Closing the Loop in Exergaming - Health Benefits of Biocybernetic Adaptation in Senior Adults

John E. Muñoz, M. Cameirão,
S. Bermúdez i Badia
Madeira-ITI, Faculdade de
Ciências Exatas e da Engenharia
Universidade da Madeira,
Funchal, Portugal
john.cardona@m-iti.org

E. Rubio Gouveia
Madeira-ITI, Faculdade de
Ciências Sociais
Universidade da Madeira,
Funchal, Portugal
erubiog@uma.pt

ABSTRACT

Exergames help senior players to get physically active by promoting fun and enjoyment while exercising. However, most exergames are not designed to produce recommended levels of exercise that elicit adequate physical responses for optimal training in the aged population. In this project, we developed physiological computing technologies to overcome this issue by making real-time adaptations in a custom exergame based on recommendations for targeted heart rate (HR) levels. This biocybernetic adaptation was evaluated against conventional cardiorespiratory training in a group of active senior adults through a floor-projected exergame and a smartwatch to record HR data. Results showed that the physiologically-augmented exergame leads players to exert around 40% more time in the recommended HR levels, compared to the conventional training, avoiding over exercising and maintaining good enjoyment levels. Finally, we made available our biocybernetic adaptation software tool to enable the creation of physiological adaptive videogames, permitting the replication of our study.

Author Keywords

Exergames; biocybernetic loops; cardiorespiratory fitness; heart rate; senior adults; physiological computing.

ACM Classification Keywords

H.1.2. User/Machine systems: Human factors; k.8.0 Personal Computing: Games.

INTRODUCTION

Exercise videogames (exergames) have been widely used as a tool to promote health and wellbeing in several populations [19,39,43]. The ultimate goal in exergaming is to overcome some of the reported barriers to physical activity such as task engagement by challenging participants to play instead of forcing them to repeatedly perform a recipe of movements. The American College of Sports and Medicine (ACSM) describes exergaming as a healthy and beneficial form of physical activity and describes the motivators for its use: a) fun, providing desirable experiences during workout times; b) social interaction through multiplayer practices; and c) choice, because players can customize many parameters in the game as well as make individual choices when playing [48]. This novel way of practicing physical activity has shown promising results in the promotion of exercise in older populations [19,39], physical functioning improvements [26], fall risk reduction [36], and cognitive enhancement [2,41].

Despite the encouraging findings in exergaming research, several issues remain unsolved hampering a widespread adoption of this technology in healthcare institutions. In the research agenda, several reviews emphasize in the need to assess both psychological and physiological impacts of exergaming to determine its benefits for short and long term uses [24,43]. For instance, there is not an agreement in regards to the physiological benefits of using exergames [5,32]. Measurements such as heart rate (HR), energy expenditure (EE) and oxygen consumption (VO_2) are commonly used to quantify the body responses during exergame interventions [47]. Although exergames have shown its potential in improving the cardiovascular system in seniors [27], the reached exertion levels are often below the fitness recommendations [23,32]. To boost exergame effectiveness, novel approaches should be considered which could optimize exercise personalization through system adaptation. The biocybernetic loop is a modulation technique from the physiological computing field, which utilizes body signals in real-time to alter the system in order to assist users [8,34]. This closed-loop control strategy has been successfully used to maximize player engagement during gameplay [7] as well as to improve health benefits during biofeedback training [20]. The use of multiple body signals such as electroencephalography (EEG) and electromyography (EMG) has allowed the creation of physiologically-aware systems able to enhance player's

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experiences in both conventional videogames and Exergames [1,7,29].

In a past research, we showed how a customizable exergame modulated the cardiovascular and electrodermal responses in active older adults by means of manually changing the game difficulty [27]. The present research has been motivated by the idea of creating an intelligent adaptation layer for exergames which can enhance its health benefits via physiological sensing. Thus, in this paper we evaluated the impact of a biocybernetic adaptation in an exergame intervention with active senior adults to assess the effectiveness of physiologically modulated systems in accomplishing fitness recommendations. We aimed to quantify the cardiovascular physiological responses of users during a 20 minutes session as well as the game user experience. We compared this adaptive approach to the conventional exercise routine of a senior gymnasium with fifteen community-dwellers. Our approach uses HR data recorded from a commercial-grade smartwatch, and the exergame online adaptation is done based on game performance and the targeted HR levels. The main goal is to validate our physiologically adaptive exergame as an effective cardiorespiratory training tool for the senior population, following the ACSM guidelines. Meeting the recommendations is particularly important in the older population since this can maximize the benefits of cardiovascular exercise while keeping the users in a safe zone avoiding risks of over exercising [6]. Furthermore, we facilitate the replication of the experiment by making available our integrated software tool developed to integrate biocybernetic loop adaptations in videogames.

