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***Abstract*—In this paper, we report on an experimental study in which we investigated the use of feedback mechanisms in exergames. We based the study around the Dual Flow model for exergame design, using biophysical feedback to control exercise intensity, and player performance feedback to control gameplay challenge. We found good success in controlling exercise intensity to achieve an effective workout, while controlling gameplay challenge to improve enjoyment and attractiveness was problematic. We offer some possible reasons for this, suggesting the need for further investigation.**

I. INTRODUCTION

Computer games that combine entertainment and exercise are growing in popularity. Starting as games for various add-on devices in the 1980s these "exergames" were seen more as novelties, with devices such as the Amiga Joyboard and Nintendo Power Pad not having long-term success. In 1998, Dance Dance Revolution, better known by its acronym DDR, was released and is now an arcade staple with various home versions. DDR, played by the user activating floor-based buttons on a 3x3 grid in time to music, was the first mainstream arcade success in a line of similar rhythm-based games. In 2006, mainstream exergaming reached the home, with the release of the Nintendo Wii. Rather than buying add-on equipment that required physical exertion, the Wii was build with motion control as its central selling point. (See [15] for more background on these and other exergames.) The success of this concept has prompted Nintendos rivals in the home console space, Sony and Microsoft to announce motion-based controllers of their own. The Sony PlayStation Move controller [12], and Microsoft's Kinect [7] are due for release towards the end of 2010.

Game controllers, such as that sold with the Nintendo Wii, that sense player physical movement, can be used to promote the movement of large muscle groups, such as arms, as opposed to traditional finger-based control devices. With mainstream acceptance of such controllers on the three major consoles looming, there is the prospect of reversing the trend of declining exercise levels in the population [5], [14]. However, for this to occur, games built to take advantage of such controllers must offer a combination of *attractiveness* in terms of compelling gameplay, and *effectiveness* in terms of physical outcomes. Unfortunately, exergaming development has generally been approached from one or the other of these directions and has often resulted in less than optimal outcomes.

The Dual Flow model, illustrated in Figure 1, as proposed in [15] encompasses the two previously mentioned dimensions of attractiveness and effectiveness of the exercise. The attractiveness of an exergame can be modelled by the standard flow model, due to Csikszentmihalyi [4]. This is a psychological model balancing the player's perceived skill with perceived challenge. The second dimension, effectiveness, is the physiological counterpart of flow the physical balance between fitness (the body's "skill" in tolerating exercise), and intensity (the challenge of the exercise on the body).

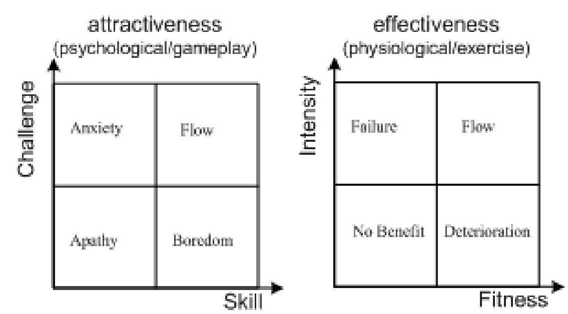

Fig. 1. The Dual Flow model for exergaming

The attractiveness half of the model illustrates the standard skills versus challenge balance of the standard Csikszentmihalyi flow model, which is often represented by such a diagram, featuring four quadrants. Boredom is reached when skills surpass the challenge, and if the challenge is too high compared to skill level, anxiety sets in. A state of apathy results when there is both the lack of skill and any meaningful challenge.

The balance between intensity and fitness is represented in a similar four quadrant balance model in the effectiveness part of Figure 1. If intensity and fitness are matched, the quadrant of physiological flow is reached and the fitness of the subject improves with continued exercise. Where the intensity of exercise far surpasses the fitness of the participant, a state of failure occurs - the exercise participant is unable to continue the exercise. If the participant has a low fitness level and there is no perceivable intensity in the exercise (e.g. playing an ordinary computer game with keyboard and mouse) there is no benefit to the participant. If fitness exceeds the exercise intensity, there is also potential for the participant to enter a state of deterioration where fitness level will drop.

