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Feedback control for exergames

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FEEDBACK CONTROL FOR EXERGAMES

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USE OF THESIS

Abstract

The concept of merging exercise equipment with video games, known as exergaming, has the potential to be one of the main tools used in addressing the current rising obesity epidemic. Existing research shows that exergaming can help improve fitness and additionally motivate people to become more active. The two key elements of attractiveness - how much people want to play or use the exergaming system; and effectiveness – how effective the exergaming system is in actually increasing or maintaining physical fitness, need to be maximised to obtain the best outcomes from an exergaming system; we put this forward as the Dual Flow Model.

As part of the development of our exergame system we required the use of a heart rate response simulator. We discovered that there was no existing quantitative model appropriate for the simulation of heart rate responses to exercise. In order to overcome this, we developed our own model for the simulation of heart rate response. Based on our model, we developed a simulation tool known as the Virtual Body Simulator, which we used during our exergame development. Subsequent verification of the model using the trial data indicated that the model accurately represented exergame player heart rate responses to a level that was more than sufficient for exergame research and development.

In our experiment, attractiveness was controlled by manipulation of the game difficulty to match the skill of the player. The balance of challenge and skills to facilitate the attainment of the flow state, as described by Csikszentmihalyi (1975), is widely accepted as a motivator for various activities. Effectiveness, in our experiments was controlled through exercise intensity. Exercise intensity was

adjusted based on the player's heart rate to maintain intensity within the limits of the ASCM Guidelines (ACSM, 2006) for appropriate exercise intensity levels.

We tested the Dual Flow Model by developing an exergame designed to work in four different modes; created by selectively varying the control mechanisms for exercise workout intensity and game mental challenge. We then ran a trial with 21 subjects who used the exergame system in each of the different modes.

The trial results in relation to the Dual Flow Model showed that we developed an excellent intensity control system based on heart rate monitoring; successfully managing workout intensity for the subjects. However, we found that the subjects generally found the intensity controlled sessions less engaging, being closer to the flow state in the sessions where the intensity was controlled based on heart rate.

The dynamic difficulty adjustment system developed for our exergame also did not appear to help facilitate attainment of the flow state. Various theories are put forward as to why this may have occurred.

We did find that challenge control had an impact on the actual intensity of the workout. When the intensity was not managed, the challenge control modes were generally closer to the desired heart rates. While the difference was not statistically very large, there was a strong correlation between the intensity of the different modes. This correlation was also present when looking at the players' perception of intensity, indicating that the difference was enough to be noticed by the subjects.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(i) Incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher degree or diploma in any institution of higher education;

(ii) Contain any material previously published or written by another person except where due reference is made in the text of this thesis; or

(iii) Contain any defamatory material.

(iv) Contain any data that has not been collected in a manner consistent with ethics approval.

RELATED WORKS

During the course of these studies, the following journal article and three conference papers were produced. Full abstracts have been included in Appendix H.

Considerations for the Design of Exergames

Sinclair, J., Hingston, P., and Masek, M.

GRAPHITE '07 - ACM Special Interest Group on Computer Graphics and Interactive Techniques, Perth Western Australia December 2007.

30 Citations according to Google scholar

(ERA Level B)

Using a Virtual Body to Aid in Exergaming System Development

Sinclair, J., Hingston, P., Masek, M., and Nosaka, K.

IEEE Computer Graphics and Applications, March/April (2009), 39-48

4 Citations according to Google scholar

(ERA Level B)

Exergame Development Using the Dual Flow Model

Sinclair, J., Hingston, P., and Masek, M.

IE 09 - Australasian Conference on Interactive Entertainment, Sydney December 2009

(ERA Level B)

Testing an Exergame for Effectiveness and Attractiveness

Sinclair, J., Hingston, P., Masek, M., and Nosaka, K

GIC 2010 - 2nd International IEEE Games Innovation Conference Hong Kong December 2010

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1 Introduction

This thesis is in the field of exergaming. Exergaming is a term coined to describe the merger of exercise equipment with video games. During this chapter, we will provide some background on exergaming. We will then look at the current problem of obesity in modern society, and consider why exergaming is seen as a possible solution to this problem and the significance of this. Finally, we will broadly outline the direction the research in this thesis will take, and the motivations behind it.