In the related work section, we describe different examples of using physiological adaptation in exergames, specifically those designed to optimize cardiorespiratory performance through HR-based adaptation. We also highlight gaps identified in the literature in applying biocybernetic adaptation to exergames as well as we describe the main contribution of this paper. Thereafter, we describe the exergame developed and the setup used for data collection, measurements, and analysis as well as the participants and the protocol of our experiment. Results are presented by interpreting the exertion responses of the participants and their subjective perception with regards to the game experience. To conclude, our game design tool to create biocybernetic loops is presented followed by a final discussion describing our learning process in applying biocybernetic loops in exergames and the challenges for the replication of these systems.

RELATED WORK

The following sections provide background on the use of biocybernetic loops for boosting cardiorespiratory training with exergames in different scenarios and populations.

Theory for the adaptation based on heart rate levels

One of the biggest limitation of exergames as a valid tool for exercise prescription in several populations is its inadequacy to elicit physiologically correct levels of physical activity [3,9,32]. An adopted approach to deal with this limitation consists in using cardiorespiratory signals, in particular HR as input in the exergames to create real-time adaptations [21]. That is, the exergame can be aware of the physiological responses of players and support them in accomplishing the desirable exertion levels. In cardiorespiratory fitness and following the ACSM guidelines [23], it means to increase and maintain the HR levels in the target HR zone in which the health benefits of the training can be maximized [10]. The target HR zone relates to the exercise intensity and is defined as a percentage of the heart rate reserve (HRR) - which is the difference between the maximum HR (HR_{max}) and the HR during resting (HR_{rest}) - as expressed in the equation 1:

$$targetHR = [\%\ exercise\ intensity * (HR_{max} - HR_{rest})] + HR_{rest} \quad (1)$$

Biocybernetic loops applied in Exergaming

Following the target HR approach, a study with 20 young participants evaluated the effectiveness of using a game mechanic called HR-power-ups to encourage more vigorous play in an exergaming intervention [17]. The mechanic consists of providing in-game rewards to players when they reach the appropriate target HR level of exertion. For instance, an avatar may have a stronger attack or change the appearance. Players seated in a PCGamerBike (pedaling device) wore a Garmin heart rate monitor and used a game controller to control the avatar's direction and launch special abilities. The pedaling pace that was used to control the avatar's movement. The study concluded that by using HR-power-ups during 5 minutes of training, players improved exertion levels leading to increases in time over the target HR zone from 50% to 100% [15] when compared with a non-adaptive version of the exergame. The approach was extended to convert off-the-shelf videogames into exergames. Preliminary results showed that this transformation did not affect players' enjoyment while the HR levels fell slightly below ACSM recommendations [16].

By using the dual flow model applied to Exergames [38], a different study investigated the cardiac responses of players while controlling gameplay modulations in two dimensions: attractiveness and effectiveness [37]. In the attractiveness adaptation, several game metrics were used for the purpose of trying to maintain players in a desirable mental flow state; this is maximizing the game performance. In the effectiveness domain, a PID (proportional integrative derivative) controller was applied to keep players exerting in the desired target HR zone. Results demonstrated that the use of a PID control loop was very successful in helping players to maintain desired exertion levels for a well-structured workout.

Two additional studies have used HR-based adaptation in exergames for children. The first investigation used a modular mobile exergaming system to prevent obesity via using a smart insole [14]. The exergame encouraged players to keep up with a flying cow by adjusting their stepping pace. The adaptation uses the HRR formula (see equation 1) and modulated the frequency of appearance of obstacles, thus affecting the pace of players. A pilot study carried out in a research laboratory with two children showed the effectiveness of the mobile system to push players to reach the target HR threshold. Finally, Martin-Niedecken and colleagues [22] developed a dynamically adaptive fitness exergame for children and young adolescents. The system used the Kinect (Microsoft, Washington, USA) and Polar H7 sensors to register the movement and HR, respectively. The exergame can be played through a haptic feedback setup that demands coordination and spatial orientation skills. Although the adaptation of the exergame parameters was done manually according to the HR levels, results showed that young players worked-out within the desired fitness zones [22].

To summarize this review of the application of biocybernetic adaptation in exergames through cardiorespiratory variables, we highlight that:

1. Studies with senior adults are scarce, hiding the potential effects of this technology to optimize exercise performance in this population.
2. Comparisons with control conditions are not commonly used, making the advantages of using this technology against conventional training methods unknown.
3. Experiment replicability is challenging due to the complexity of the setups, cost of the sensors, the unavailability of the systems, and the specialized knowledge required.
4. There is a lack of field experiments, confining the use of biocybernetic adaptation to laboratory studies.
5. Most of the studies evaluated the use of biocybernetic loops in short time periods (less than 10 minutes), which do not fully reflect realistic or recommended times for cardiorespiratory training.

Our contribution aims to tackle the above-mentioned issues via: a) developing a cross-sectional field study with senior citizens to compare the cardiac responses of a physiologically adaptive exergame against a conventional workout routine, and b) providing a tool to simplify the replicability of experiments and the creation of biocybernetic loops in exergames, therefore aiding the dissemination of this technology.

