from an actuation point of view, at the end of the entire system program, a graph is produced, illustrating the user's successes and failures in terms of his or her punches. This graph is obtained through MATLAB.

IV. Biofeedback Interactive Boxing System

Figure 2 shows an overview of the proposed biofeedback interactive boxing system. The boxer wears an ECG belt that reads the heart signal and sends the heart rate to the main processing unit via Bluetooth. The boxing bag is equipped with targets composed of RGB LEDs and FSR force sensors to provide real-time feedback about the boxer's performance. The sequence of targets as well as the speed of punching is biofeedback dependent to optimize the boxer's performance.

A. Software Architecture

The software architecture for the interactive boxing bag system is shown in Figure 3. The components of the software architecture are described briefly here:

- *Biofeedback Input:* This component acquires various biofeedback information about the boxer and sends the data, via wireless communication, to a remote processing unit for further analysis. In particular, the proposed system utilizes two biofeedback properties: the heart rate and the applied punching forces. For that purpose, an ECG belt device and an FSR sensor are used to read the corresponding data.

- *Signal Conditioning and Processing:* This component minimizes (and possibly eliminates) signal artifacts such as ectopic beats, arrhythmic events, and information damage that severely deteriorate the heart rate and force estimation and thus the quality of boxer performance analysis.
- *Adaptation Manager:* The Adaptation Manager is responsible for implementing the adaptation logic including estimating the intensity of the exercise (using the Intensity Estimator component) and generating the target sequence depending on the boxer's performance (using the Target Sequence component). Furthermore, the Adaptation Manager contains the User Interface component that enables the boxer or a trainer to customize and set targets for the boxer training.
- *Boxer Datastore:* The Boxer Datastore is a database that stores the training user profile, training goals and settings, as well as performance data. Examples of user's profile information include, but not limited to, target intensity and speed of exercising, boxer age and gender, amount of calories to be burnt and training goals.
- *LED Controller:* The LED controller converts the commands received from the Adaptation Manager and generates electrical signals that control the RGB LEDs. It is composed of a microprocessor that simultaneously controls the various targets.

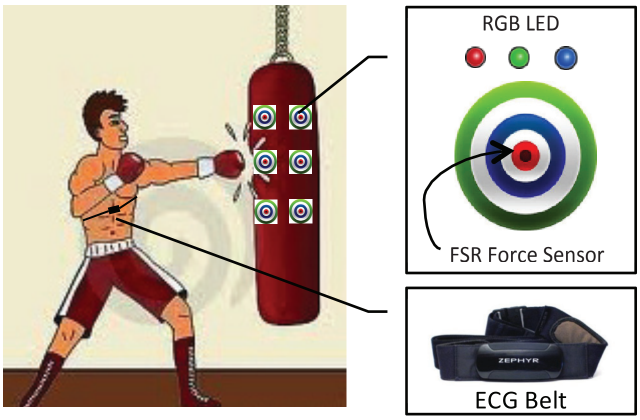

Fig. 2. Overview of the interactive boxing bag system

- *User Interface:* The User Interface component is typically a Graphical User Interface (GUI) that facilities the interaction between the boxer and the system. For instance, the user uses the GUI to set training goals and settings, boxer profile, and performance data. The GUI also enables the boxer to display performance data in a user-friendly manner and derive statistical measures.

B. Adaptation Algorithm

The adaptation algorithm satisfies rules to:

1. Decide, on the basis of the user psychology and punching forces, if the user should put less or more physical effort in the boxing session;
2. At the beginning of each boxing session, the difficulty level is set (punching sequence and speed) that ultimately determine the intensity of the physical effort required for the boxer;
3. Consequently, during the boxing session, the adaptation manager changes the speed and sequence of punching in order to motivate the user to exercise at the optimal intensity; more specifically, three possible exercising modes are defined: keep, to keep the user in the same current configuration, relax, to reduce the intensity of the exercise, and exert, to increase the intensity of the boxer's exercise. The transition from one state to another is defined as shown in Figure 3.
4. Update the user profile in the Boxer Datastore to keep track of the relation between the performance and the physical fitness of the boxer.

The algorithm that defines the relationship between the force detected by the Force Sensitive Resistors and the LED lights sequence is run on a microprocessor (Arduino). In this algorithm, five different states are defined – when all the LED lights are off, when the first LED light is on and all other LED lights are off, when the second LED light is on and all other LED lights are off and so on. Depending on whether the force exerted on the sensor crossed the specified threshold or did not, the LED light will either turn green or turn off.