In this paper, we present an experimental study that tests the Dual Flow model. After reviewing the recent related literature, we present our experimental design, which is based around an exergame that allows us to control intensity and challenge levels of the game. We describe the equipment used to play the game, the gameplay design of the game, and the feedback mechanism that we built into it. We then present experimental results on the effectiveness of the game as an exercise workout, and the attractivenss of the game in terms of player interest, under different feedback regimes. Finally, we discuss these results and their implications regarding the efficacy of the Dual Flow model, and avenues for future research.

II. Related Work

There is increasing evidence in the literature to show that exergames can provide adequate levels of exercise (for example, [8], [10]). Thus, if exergames can be made interesting and entertaining, while maintaining appropriate exercise levels, they have the potential to improve general fitness levels and combat health problems like obesity, especially, but not only, in children.

In recent years, more attention is being paid to making exergames engaging and attractive. For example, in [6], the author examined entertainment, usability and suitability of exergames, using a series of case studies : a children's game and a martial arts game, both using a camera and full body motion, and one using DDR. Among her findings were the importance of physical feedback for effective training, and of social interaction as a factor in the popularity of DDR. In [16], the author identified four important factors in exergame success: warm-up and cool-down, management of game load times, integration of physiological measures and dynamic gameplay adjustment. In a study using pedometers to challenge participants to compete against each other in being active, [3], the authors found that it is important to give participants proper credit, to provide personal awareness of activity level, and to take into account social factors.

In [18], the authors used the PlayWare tile platform [11] to investigate the three factors of challenge, curiosity and fantasy, finding that fantasy made the game more fun for all players, while the best balance of challenge and curiosity depended on the individual. More recently [1], a study was made of a number of exergames, concentrating on their use of learning theory principles. The authors propose that these principles might be used to manipulate game contingencies (e.g. using intermittent reinforcement) to encourage long-term use of exergames. Another recent study [17] examined skill levels in dance games, and concluded that skill requirements in dance games should initially be set very low, counterbalancing exertional discomfort. A different approach is taken in [13], where the researchers investigated motivations for players of exergames (achievement and relaxation), and also movement-specific factors influencing immersion (natural control, mimicry, proprioceptive feedback and physical challenge).

The current state of the art in understanding the interplay between effectiveness and attractiveness in exergames is rather exploratory, with a number of complementary approaches being investigated. Our particular approach concentrates on using feedback control for both the physical exercise and mental gameplay aspects of exergames, based around the Dual Flow model.

III. Experimental Design

In order to explore the dual aspects of effectiveness and attractiveness, we carried out an experiment in which subjects were asked to play variations of an exergame, in which either physical or gameplay intensity was controlled in an attempt to maintain flow. Each subject played a session with no feedback control, one with physical intensity control only, one with gameplay intensity (challenge) control only, and one with both. The physical state of the subjects was measured throughout these sessions, and a questionnaire was used to gather further information from the subjects about their experience in playing the game.

There were 21 subjects, 8 male and 13 female, all between the ages of 21 and 41. Three subjects reported that they did no regular exercise, three exercise 10 or more times each week, and the remainder exercise between 1 and 7 times per week.

The experiment is basically a two-factor design. The independent variables are *Exercise Intensity Control* and *Game Challenge Control*. Exercise Intensity Control has two levels: *constant* and *dynamic*, and Game Challenge Control has two levels: *linear* and *dynamic*. This provides four different "game modes", as laid out in Table I.

TABLE I
Game modes

	Intensity Constant	Intensity Dynamic
Challenge Linear	Static (Mode S)	Intensity (Mode I)
Challenge Dynamic	Challenge (Mode C)	Full (Mode F)

The dependent variables are *Effectiveness* and *Attractiveness*. Effectiveness is evaluated by monitoring the subject's heart rate, and comparing it with an ideal heart rate pattern based on accepted exercise effectiveness requirements. Attractiveness is evaluated using a questionnaire in which subjects are asked to rate their enjoyment levels.

IV. Materials

In order to carry out this experiment, we obtained a number of GameBikes and made various modifications to them. We then designed and created a simple exergame that is played using the GameBike as an input device. In this section we describe these modifications and the game.