EVALUATING BIOCYBERNETIC ADAPTATION WITH SENIOR ADULTS USING AN EXERGAME

To evaluate the effectiveness of using biocybernetic adaptation for helping senior adults in accomplishing cardiorespiratory fitness guidelines, we performed a cross-sectional study using a customizable exergame. In a between-subjects study, we compared the cardiorespiratory performance of the participants while playing a physiologically adaptive exergame versus a conventional exercise routine in a senior gymnasium. We address the three following research questions: i) Is our physiologically adaptive exergame more effective than a conventional fitness routine? ii) Is the biocybernetic adaptation complying with health recommendations for the older population? and iii) How is the exergaming experience perceived in terms of playfulness and self-reported efficacy?. Subsequently, we show how this biocybernetic adaptation can be replicated and extended beyond our experiment through an integrated software tool.

Physiologically Adaptive Exerpong

Exergame Design

The customizable exergame called Exerpong was conceived as an adaptation of the classic 2D pong encouraging users to hit a ball using a virtual paddle [27]. Inspired in the breakout game and with the idea to make Exerpong more stimulating in terms of gameplay, we added a layer of virtual and colorful bricks in such a way that when a brick is hit twice, it is destroyed. After destroying all the bricks on screen, a different brick distribution is presented. It is worth clarifying that bricks have not physical influence in the ball's trajectory. Players score via destroying individual bricks as well as when clearing all brick in a level. The game was developed in the Unity3D game engine (Unity Technologies, San Francisco, USA) allowing a complete game customization and data logging for every event registered during the interaction. Audiovisual stimuli are presented once the ball is hit with the paddle, displaying sparkling particles and a thumbs-up icon, and reproducing a reinforcing sound. In the same way, a punishing sound and a red screen are used every time a ball is missed, reflecting low game performance. The game allows the physical training of balance, flexibility and lower limbs strength while the physiological adaptation is oriented to maximize the cardiorespiratory performance.

Experimental Setup

To create a cardiorespiratory-demanding exergame, Exerpong is projected on a white 2.5m x 3.0m PVC surface that is placed on the floor (see figure 1). The projection used a resolution of 1280x720 pixels and a mapping application was used to correct the projection perspective.

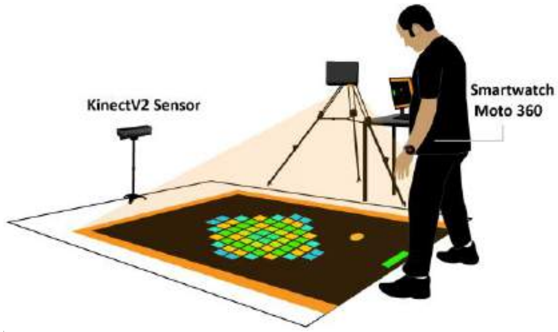

Figure 1. Diagram depicting the experiment setup for Exerpong that uses a KinectV2 sensor, the projected game in the floor and a smartwatch for HR recordings.

For players' position tracking, we used the KinectV2 sensor (Microsoft, Washington, USA), which sensed the player's waist position and mapped it to the paddle position. For the HR data, we used a Motorola 360 smartwatch synchronized with a cellphone. The smartwatch used a photoplethysmography (PPG) sensor to record and stream the heartbeats using the PhysioVR framework [28], which sent the data at 1Hz directly to a signal acquisition panel on a host computer. When compared with the gold standard (ECG), it has been shown that PPG sensors possess a very high accuracy for measuring HR even in complex conditions such as exercising [25]. The connection between the smartwatch and the exergame was done using UDP communication through a software previously reported called the Biocybernetic Loop Engine (BL Engine) [12].

Adaptation Rules

The ultimate goal of the biocybernetic game adaptation is to drive players to reach their target HR zone following the cardiorespiratory fitness guidelines for seniors. For the target HR, we used 55% of the HRR which is in the midst of the ACSM guidelines (40% - 70%) for older adults [10]. Considering that and following the dual flow model for exergaming [38], the Exerpong adaptations were developed for *Gameplay* and *Cardiorespiratory Fitness* as follows:

- For the *Gameplay* adaptation, two adaptive rules were used to improve the game attractiveness and balance the challenge: i) the paddle size increases once the player misses a ball and decreases once he/she hits it, and ii) the ball velocity automatically decreases if the player misses three consecutive balls.
- For the *Cardiorespiratory Fitness* adaptation, we implemented a proportional controller ($\mathrm{P_c}$) using the real-time HR data. The ball velocity increases if the 30 seconds HR average ($\mathrm{HR_{30sec}}$) is under the target HR and decreases it otherwise. K_p is the proportional constant used for system's triggering ($K_p = 0.06$ in this experience). The proportional control followed equation 2:

$$\mathrm{P_c}=\mathrm{K_p}(\mathrm{targetHR}\text{-}\mathrm{HR_{30\ sec}}) \qquad (2)$$

Participants

We recruited fifteen community-dwelling older adults (11 females, ages 66 ± 7 years, height 1.60 ± 0.08 meters, weight 73.7 ± 14.8 Kg) from a local senior gymnasium. The characteristics and fitness parameters of the recruited users are described in table 1. As inclusion criteria, we used the 6-min walk test from the senior fitness test battery [35] and identified users in the 45th to the 60th percentiles (see table 1). The 6-min walk test score measures the distance (in meters) walked over 6 minutes. The short form of the International Physical Activity Questionnaire (IPAQ-SF) was used to screen the health-related physical activity behaviors of the population, illustrating that four participants were physically active and ten were minimally-active. Only one user fell into the inactive category. Twelve reported never having played videogames before, while three reported playing videogames a few hours per week as a leisure activity. Two users reported being medicated for high levels of blood pressure and two reported past heart-issues.