1.1 Background on Exergaming

The origin of the term Exergaming is not clear. Gieson Cacho (2007) writes that Exergaming is a term first coined by Joshua Trout Associate Professor of Kinesiology at California State University, CHICO. The Wordspy web site (McFedries, 2007) however, credits Raju Nudhar, of The Toronto Star with the first usage on April 20, 2004 in an article about the neXfit exercise bike. The word exergaming is now commonly used in the domain of populist media and the advertising world. Exergames are also referred to using the following terms; Activity promoting video games (Lanningham-Foster et al., 2006); interactive video games (Hoysniemi, 2006; Luke, 2005), and exertion interfaces (F. Mueller, Agamanolis, & Picard, 2003; Brian K. Smith, 2007).

Using exercise equipment to interface with a video game is not a new concept. The Atari Puffer project (Atari Gaming Headquarters Website, 2009) from 1982 looked at the idea of attaching an exercise bike to a game console. The Amiga Joyboard released in 1983 was promoted as a means of getting fit (Knight, 2002). Exergaming has come a long way since the early 1980s.

The Nintendo Wii, released in November 2006 for the home entertainment market, was the first mainstream game console which contained a built in exergaming system. The Nintendo Wii uses wireless hand held controllers which sense motion using a three axes accelerometer. The accelerometer in the controllers is used in a number of games which require the user to make physical motions to play the game. This feature has seen the Wii promoted in various media as a means for getting people to be more active. The release of the Wii resulted in a raised awareness of the idea of using video games to promote exercise.

Late in 2010, the other major game console makers, Sony and Microsoft, released exergame systems of their own. Sony released the PlayStation Move system in September 2010, which consists of two wireless motion controllers in the fashion of the Wii, but which are additionally tracked using a motion sensing camera. In November 2010 Microsoft released the X-Box Kinect. The X-Box Kinect uses an infrared laser and image sensor to produce a depth map of what is happening in front of the system (Gizmodo, 2010). Combined with an image sensor and voice recognition system, it is an attempt to do away with the need for a hand held controller.

1.1.1 Outline of an Exergaming System

There are five standard components used in exergaming systems, though not all components are used in every exergame system (see Figure 1):

a) **Human player**

The human player, central to all exergame systems (Figure 1 a), undertakes the physical exertion required to perform the physical actions needed to play the exergame. The player gets feedback from the exergame control device and the audio-visual systems.

b) Exergame control device

Exergames cause the human player to exercise by using a game control device (Figure 1 b). Energy expenditure may be caused by two main methods or a combination of both. The controller may require the movement of major muscle groups against some form of resistance provided directly by the controller, for example using an exercise bike. The other mechanism is where the user is required to make large muscle movements in order to operate the controller, but no direct resistance is offered by the control device, for example when using a dance mat. There exists a wide range of exergame controllers, from modified gym equipment to computer-specific peripherals. Some examples of controls are Wii motion controllers, exercise bikes, and Dance Dance Revolution dance mats.

c) Game software

The game software (Figure 1 c) takes inputs from the player by examining the state of the exergame control device and reading any Biosensors attached to the system. It manages the game play and interactions and passes feedback to the player. The game software might be running on dedicated hardware, a general-purpose gaming machine, or even a standard PC.

The software then sends feedback about the game to the user. Standard feedback travels through traditional channels such as the video display and sound system. Other forms, such as haptic feedback or some other change to the control device (such as increased resistance or reduced sensitivity) are delivered via adjustments to the control device.

d) Biosensors

Biosensors (Figure 1 d) are defined as analytical devices which convert biological responses into electrical signals. Biosensors can monitor some physiological states of the player. This information can then be used to influence the game.

At the current point in time, few commercially produced games use the player's physiological state as input. One example is the 1998 Amtex release of Tetris for the Nintendo 64 which worked with a biosensor. The game shipped with a heart rate sensor that clipped onto the ear of the player. Based on the player heart rate the game would either slow down or speed up (Schneider, 1999). As another example, Fabio Buttussi and colleagues developed two physically interactive video games where the player's heart rate controls game play intensity (Buttussi, Chittaro, Ranon, & Verona, 2007).

The exergame software might not use the player's physiological state data, but the game designers need this data to tune the game and make it effective as exercise for the target market.

e) Audio-visual feedback device

In addition to the physical stimulus, exergames typically include audio-visual feedback (Figure 1 e). As well as being useful in facilitation of the game mechanism, audio and visual feedback can be used to provide a more immersive environment. In a study of an exergame system comparing a highly immersive system, with a low immersion system, IJsselsteijn, Kort, Westerink, Jager, & Bonants (2004) concluded

“In the highly immersive environment, where the presence experience was stronger, participants reported more interest and enjoyment”.