A. The GameBike

For our study, we chose the GameBike from Cateye, mainly due to its price and availability. The Gamebike works as a PS2 controller and is equipped with a heart rate sensor and computer controlled resistance. It was noted during the study by subjects who did a reasonable amount of normal cycling, that the bike was not particularly well suited for extended cycling. The handle bars on the Gamebike are very short and flat, much more so than is normal in a street bike. Also the Gamebike is quite wide in the centre frame and as such has pedals that are further apart than normally encountered on a bike.

The CateEye GameBike was originally designed as an adaptor kit for standard bicycle. The game bike is now sold essentially as the adaptor kit pre-installed on a supplied exercise bike. Because of this the heart rate functionality and resistance settings of the GameBike are not accessible via any external computer interface. To overcome this limitation, some modifications to the bike were made. The standard exercise control computer was removed since this functionality will be controlled via the PC for our exergame system. A standard RS232 serial connection was added to the front of the bicycles to allow access to the heart rate sensor and provide the ability to set the resistance of the exercise bike.

The modified Gamebike has two connections to a Windows PC, as shown in Figure 2. One connection is used to provide feedback on the user actions. There are three key inputs through this interface. The Cycling speed, the steering direction and the handle based fire button. The other connection to the PC is used to receive information about the players physiological state, in this case through the monitoring of heart rates. This connection is also used to output resistance control back to the bike. Implementation details for these inputs and outputs are as follows.

1) Heart rate: The bike is equipped with a wireless receiver. The receiver is used to pick-up heart rate signals from a standard heart rate device such as the Polar chest strap. For our GameBike, the receiver was removed from its normal mounting and remounted in a separate plastic front mounted box. The controller box was provided with its own external mains power supply, which removed the need for the large battery compartment. To make for the best reception for the heart rate signals, the control box was front mounted in the center of the steering column on a plastic mounting bracket.

2) Resistance: The front mounted plastic box also houses the control interface for setting the bike cycling resistance. The bike flywheel is run in magnetic field which generates the resistance for the pedalling. A small electric servo motor is used to pull the magnets closer to the flywheel in order to generate a higher resistance.

3) Game controller: The Cateye Gamebike functions as a standard PS2 controller. The PS2 controller uses a 9 Pin D connector and a partly analogue interface. There are various adaptor boxes available to convert a PS2 controller over to the fully digital USB interface for use with the PC. We use a generic PS2 to PC adaptor to convert the PS2 Controller to a standard Human Interface Device class USB device. This then causes the Gamebike to appear as a standard joystick under windows.

The pedal motion of the bike is seen as repeated presses of one of the gamepad fire buttons. There is a slider on the game pad which can be used to control the length of the fire button triggering for each sensor reading. Increasing this length of this period causes the individual presses of the fire button to run together after a certain threshold. This could be useful where a game was looking for a more binary response (cycling versus not cycling) rather than an actual pedalling rate. The turning of the handle bars on the bike translates into the x-axis value on the joy stick. There is a slider on the controller which can be used to manage the sensitivity of the x-axis change to changes in the bike steering. We did not use steering for our game.

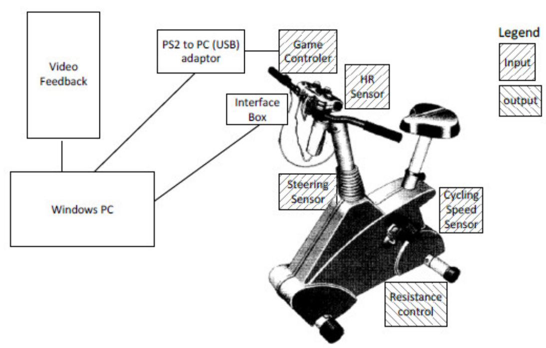

Fig. 2. Modified GameBike system overview

B. The Game

The game that we developed is of the simple "platform game" type. The player controls a helicopter, which flies through a passageway, collecting special "items" to achieve a score. Adding to the challenge, "aliens" attempt to disrupt the player by knocking the helicopter from its intended path. The player can shoot these aliens down, earning extra score by doing so. Figure 3 shows a screenshot of a game in progress.