Characteristic	**Values ± SD**
BMI (kg/m^2)	28.9 ± **5.2**
Resting HR (BPM)	72.9 ± **12.9**
Maximum HR (BPM)	161.7 ± **4.7**
$\mathrm{VO_{2max\ (unit)}}$	2.3 ± **0.4**
6-min walk test (m)	540.7 ± **31.9**

Table 1. Fitness parameters describing health status and endurance characteristics of participants. BMI: body mass index, $\mathrm{VO_{2max}}$: maximum oxygen uptake, BPM: beats per minute.

Users were voluntarily recruited following a detailed explanation of the experiment and after having a first contact with the system that was already installed at the senior gym. The only compensation offered by the research team was a post-gaming explanation of the HR data after the experiment.

Measures

The collection of data was carried out through custom log files automatically generated by Exerpong and the BL Engine, both recording data with a sampling frequency of 25 Hz approximately. For the feature extraction process of HR, fitness and kinematics parameters, we used Matlab v.2013a.

Heart Rate and Effectiveness Metrics

HR data from the smartwatch was used for the comparative analysis. Effectiveness metrics encompass the root mean square error (RMSE) between the HR and the target HR and the time in the target zone ($\mathrm{T_{in\text{-}target}}$), which expresses the total duration that people spend in the expected fitness zone (40% - 70% HRR).

Fitness and Kinematic Metrics

The maximum oxygen uptake ($\mathrm{VO_{2max}}$) which describes the functional capacity of the cardiorespiratory systems was computed using the ratio between the $\mathrm{HR_{max}}$ and the HR during a resting state [45]. The $\mathrm{HR_{max}}$ was computed using Tanaka's formula [44], an age-dependent model to compute the maximum stress level of the cardiac muscle. Energy Expenditure (EE in $\mathrm{KJ{*}min^{-1}}$) was calculated using the prediction equation developed by Keytel et al. [18] and converted to Metabolic Equivalent (METs) to express the amount of energy that a participant uses in the exercise. A pictorial version of the OMNI perceived exertion scale [10] was used to assess the perception of exertion in a 0 to 10 scale (0 extremely easy, 10 extremely hard) of each exercise right after the workout.

Questionnaires

A custom-made questionnaire was designed to collect information regarding the user experience during the exergame interaction (see table 2). The questionnaire's responses were gathered with individual short-interviews. Eight items were evaluated using a 5-points-scale questionnaire (1- low scored, 5- high scored).

Protocol

Using the smartwatch and the cellphone, the HR data from each participant was recorded during a conventional workout session (*Control*) in the senior gymnasium. This training usually consists of a set of different routines that include (but not limited to): i) cardiorespiratory circuits with steps, weights and motor coordination exercises; ii) upper and lower limbs movement's routines for strength training using sticks and weights; and iii) ball exercises for balance, stability and flexibility training. These exercise routines were focused on the functional fitness training that particularly aims at reinforcing the aerobic, strength and balance abilities in the older population. An introductory training session with the Exerpong was carried out in a different day to familiarize participants with the game mechanics and the setup before doing the final intervention. This was also used as a strategy to reduce the novelty effect associated with playing exergames.

Question	Statement
Q1	How exhaustive in terms of the exercise was the experience?
Q2	To what extent do you think the exergame was fit for your fitness level?
Q3	How challenging was the experience?
Q4	To what extent are you satisfied with your performance in the game?
Q5	To what extent did you put energy in this experience?
Q6	To what extent do you think the game was responding to your tiredness levels?
Q7	How enjoyable was making exercise with this game?
Q8	To what extent will you play again this game as an exercise routine?

Table 2. The custom questionnaire developed for the exergame experience.

In addition, we used the collected data from the Exerpong training session to infer the proportional constant (K_p) and use it for the final control adaptive system. Right before the Exerpong training session, we collected information regarding the demographics, previous experience with videogames and participants' heart-related issues as well as the IPAQ-SF survey.

Finally, in a different day, the interaction with the physiologically adaptive Exerpong (*Adaptive Exerpong*) was carried out (see figure 2) as follows:

- Participants were asked to be seated and calm for 5 minutes to record the HR_{rest}.
- A 5-minutes stretching session was performed to facilitate muscle exertion of the lower limbs.
- The age, HR_{rest} and the targeted exercise intensity (55 %) were manually introduced per participant in the adaptive system to compute the target HR.
- Participants interacted in a 20 minutes session with the adaptive Exerpong.
- Participants answered the questionnaire.