Yim & Graham (2007) reviewed existing exercise motivation literature in order to develop a set of requirements for development of exergames systems. One of the findings considered was the integration of music. They concluded that to enhance enjoyment, an exercise game should have music that is upbeat.

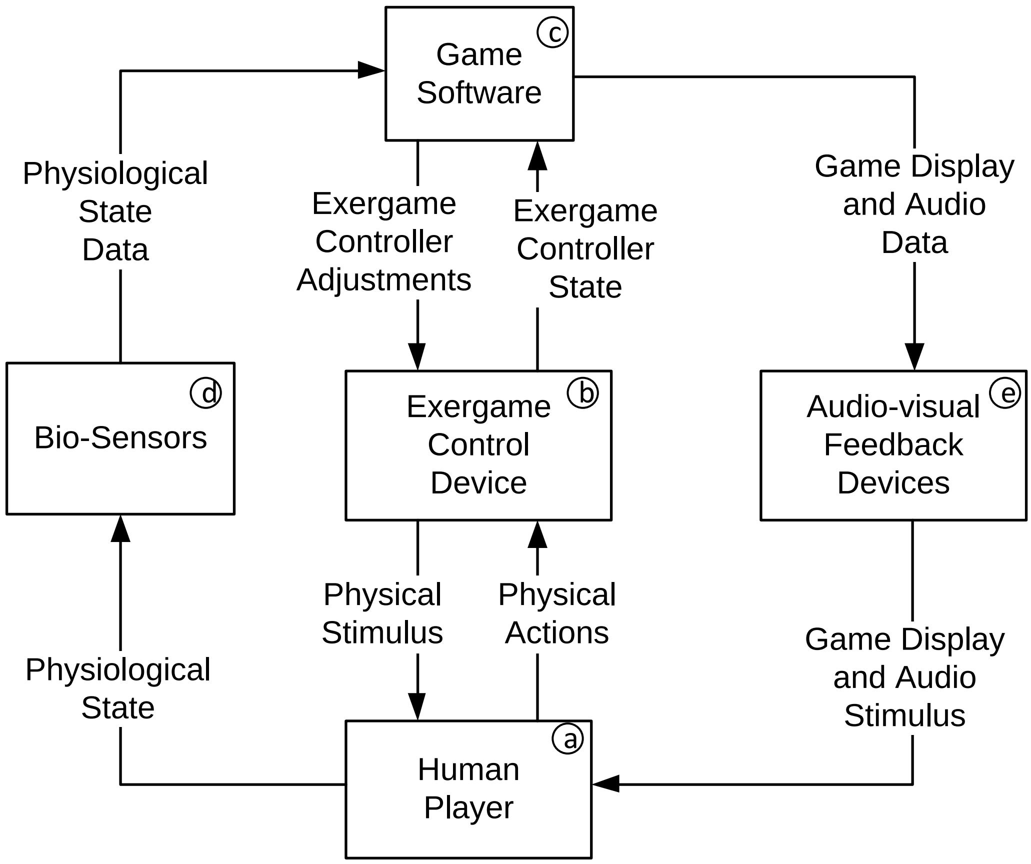

Figure 1 A standard exergaming system, showing the system components and interfaces.

1.2 Obesity

One of the current reasons for the interest in exergames is obesity. Obesity is an increasing problem in modern society (Booth et al., 2004; Hersey & Jordan, 2007), and the rate has continued to rise greatly over the last thirty years (Lanningham-Foster, et al., 2006). From 1985 to 1997 the number of overweight 7-15 year olds in New South Wales schools almost doubled, and the number of obese children has more than tripled (Booth, et al., 2004).

In 2009 the Australian Standing Committee on Health and Ageing heard that the estimated cost of obesity to the Australian economy in 2008 was $8.283 billion. If the cost of lost wellbeing is included the figure reaches $58.2 billion (House of Representatives Standing Committee on Health and Ageing, 2009). Looking forward, we can see that addressing the causes of obesity and looking at potential solutions, is something that is demanding immediate attention.

While the cause of obesity is multi-factorial, obesity is generally caused by lack of physical activity, unhealthy eating patterns, or a combination of the two, with genetics and lifestyle both playing important roles (Stubbs & Lee, 2004). A decline in physical activity is one of the main factors predisposing a child to obesity (Marshall, Biddle, Gorely, Cameron, & Murdey, 2004). It is also suggested that exercise rather than limiting food intake is the best, safest, and most effective way to stay healthy (Children, Youth and womens health service 2008)

In recent times children tend to spend less time performing physical activities, and spend more time in front of the television, watching DVD's, and playing video games (Salmon et al., 2005). Engagement in these types of activities uses up time that was previously spent on physical activity in prior generations. Children aged 8 to 18 spend more time in front of computer, television, and game screens (44.5 hours per week) than any other activity in their lives except sleeping (Kaiser Family Foundation, 2005).