The game is made into an exergame by using a GameBike as the player's input device. The core game mechanics were designed with the key consideration of controlling the cycling rate of the player. The player sits on the GameBike to play, and must pedal to keep the helicopter at the desired height to navigate the passageway. Figure 4 shows one of the subjects playing the game. The vertical thrust is linked to the cycle rate of the bike. The faster the player cycles the higher

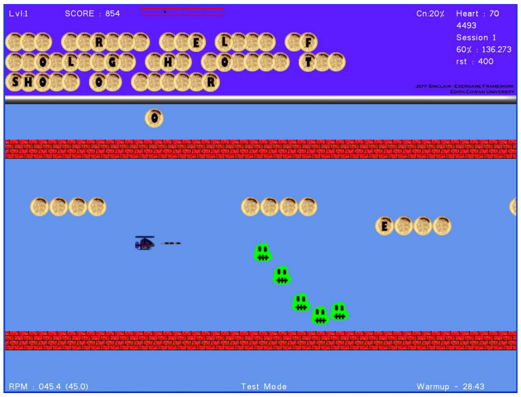

Fig. 3. A screen shot of the exergame

the helicopter moves and conversely the helicopter will drop down as the player cycling slows. The forward motion of the player is automatic. While the player is cycling within certain minimum and maximum speed thresholds, the helicopter will automatically fly in the required direction. Pedalling too slow or too fast will cause the helicopter to crash into the floor or ceiling of the play area and cause forward motion to be severely reduced. Sets of collectable items, in the form of coins marked with letters of the alphabet, are (adaptively) placed into the game. The player collects these letters by flying into them. When these letters are collected they are placed at the top of the play area to spell out a phrase. The game then cycles through a collection of phrases.

Fig. 4. Subject playing the exergame

Sets of enemy characters, in the form of green aliens, fly though and attack the player. The player loses points when struck by the aliens and in addition is pushed up or down, away from the centre of the play area. The player helicopter is equipped with standard generic video game "laser cannon", which can be fired (using a button on the handle of the GameBike) in order to shoot the aliens. Additional score is gained by shooting the aliens.

C. Dynamic adjustment of exercise intensity and challenge

The game can be manipulated by adjusting the relationship between cycling speed and helicopter height. For example, if we want to increase the physical intensity of the game, the relationship can be changed so that the player has to pedal faster to keep the helicopter at the correct height. The mental challenge of the game can also be adjusted, by manipulating the placement of the coins, and also the frequency of alien attacks. By these means, the game can be configured to attempt to adjust the physical and/or gameplay intensity, either according to a fixed schedule, or using feedback based on the player's physical and mental state.

For each subject, a *target heart rate* was determined using the procedure described in Section V-A. The resistance level of the GameBike was then calibrated so that, by pedaling steadily at 70 RPM, the subject's heart rate would be maintained at approximately the target level. A warm up and cool down period at the start and end of the session was added. Figure 5 shows the desired heart rate profile over the period of a session for a subject with target heart rate around 147 beats per minute. Figure 6 shows the actual heart rate achieved in one of the intensity-controlled workout sessions.

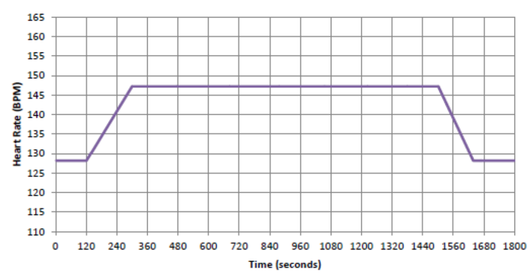

Fig. 5. Desired heart rate for a specific subject during a workout session

In the constant intensity modes, the cycling rate required to keep the helicopter centred was kept at a constant 70 RPM after the warm up and before the cool down phases. In the dynamic intensity modes, the subject's heart rate was continually monitored, and a PID feedback control loop was used to adjust the RPM required to keep the helicopter centred, using Equation 1 below:

$$RPM = K_p \cdot e(t) + K_i \cdot \int_0^t e(t) + K_d \cdot \frac{d}{dt} e(t), \quad (1)$$

where $e(t) =$ desired heart rate-actual heart rate, and K_p, K_i and K_d are tunable constants.