Three training modes are defined in the proposed algorithm: RELAX, KEEP, and EXERT. A training mode is defined as a vector of three attributes: the reference punching force (Fo), the reference punching speed (Vo), and the intensity factor (α), as shown in equation 1.

$$S_i = \{\alpha_i \times F_o\, , \alpha_i \times V_o, \alpha_i\} \qquad (1)$$

$$\text{where } \alpha_i = \begin{cases} 1 & for\ KEEP\ state \\ > 1 & for\ EXERT\ state \\ < 1 & for\ RELAX\ state \end{cases}$$

and Fo and Vo are defined by the trainer and/or boxer.

The system is always initialized at the 'KEEP' state. Depending on the heart rate measurement and the desired intensity, the next state is called. The 'EXERT' state is meant for hard punches where the user is required to punch the same position ten times and a single round continues for three minutes. The 'RELAX' state is meant for soft punches where the user is required to punch the same position only once and as evident from the name, requires lesser force than hard punches and for three minutes as well. The delay factor to transit from one state to the other is adjusted accordingly so that the speed of the punching sequence alters based on the heart rate of the user.

As shown in Figure 4, four parameters define the transitions from one state to another, namely the maximum heart rate for the boxer (hrMax), the lower and higher punching forces (FavgH and FavgH), and the minimum and maximum punching forces (Fmin and Fmax). These parameters are stored as boxer-specific profile in the Boxer Datastore database.

I. Performance Evaluation

In order to demonstrate the effectiveness of the proposed system, we have conducted a performance evaluation with an adult boxer; a 21 years old male who weighs 78Kg. The

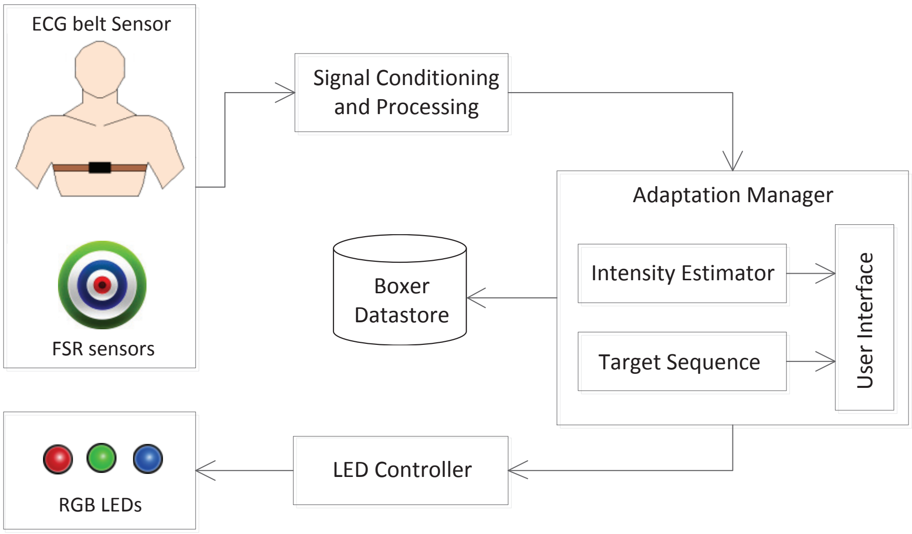

Fig. 3. The software architecture for the interactive boxing bag system.

boxer was asked to perform boxing exercises with and without the feedback while the boxing intensity and the heart rate were monitored. A boxing session took 3 minutes with breaks between sessions of 5 minutes. The objective of the performance evaluation is to prove the ability to adapt to a desired heart rate or intensity during boxing sessions.

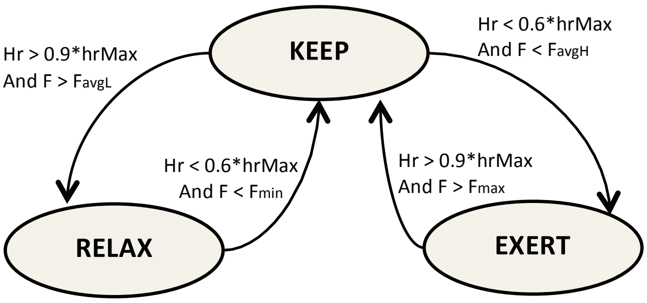

Fig. 4. Finite state automata to switch among various training modes during a game session (hrMax is the user's maximum heart rate, determined by his/her age and gender).

Figure 5 shows the variations of the boxer heart rate (defined as a percentage of the maximum heart rate hrMax) over boxing sessions. Note that without using our system the boxer did not operate at the desired heart rate whereas while using our system, the desired heart rate is maintained around the desired value (75% of the maximum heart rate). Figure 6 shows the variations of the exercising intensity (defined as a percentage of the maximum desired intensity) over boxing sessions. Note that without using our system the boxer did not operate around the desired intensity whereas while using our system, the boxing intensity is maintained around the desired value (75% of the maximum intensity).