Vandewater et al. (2004) looked at the activities of a number of children up to the age of 12 over two 24 hour periods. The activities performed, and the percentage of time for the activity, were then examined in order to determine any relationship with obesity. No relationship between levels of television watching and obesity was found, however they did find a strong correlation between video game play and obesity. Hersey and Jordan (2007) also state that the link between childhood obesity and media use by children is firmly established. According to a report from market research group NPD (2007) American children in 2007 spent significantly more time playing video games than they did in 2006. There is a pressing need for solutions to the problem of rising obesity.

1.3 Significance of Exergames

The key concept behind exergaming is that exercise for its own sake is relatively boring and as such, not undertaken by large segments of the general population at levels which are required to maintain general health levels. The idea is that an unpopular activity, when combined with another, more enjoyable activity, can be made more popular or enjoyable. The joining of exercise with video games may be one such avenue to making exercise more desirable. There have been a number of studies which support this theory (Goldfield, Kalakanis, Ernst, & Epstein, 2000; Saelens & Epstein, 1998). These studies will be discussed further in Chapter 2.

1.3.1 Increased Interest in Exergaming as a Means to Managing Obesity

Given the increase in “screen time” and decrease in “physical activity”, Exergaming is seen as something that could potentially help address the current obesity problem. Since mid-2006 we have seen an upswing in activity and interest in the field of exergaming. There are arguably many varied reasons for this upswing, but there are two factors in particular that stand out; the release of the previously mentioned Nintendo Wii® game console in 2006, and the current high and rising levels of obesity in Western society. While many people think of video games as associated with children and teenagers, this in reality may no longer be the case. According to industry statistics, the average game player in 2009 was 35 years old (Williams, Martins, Consalvo, & Ivory, 2009), with 25% of gamers over the age of 50 (Entertainment Software Association, 2009). The usage of computer games across the entire population continues to rise every year. With video game usage increasing across the entire population, exergaming is something that may have a wide reach in tackling obesity.

1.3.2 Current Research

As a potential solution to help address the rising obesity problem, it is important that exergaming is researched to maximise the benefits arising from exergaming. If exergames are being promoted to help combat the rising obesity problem, it is important that quality exergames are produced. Some exergames produce levels of energy expenditure which are quite low. Other exergames produce high levels of energy expenditure in participants, but might have game play which is not engaging enough to produce result significantly better than the vast array of existing exercise equipment. The production of poor quality exergames, which do not combat obesity, tarnishes the image of exergaming at as a potential tool in the fight against obesity. This could prevent the potential of exergaming, as a means of combatting obesity, from being reached.

Most existing exergame research has focused on the validity of exergaming as a solution to the problem of rising obesity. This research has proven that it is possible to make an exergaming system that causes enough physical exertion to be used as a legitimate form of regular exercise. Additionally the research allows us to conclude that for some people, video games, in the form of an exergame, would be a significant means of motivating them to perform physical exercise (Saelens & Epstein, 1998; Warburton et al., 2007).

The existing exergame literature fails to adequately cover the design or development of exergames. Now that we have seen that the idea of exergames is valid, further study of exergaming is needed in order to assist in the development of exergames that can make a difference to the current obesity issue. It is critical to speed development and breakthroughs in this area before obesity becomes a major negative impact on the life of many people.

1.3.3 New Research

The crucial next step in exergame research that we tackle in this thesis is the development of a design frame work for exergame control systems. It is important that we try and produce quality exergames, and once produced, we know how to consistently do so. In this research we put forward a model for the design of exergame control systems. We then take the model and develop an implementation in the form of an exergaming system framework. An exergame system is then built with the framework and tested to assess the validity of the model. This framework could be the basis for a well-founded methodology behind exergame development.

1.4 Summary

Exergaming is a field that is seen as a possible solution to the rising obesity problems facing the western world. Existing research has been done to show that in theory, exergames could be at least part of the solution. They can increase levels of activity to a reasonable level and motivate people to undertake more exercise.

Further research is now required to see exactly how to make exergames which will successfully fulfil these two challenges and help combat the current obesity problem. In this thesis we will put forward a model for the development of exergames and undertake a trial to demonstrate the validation of the new model. Firstly we will take a look at the existing literature on the subject of exergaming, and then examine the main lines of research which have been carried out.