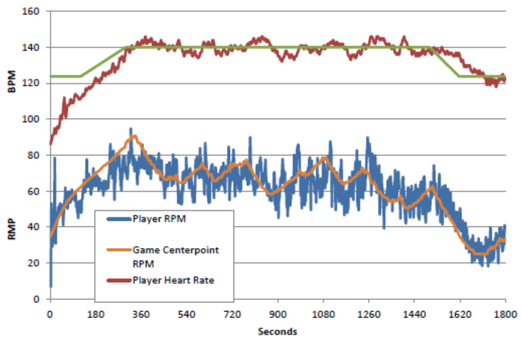

Fig. 6. The heart rate response of one subject for an intensity controlled exergame session. Notice here how the game center point RPM continues to change in order to push the player cycling rate up or down. This is used to manage the heart rate of the player and to successfully achieve the desired player heart rate.

The control of gameplay difficulty is less straightforward, as there is no simple measure of the challenge level currently being experienced by the player. We used a fuzzy inference system, with rules taking into account

1) The percentage of the coins collected.
2) The percentage of aliens that were shot down.
3) The percentage of shots fired which hit an alien.
4) The number of letters within the phrase which are collected.

An example fuzzy rule is:

If percentCoinsCollected is low then gameChallengeChange is smallReduction

If the fuzzy system determined that the challenge level should be increased, then the speed of the helicopter was increased and the placement of coins to be collected was made more difficult (they were placed at different heights so that the player would have to plan ahead in order to be able to have the helicopter at the right height at the right time). Conversely, if the level needed to be decreased, the helicopter speed was reduced and the placement of coins made easier.

In the linear gameplay challenge modes, the speed and difficulty of placement were slowly increased over workout session.

V. Procedure

Subjects were asked to attend 5 one hours sessions on different days during a two week period. The first session involved an introduction to the study and the use of the non-game mode of the exergame. The remaining four sessions corresponded to the four game based workout modes.

A. First session

The first session was an introduction session. The subject provided informed consent and answered a short medical questionnaire to ensure they could safely participate in the study. When initial paperwork was completed the subjects were shown the chest strap mounted heart rate monitor. The subjects were instructed on how to wear the heart rate monitor and a monitor was fitted and adjusted. The subjects stood beside the heart rate receiver on the bike to ensure a reading could be retrieved and that the monitor was sitting comfortably.

The subject was then asked to sit on the GameBike. The height of the bike was then adjusted to be at a comfortable height. The seat height was recorded and maintained constant for each of the following sessions.

The subject sat on the bike in a resting state for five minutes while the heart rate was measured. The resting period allowed the subjects heart rate to return to its normal resting state, in case the subjects HR was elevated due to any external factors, such as hurrying to make the session or nervousness. The average of the last minute of the five minutes of rest was then recorded and used as an indication of the subjects resting heart rate. The resting heart rate was used in conjunction with the subjects age to determine a heart rate level of approximately 60% of the heart rate reserve. This heart rate was the target level for the workouts.

After the heart rate test, a simple ramp-up test was performed. Based on the subject's responses to the medical questionnaire, and a visual assessment of the subject's physical condition, a starting resistance level for the bike was selected for the ramp-up test. The subject commenced cycling at a steady 70 RPM. After 3 minutes the resistance increased by a predefined amount and then again at the 6 minute mark. The information from the ramp-up was used to manually estimate a resistance which would get as close as possible to the previously determined heart rate target.

After completing the ramp-up test, subjects took a 10 minute break. During the break the subjects filled out a questionnaire which indicated their general demographics and questions around their game playing and exercise behaviours. Following the break they did a 30 minute workout consisting of:

- 5 minute warm-up period. The player was required to cycle at 45 RPM for the first 2 minutes. The cycling rate the linearly increased until it reached 70 rpm at the 5 minute mark.
- 20 minutes moderate exercise, where they need to cycle at close to 70 RPM and with the resistance that was previously calculated. This resistance was expected to bring the subject close to the target Heart Rate.
- 5 minutes cool down period. The required RPMs decreased linearly until it reached 45 RPM after 3 minutes. It remained at 45 RPM for the remaining 2 minutes of the cool down.