Figure 2. One of the participants interacting with the Exerpong. The equipment setup was done in a local senior gymnasium.

The OMNI rating was collected shortly afterward the exercise routine for both *Control* and the *Adaptive Exerpong*.

Statistical Analysis

The Kolmogorov-Smirnov test was used to revise the normality of the distributions. A one-way repeated measures ANOVA was used to compare experimental conditions and physiological responses. Furthermore, we used the Wilcoxon signed-rank test to compare the perceived exertion through the OMNI in both conditions. All statistical tests were performed using SPSS (21.0, BPM Corp, Armonk, NY) with a significance level of 5% ($p < 0.05$).

RESULTS

Results are presented around three questions proposed regarding health benefits of exercising with the Exerpong and the perceived user experience.

Is a physiologically adaptive exergame more effective than a conventional fitness routine?

Exercise effectiveness is measured through the compliance with the ACSM recommendations for light-to-moderate aerobic exercise in older adults [23], meaning exertion levels between 40 % and 70% of the HRR. his is measured considering two main variables. The first is the RMSE, the difference between the current HR and the target HR for each participant. Players showed lower RMSE values in the A*daptive Exerpong* (M=15.2, SD=8.3) when compared with the *Control* condition (M=24.3, SD=6.4). Statistical analysis revealed that the difference was significant, $F(1.0, 14.0) = 12.3$, $p<0.05$, $r = 0.44$.

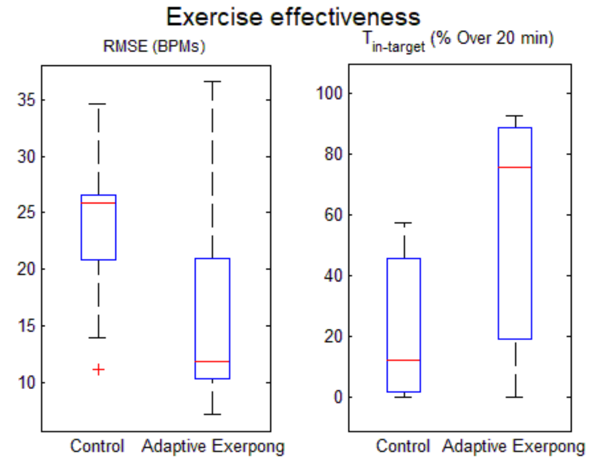

Figure 3. Boxplots of the metrics used to quantify exercise effectiveness, RMSE (left) and $T_{in\text{-}target}$ (right)

The second measurement of exercise effectiveness was the $T_{in\text{-}target}$, which was assessed as a percentage considering the 20 minutes length of each condition. Significantly higher values, *F*(1.0, 14.0) = 12.3, $p<0.05$, $r = 0.47$ were observed for the *Adaptive Exerpong* condition (M=60.7, SD=38), compared with the *Control* condition (M=22.0, SD=22.5). The exercise effectiveness metrics for both conditions are illustrated in figure 3.

Is the biocybernetic adaptation complying with the health recommendations for the older population?

We wanted to know about the exertion levels associated with each condition and inquiry into whether the exergaming experience was consistent the healthy limits of cardiovascular training. To do that, we relied on both objective and subjective measurements. As an objective measure, we computed the metabolic expenditure. The energy expenditure in METs exhibited significantly higher values for the *Adaptive Exerpong* condition (M=8.0, SD=3.1), compared with the *Control* condition (M=6.8, SD=2.9), *F*(1.0, 14.0) = 10.9, $p<0.05$, $r = 0.35$. Nevertheless, the computed METs showed that both the *Adaptive Exerpong* and the *Control* conditions can induce vigorous physical activity levels (> 6.0 METs), therefore complying with the recommendations for exercising during 20 minutes [10].

Lastly, subjective physical exhaustion was individually measured through the OMNI pictorial scale for each condition showing very similar levels of perceived exertion for both *Control* (M= 5.7, SD=3.0) and the *Adaptive Exerpong* (M=5.1, SD=2.3) conditions. The values never exceeded the intensity of hard (score = 8) which is aligned with the ACSM guidelines for the perceived exertion [13]. OMNI differences were not significant following a Wilcoxon signed-rank test. To aid the visualization of the HR behavior of each condition, exercise profile curves from the *Control* and the *Adaptive Exerpong* were created (see figure 4). The HR data from all participants were averaged over the whole session and the curves are presented together with the standard deviation, the average values from the HR_{rest}, HR_{max}, and the target HR (55% of the HRR).

How is the exergaming experience perceived in terms of playfulness and self-reported efficacy?