2 Review of Literature

In this chapter, we review the historical development of exergaming, and look at the various machines and input devices that have been utilized in the past. We then examine the existing studies in the field of exergaming, in order to identify the key existing lines of thought in the field, and areas where further depth of research is required.

2.1 Commercial Exergaming Systems

In this section, we review the historical development of exergaming in the context of commercial systems and the various machines and input devices that have been utilized. We can then draw on this history later when looking at success factors and research regarding the design of games.

2.1.1 Exercise Bikes

The exercise bike has arguably been the most prolific candidate for teaming with computer games. The Atari Puffer project from 1982 is an often mentioned early example (Atari Gaming Headquarters Website, 2009). Atari developed and prototyped an exercise bike in 1982, which connected to a game console. Although this project was not commercialized due to internal changes within Atari, similar products soon followed. In 1983, Antic magazine pictured a Suncom exercise bike game controller in the "new products" section of the September edition (Atari Magazines Website, 1983). A later example from the mid 80's was the HighCycle from Autodesk, which allowed users to pedal an exercise bike across a virtual landscape (Rizzo, 2007).

Today there is quite a wide range of exercise bikes designed to be used as video game controllers. The Tacx Fortius Trainer - produced as a training aid for cyclists, the Fisher Price Smart Cycle - aimed at younger children, and the Wii Cyberbike, early 2010, are just some of the products on offer. There are also a number of kits which are designed for modification of off the shelf exercise bikes for use with video game consoles.

The Gamebike Controller (Cat Eye Company Ltd, 2002), released in 2002, was designed as an adaptor kit for using a standard bicycle as an interface to a video game console. The components of the Gamebike Controller are shown in Figure 2.

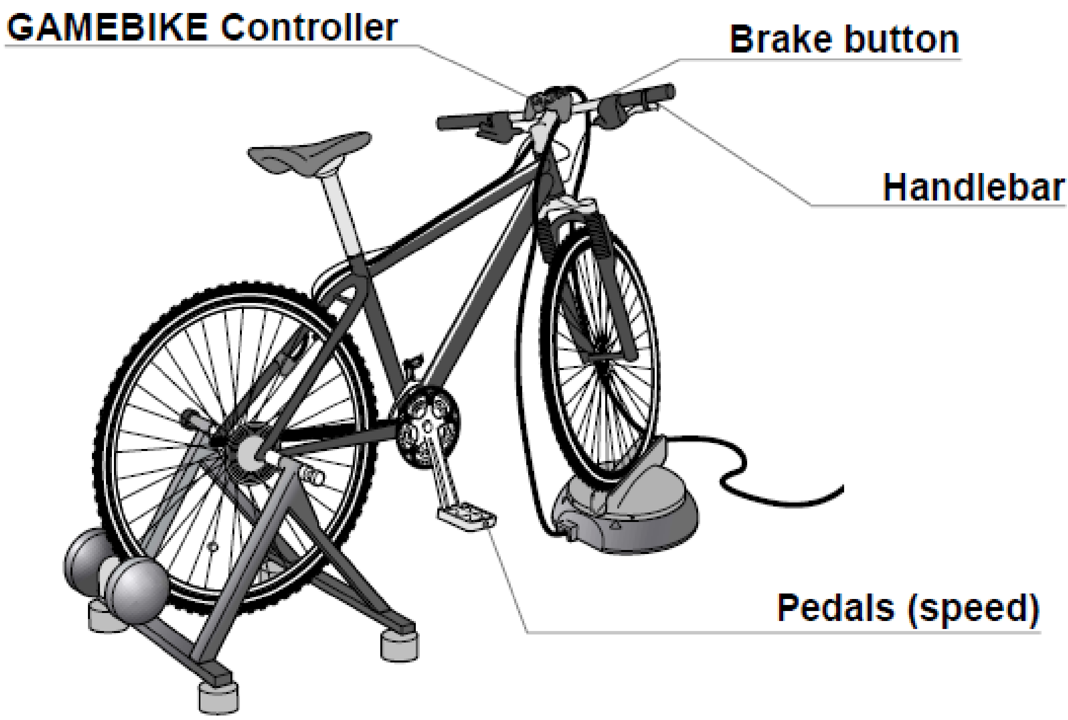

Figure 2 Cat Eye Gamebike controller (Cat Eye Company Ltd, 2002).