During this workout the subject needed to maintain the correct RPM to maintain a marker centred in the screen. This first session without the game allows us to do some comparisons between exercising with the game and without the game.

B. Gaming sessions

After the first session, subjects returned on 4 separate following occasions and performed another 30 minute workout each time. While performing these workouts the subjects played one of the variants of the videogame. For each of the four sessions a different control mechanism for the game was used. The four different variations of the game meant that there are twenty four different orders in which the games can be played. The subjects were each randomly assigned one of the orders in which to play the games. After each session the subjects completed a questionnaire designed to help evaluate the different control mechanisms.

After the completion of all four workout sessions and the associated questionnaires, the subjects were also asked to complete another questionnaire which asked them to compare the different game sessions.

C. Questionnaires

The session questionnaire asked the subjects to respond to the following 12 questions, most of them on a 5 point Likert scale:

1) In terms of exercise how strenuous do you feel today's workout was on a scale of 1 to 5?
2) What do you think about the appropriateness of the length of time the workout took?
3) How exhausted do you feel?
4) Do you feel that you got a good workout?
5) How difficult did you feel today's video game was on a scale of 1 to 5?
6) On a scale of 1 to 5 how interesting did you find today's game?
7) How quick did the time pass during the exercise period?
8) During the workout, roughly how much of the time were you focused on the time remaining? (Subjects nominated a %).
9) How difficult was it to focus on the game?
10) How difficult was it to control the game using the exercise bike?
11) During the Game my main focus was : (Subjects chose from Hitting the markers, Collecting letters/completing phrases, Shooting aliens, Score, Time remaining, Maintaining the correct RPMs, Other)
12) As a form of exercise I rate this workout as a (Subjects nominated a value out of 10).

VI. Results and Discussion

A. Exercise intensity control

In order to evaluate effectiveness, we calculated the mean heart rate error for each subject over sessions with specific modes. The instantaneous heart rate error is simply the absolute value of the difference between the target heart rate for that point in the session and the actual heart rate. Table II displays the mean heart rate error for each subject over the Mode S and Mode C sessions (static intensity), and over the Mode F and Mode I sessions (dynamic intensity). It is clear that the dynamic intensity sessions kept the subjects much closer to the target heart rate, with the mean heart rate error being less than half that for the static intensity sessions. Nearly all the subjects gained considerable benefit in terms of effectiveness when intensity was dynamically controlled.

TABLE II
Mean heart rate errors for static and dynamic intensity modes

subject	mean HR error static intensity	mean HR error dynamic intensity
1076	14.82	7.21
1134	9.80	4.26
1377	13.38	4.69
1464	5.96	3.20
2457	15.06	3.68
2565	14.30	2.78
2810	6.62	6.46
2830	14.85	4.07
2866	13.19	4.61
4102	4.53	3.45
4228	4.53	2.04
4386	5.59	4.21
4446	7.58	4.16
4496	26.69	4.70
4501	3.25	4.57
4567	5.49	5.41
4623	10.98	4.30
4771	3.93	5.18
4881	10.38	4.87
4882	5.14	5.13
4982	9.49	4.10
Mean HR error	9.79	4.43

Figure 7 shows the mean heart rates over the session time, across all subjects, comparing static and dynamic intensity. The dynamic intensity heart rate reaches the target heart rate faster, and is more consistent over the duration of the session, whereas the static intensity sessions show a steady increase in heart rate, due to cardiac drift.

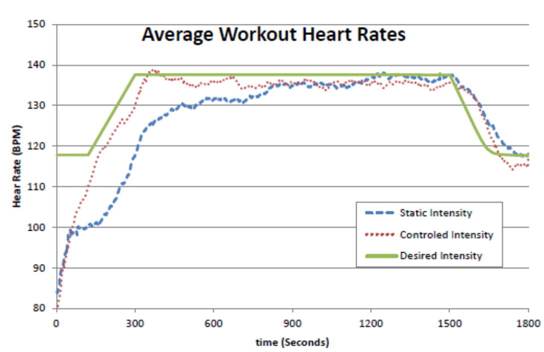

Fig. 7. The mean heart rate across all subjects, grouped by static intensity and dynamic intensity sessions.