It is desired to understand the interaction between enjoyment, self-perception of efficacy and objective metrics of game performance and cardiorespiratory efficiency. To investigate these factors, playfulness and self-reported efficacy were measured through various dimensions following the questions in table 2, which were matched in eight dimension as follows (see figure 5): Q1- exhaustiveness, Q2- adaptability, Q3- challenge, Q4- competence, Q5- effort, Q6- responsiveness, Q7- enjoyment, and Q8- replayability. Results revealed high levels of

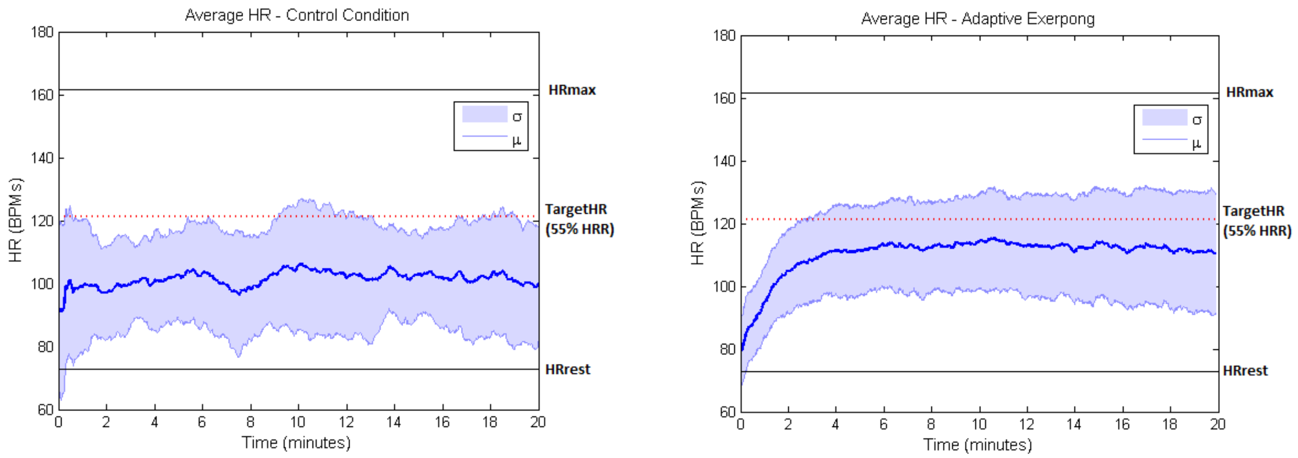

Figure 4. Average HR behavior during the Control (left) and the Adaptive Exerpong (right) conditions over the 20 minutes of exercise. The charts depict the mean participant profile for each condition (blue line), the ± standard deviation (blue shadow), the HR_{rest} and the HR_{max} (black lines) as well as the average target HR value used for the physiological adaptation (red dotted lines).

enjoyment (4.4) and competence (4.4), reflecting a positive user experience and performance perception. The lowest scores were in the system's responsiveness (2.8) and user's exhaustiveness (3.1).

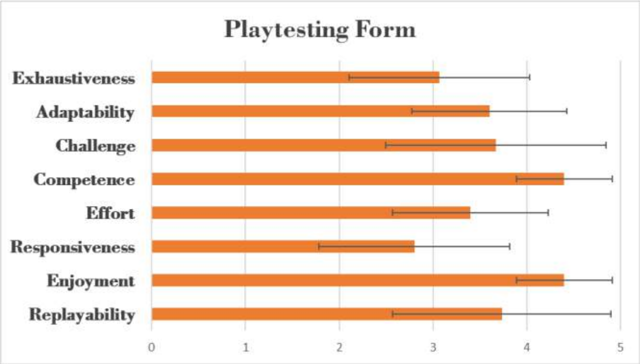

Figure 5. Results from the custom questionnaire used to investigate perceived playfulness in the *Adaptive Exerpong* condition.

EXPERIMENT REPLICABILITY: THE BIOCYBERNETIC LOOP ENGINE

With the purpose of tackling one of the biggest limitations of biocybernetic adaptation, the system's replicability, we developed an integrative tool that covers the acquisition, analysis and translation stages of the physiological computing systems [11]. The BL Engine served as a unifying tool for i) the acquisition of HR data from multiple sensors including wearables and DIY kits (acquisition panel), b) the creation of adaptive rules based on a visual programming language (biocybernetic console), and iii) the incorporation of game variables that can be modified following the physiological adaptive rules (game connector). The software tool developed in Unity3D allows a simplified transformation of any videogame developed in such engine, into its physiologically adaptive version. Using this approach, we elaborated a target HR adaptation scenario that allows replicating our experiment using the Exerpong and any other exergame (see figure 6).

Both the Exerpong and the BL Engine are freely available at https://neurorehabilitation.m-iti.org/tools/en/ble. In order to use the tool for cardiac-based adaptations, game developers have to: a) acquire the HR signal using the acquisition panel, b) include a script to define the game variables that are going to be modified following the physiological rules, c) create the adaptive rule using the biocybernetic console, and finally d) run the videogame for testing. The iterative process of designing new adaptive rules beyond the target HR adaption is achieved through programming-blocks provided in the biocybernetic console.

DISCUSSION AND IMPLICATIONS FOR EXERGAME DESIGN AND PHYSIOLOGICAL COMPUTING INTEGRATION

The success in the implementation of biocybernetic adaptation for exergaming evidence the potential of closing-the-loop for boosting health benefits. In this section, we discuss the implications of merging physiological computing principles with exergames looking for a more personalized, effective, and controlled experience.