Furthermore, a usability testing for the proposed system is conducted where ten adult subjects (5 male, 5 female) participated in the experiment (aging 19-25). The subjects were given 20 minutes of boxing exercise divided into 3 minutes sessions. The subjects were debriefed at the end of the experiment and asked to fill in a questionnaire. The most important four questions in the questionnaire are listed in Table 1 along with the results.

As shown in Table 1, the results are promising. Ninety percent (90%) of the subjects confirmed that the targets were clearly visible and they were able to follow the punching sequence. Furthermore, ninety percent (90%) could not notice any delays or discontinuity in the punching sequence. Finally, eighty percent (80%) of the subjects have expressed interest in purchasing the system for affordable price.

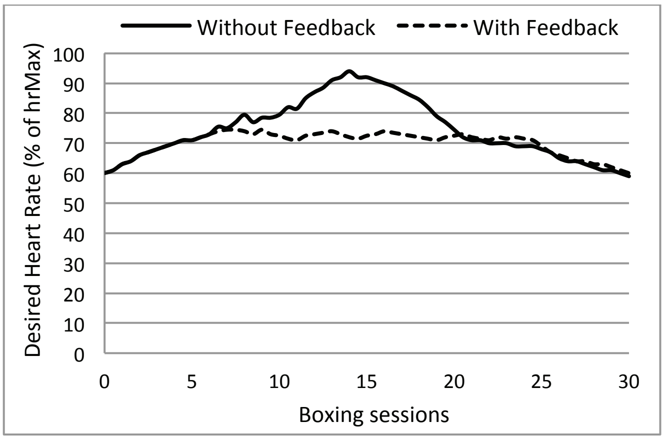

Fig. 5. Desired heart rate (Percentage of maximum heart rate) versus boxing trials.

II. Conclusion

The system proposed in this paper is capable of achieving its objectives of adaptive and personalized boxing. As shown in the performance evaluation section, the proposed system is capable of defining a boxing sequence and intensity to maintain a specific level of heart rate and/or exercising intensity. This eventually helps boxers set goals and exercise accordingly.

However, there are aspects that need to be further developed in order to enhance the system efficiency. For instance, other physiological measures (such as stress and fatigue) can also be incorporated to increase the customization of the system. In addition to this, an

TABLE 1: BOXERS RESPONSES TO FOUR KEY QUESTIONS IN THE QUESTIONNAIRE.

Subjects	Q1: Would you like to use the system again?			Q2: Did you find the targets clearly visible under different intensities of exercise?			Q3: Did you experience extensive delays in punching sequence/feedback?			Q4: Are you willing to buy the system if affordable?		
	Yes	No	Not sure	Yes	No	Not sure	Yes	No	Not sure	Yes	No	Not sure
4 (female)	4	0	0	4	0	0	0	4	0	3	1	0
6 (male)	5	0	1	5	1	0	1	5	0	5	0	1
Total	9	0	1	9	1	0	1	9	0	8	1	1
% of total	**90%**	**0%**	**10%**	**90%**	**10%**	**0%**	**10%**	**90%**	**0%**	**80%**	**10%**	**10%**

entertainment dimension can be added to the boxing experience by creating a game which can be played individually or with other boxers to make the boxing experience more entertaining and appealing to the boxers (similar to the work in [13]).

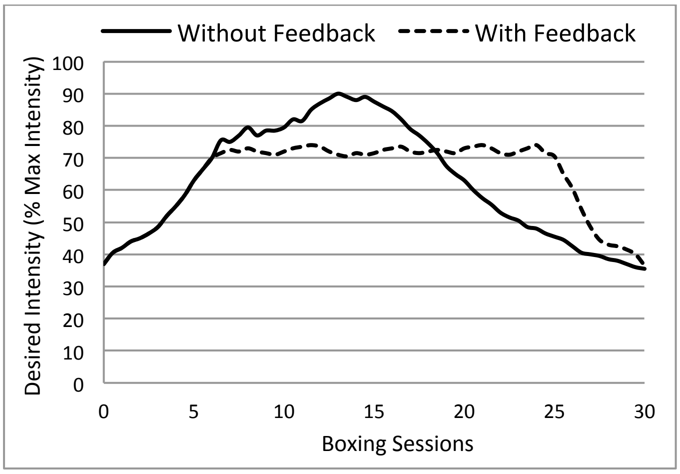

Fig. 6. Desired intensity (Percentage of maximum intensity) versus boxing trials.

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