B. Challenge control

In order to evaluate attractiveness, we refer to questions 6–8 of the questionnaire, beginning with question 6. Table III shows the mean and standard deviation of answers given to questions 6, grouped by mode. There is no statistically significant difference between the scores for the four modes.

Questions 7 and 8 ask about the player's perception of time, which could be taken as an indication of how "immersed" in the game the subjects were. Means and standard deviations for answers given to these questions are given in Tables IV and V. Again, there is no significant difference between the means for the different modes.

TABLE III
INTERESTINGNESS SCORES FOR DIFFERENT MODES

	Intensity Constant	Intensity Dynamic
Challenge Linear	3.38 ± 0.92(Mode S)	3.14 ± 0.85 (Mode I)
Challenge Dynamic	3.1 ± 1.26 (Mode C)	3.14 ± 0.91(Mode F)

TABLE IV
PASSAGE OF TIME FOR DIFFERENT MODES

	Intensity Constant	Intensity Dynamic
Challenge Linear	4.43 ± 0.81(Mode S)	3.90 ± 1.18 (Mode I)
Challenge Dynamic	4.14 ± 0.73 (Mode C)	4.05 ± 0.86(Mode F)

TABLE V
FOCUS ON TIME FOR DIFFERENT MODES

	Intensity Constant	Intensity Dynamic
Challenge Linear	13.57 ± 14.13(Mode S)	17.05 ± 17.77 (Mode I)
Challenge Dynamic	12.43 ± 13.56 (Mode C)	15.76 ± 16.15(Mode F)

We hoped and expected to see the subjects report that the challenge controlled modes kept the subjects "in the zone" and so were more interesting and resulted in greater immersion. However, we did not see this effect.

There are a number of possible explanations for this. Recall that we attempted to keep the subjects in the zone by manipulating the challenge level of the gameplay. In order to do this effectively, we would need to correctly judge the level of challenge being experienced by the subject, and then appropriately adjust the challenge level if needed.

In the case of intensity control, we have a readily-measured, unambiguous means to tell if the intensity is in the desired range – the heart rate. Here there is no such easy way to judge the level of gameplay challenge relative to the subject's ability and capacity. We used a combination of measurements that intuitively might be directly related to it, but we do not have any actual evidence of this relationship.

Likewise, in the case of exercise intensity, we can be confident that increasing (respectively decreasing) the required pedaling rate will increase (respectively decrease) the exercise intensity. In the case of challenge control, once again we have no direct evidence that our increase in speed and in height variation was an appropriate way to manipulate the challenge level. For example, if the changes in the right direction but too large, gameplay difficulty might oscillate, which the player might find frustrating rather than interesting.

A final possibility is that dynamic control of challenge does not keep the subject in the zone, and so does not contribute to the attractiveness of the game. However, until other possibilities have been investigated, we can only say that our results in this regard are unclear. It does appear that dynamic challenge control is difficult to achieve. For example, in [2], the author notes the difficulty of achieving flow based solely on dynamic difficulty adjustment, and suggests that some other aspects of the flow state, such as a sense of control, also need to be considered. Another recent study [9] had similar findings.

VII. CONCLUSION

In this paper, we have presented an experimental study in which we tested combinations of feedback control to improve the effectiveness and attractiveness of an exergame. We described an exergaming system that uses a heart rate monitor, classical PID control for exercise intensity, and a fuzzy control system for dynamic gameplay challenge adjustment.

We demonstrated that using a PID control loop to dynamically adjust the exercise intensity level of the game, based on heart rate, is very successful in helping the player to maintain desired exertion levels to achieve a well-structured workout.

The control of gameplay challenge levels in order to achieve a "flow" state was less successful, with further work needed to better understand how to measure and manipulate gameplay challenge levels, and how to incorporate other flow elements into exergame gameplay.

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