Stressing the dual flow model for exergaming

One of the main concerns in applying physiological adaptation in exergaming is the possibility of transforming an enjoyable experience in an exhausting exercise routine. In our experiment, we carried out multiple iterations searching for the best way to balance both effectiveness and attractiveness [38] in the Exerpong. As we have shown, in the A*daptive Exerpong* participants exerted more than 60% of the training time in their individual target HR zone, showing in average RMSE values of 15 BPMs (difference with the desirable level). These results indicate the feasibility of using HR-based adaptation rules combined with game performance to produce effective real-time modifications aiming at fulfilling the ACSM guidelines. Furthermore, perceived levels of exertion measured through the OMNI

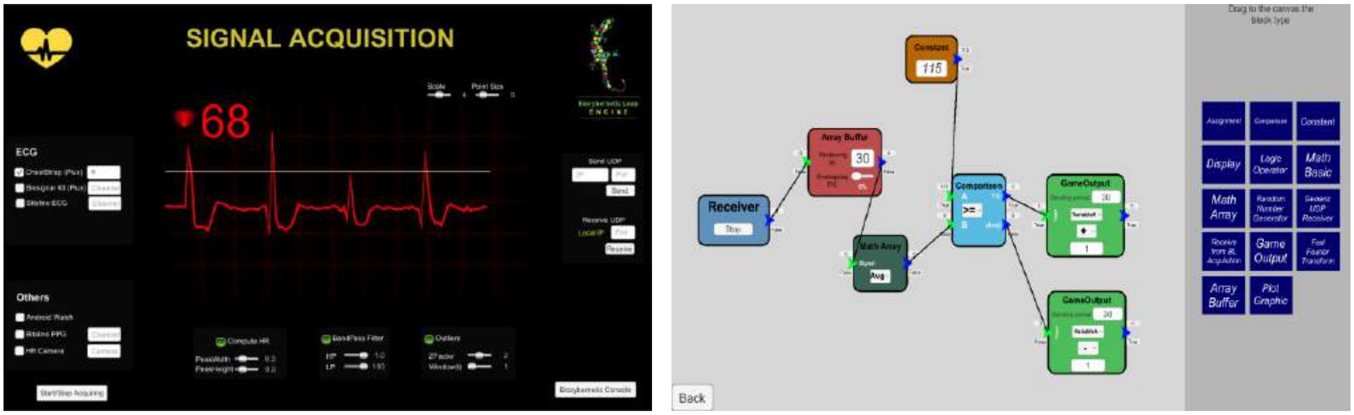

Figure 6. The Biocybernetic Loop Engine tool illustrating the acquisition panel (left) for getting HR from different sensors and the biocybernetic console (right) for the creation of physiologically-adaptive rules.

scale were not significantly different between the two conditions. This could indicate that although the *Adaptive Exerpong* was more physically demanding than the *Control* condition, players might not have felt so fatigued, therefore favoring the user experience and improving the likelihood of replayability and technology adoption. These outcomes were reinforced by the custom questionnaire data. These data on game user experience indicated that exhaustiveness scored low (3.1) while replayability was considerably higher (3.7). Those results were achieved without sacrificing fun and enjoyment, which scored the highest (4.4) in the playfulness inquiry. Indeed, four participants manifested that Exerpong demanded training some cognitive skills such as attention and anticipation, which encouraged them to exercise harder. In this way, the complementarity of the dual flow model implemented in Exerpong allowed to capitalize on attractiveness and reinforce effectiveness, thus maximizing efficiency in exergaming.

Applicability of biocybernetic loops

This work illustrates our determined effort of getting this sophisticated cybernetic technology for out-of-the-lab experiments. Our findings can be seen as one important milestone for extending its use in multiple everyday life scenarios [31]. We consider two main factors that eased the implementation of the system in the field: first, the use of smartwatches as wearable physiological sensors, which significantly reduced the complexity of wiring participants without big expenses in accuracy [25]. Hardware is a renowned issue in physiological computing and is also referred as the trade-off between unobtrusiveness and accuracy [30]. Secondly, the integration of all the physiological computing components of acquisition, analysis, and translation [11] in the game engine Unity3D, helped us to create a fluid communication pathway between the biocybernetic loop and the exergame. This simplified the integration with third-party applications aiding data transmission and the general operability of the system in the field and in real-time. From the user experience perspective, while biocybernetic adaptation has presented potential risks for cardiorespiratory training in the past [17], we demonstrated how both METs and perceived exertion scores did not exceed the recommended values for the senior adults, a very delicate population in terms of exercise training. Interestingly, this demonstrates that the novelty of playing exergames did not negatively affect the cardiorespiratory performance (measured and perceived) of players avoiding counterproductive effects such as over-exertion. Moreover, by looking at figure 4, one can observe that the *Adaptive Exerpong* training exhibited a more controlled cardiac response around the target HR than the *Control*. This illustrates a desirable behavior considering safety issues and training efficacy [10]. In the older population, accomplishing the ACSM guidelines of physical activity represents a reduction of risks associated with diabetes, coronary heart disease, hypertension, osteoporosis, and obesity and weight control [33]. Moreover, several aspects of mental health can also be positively impacted by means of regular physical activity at the adequate intensity levels [23].

Replicability of biocybernetic adaptation experiments

To our knowledge, the BL Engine is the first fully integrated tool designed to create and iterate biocybernetic loops in videogames. Its design responds to a common problem of physiologically adaptive systems, replicability. Through this experiment, we improved our initial design of the BL Engine, which includes now multiple HR sensors and a simplified method for its integration with videogames developed in Unity3D. Through this tool, novel exergames can include biocybernetic adaptation aiming at improving the effectiveness of cardiovascular training. We believe that our work contributes to a more personalized and physiologically correct use of novel exergaming approaches, adding a new layer of sophistication in the field. This strategy has the potential of being a first milestone to diversify the creation of truly health-effective Exergames for different populations and purposes. Moreover, in a more general purpose, the BL Engine approach can be also used to create physiologically-aware serious games beyond Exergames. Although psychophysiological signals have been used as a powerful elements in game user research to understand player's behaviors [40], only few studies have explored the impact of biocybernetic adaptive strategies in fields such as education [4,46] or mental wellbeing [20] by means of serious games [42]. Lastly, replicability will enable the community to build on the presented work and address further research questions such as the impact of different adaptation strategies and the long-term effects of biocybernetic adaptation.

CONCLUSION

In this paper, we have emphasized the need to create exergames that can fulfill the recommended levels of exertion, arguing that biocybernetic adaptation provides remarkable features for it. To demonstrate this, we conducted a comparative study with a conventional exercise training method and a cardiovascular adaptive exergame. We have shown that using real-time adaptation based on HR in an exergame, a group of senior adults increased nearly 40 % the time they spent in the recommended levels of exertion compared with conventional training. The biocybernetic adaptation delivered a more controlled, safe and effective cardiovascular training avoiding risky situations while maintaining good levels of enjoyment. Moreover, we supplied a software tool that can be used to integrate physiological adaptation in exergames, therefore contributing to the advancement in the adoption of this technology. We concluded highlighting the importance of embedded physiological computing systems into people's daily life activities, providing an outstanding opportunity to foster health and wellbeing.

FUTURE WORK

A 6-weeks study is being designed to longitudinally investigate the effects of biocybernetic adaptation in terms of cognitive and cardiorespiratory fitness in a group of older adults. This study will extend the findings reported here and will allow revealing the long-term impacts of exercising through our physiologically-adaptive Exerpong. Besides, a longitudinal study with a set of context-aware exergames designed for the target population will be carried out to demonstrate the long-term effects of biocybernetic adaptation. Adaptive rules considering robust controllers (such as the PID) should be tested and iterated in the exergames to guarantee exercise effectiveness. Moreover, more technologies are being integrated with the BL Engine (such as emotion recognition and wearable brain computer interfaces) which will allow users to design adaptive rules with inputs beyond cardiac measurements. Since the BL Engine tool was made in Unity3D, novel virtual reality exergames [49] can easily be made to integrate physiological signals and explore new biocybernetic adaptation mechanisms to improve the game user experience.

LIMITATIONS

Despite the encouraging results presented and the possibility to contrast the results via replication of the experiment; this paper encloses several limitations. First, although we used validated functional fitness criteria to include senior adults in our study, the final group is still heterogeneous. This is partially reflected in the high dispersion of the HR data presented in the figures 3 and 4. Being an out-of-the-lab experiment, a number of variables are difficult to control such as the homogeneity of groups presented in some public senior gymnasiums in the city. In addition, the *Control* condition could not be homogenized since the normal routine of the senior adults cannot be modified. On the other hand, this reflects the robustness of our system to be adaptive to different user profiles. Comparing our physiologically adaptive Exerpong versus its non-adaptive version or any other exergame was also discussed as a possible limitation of the study. However, we found more valuable at this stage, the comparison of our biocybernetic system against a standardized, accepted and validated methodology by sports scientists; this is exercise routines designed for the older population and delivered by professional personal trainers. All in all and to our best knowledge, there are not Exergames scientifically validated for accomplishing the cardiorespiratory recommendations for the senior population. Additionally, we decided to use a custom questionnaire instead of a standardized instrument considering: a) limitations regarding the Portuguese translation of questionnaires such as the Game Experience Questionnaire, and b) the need to investigate in specific physical activity domains such as exhaustiveness and effort as well as the self-reported efficacy questions. Considering that the seniors that visit the gym have more motivation to make exercise than those less active users, at this point, it is unknown how more sedentary elders will react with the physiologically adaptive Exergames.

Finally, though initially, we recruited 17 participants, two of them dropped the study because of health-related issues, which made it difficult for them to interact with Exerpong. For instance, visual impairments (very common in the older population) are important limiting factors in the interaction with exergames. Novel exergaming approaches should consider solutions to overcome this issue.

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