The system was designed for a standard bicycle and rear mount trainer stand. With the bike fitted into the rear mount trainer stand the front wheel is set into a swivel block which measures the left and right turn. A rear wheel sensor is added to measure the peddling speed. A sensor button is then mounted on the handle bars. The three different sensors are then connected to a game controller which is mounted to a headlight clip in the centre of the handle bars. The mounted game controller is very similar to a standard Play Station 2 controller, but it has additional sliders for managing the sensitivity of the remote bike sensors. The modified controller is shown in Figure 3.

Figure 3 Gamebike handlebar mounted controller

This setup can be used as a standard Sony Playstation 1 or Playstation 2 controller. The cycling action of the Gamebike translates to a series of repeated button presses on the standard controller. The steering action translates to movement on one of the controller’s axes. The button on the handlebars acts as a fire button.

The Gamebike pro from Cat Eye, which we have used for this study, is in essence the same setup, but comes pre-installed onto an exercise bike from Cat Eye. The Gamebike includes its own computer with heart rate detection hardware and resistance setting capabilities. A standard Polar Chest transmitter is worn by riders to provide heart rate readings to the wireless receiver. Unfortunately Cat Eye has not integrated any of the resistance setting and heart rate measurement functionality into the game controller. No interface is provided so the built in computer and its functionality can be accessed by a PC. This required us to make some modifications to the standard Gamebike for our study. We discuss the Gamebike, and the modifications required for our study in detail in section 4.3.4.

2.1.2 Motion Sensors

Nintendo released the Power Glove in 1989. The Power Glove consisted of a glove worn by video game players, which contained a motion sensor and additionally broadly registered the positioning of the fingers. The Power Glove was initially successful, eventually selling 1.5 million units. This success was short lived and the Power Glove was commercially available for little over a year. Two video games were specifically released for the Power Glove. Bad Street Brawler, which is a standard side scrolling fighting game, and Super Glove Ball which is a Breakout style clone, where the player throws balls to knock down walls in order to advance.

The Sony EyeToy® was first released in 2002. This consists of a special camera connected to the Playstation 2 ®. There are a number of games available which use the camera to track actions performed by the game player. The EyeToy has had a solid commercial performance but has yet to have a blockbuster game release. The updated version for the Playstation 3 ® entitled Playstation Eye was released in October 2007 (Valledor, 2007). The newer release has double the original eye toy sensitivity.

In 2006 Nintendo released the Nintendo Wii. This consists of a game console in which the controllers contain built in motion sensors. The Wii comes pre-packaged with a software title called Wii Sports. This is a collection of five sporting titles designed to showcase the motion sensor abilities of the controller. The games included are tennis, baseball, bowling, golf and boxing. Boxing uses the additional add-on known as the Wii Nunchuk. The Nunchuk contains a motion sensor and connects to the normal controller to extend it into a two handed device. The Wii has been heavily promoted as activity-inducing and this product release caused a surge in interest in the area of exergaming.

The Wii controller, called the Wii Remote has a three axes accelerometer for tracking motion. It also has a built in infrared light sensor that is used to help detect the position of the controller relative to an infrared light emitting bar placed above or below the video screen being used. In July 2008 the Wii MotionPlus expansion device was released. The Motion plus add a two axis gyroscope to the base of the standard Wii Remote. This provides additional rotational movement sensing capabilities to the controller.

Sony’s latest offering in the motion sensing arena is the Playstation Move, released in September 2010. It has a wireless controller that contains a three-axis linear accelerometer, a three-axis angular rate sensor and a magnetometer (Mikhailov, 2009). The controller is also topped by a glowing orb that the Playstation uses to visually track the position of the controller using a motion sensitive camera.

Microsoft has also developed a motion sensing system for the X-box 360 called Kinect which was released at the end of November 2010. The Kinect does not use a hand held controller for motion sensing, rather relying on a passive motion sensing system combined with and voice activation. The Kinect uses an infrared laser and image sensor to produce a depth map of what is happening in front of the system.

2.1.3 Foot Operated Pads

The use of foot operated pads as exercise-based input controllers has seen mixed success. In 1983 Amiga released the Joyboard, a stand-on pad used for controlling video games on the Atari 2600. This was promoted as a means to get fit while playing video games (Knight, 2002). The Joyboard was similar in size to a set of bathroom scales and balanced on a central disk. A player would stand on the board, leaning in any of eight directions to make a contact. This was then used in much the same way as a conventional joystick would be used. While the Joyboard was claimed to be compatible with almost all Atari compatible video games, there were four games released specifically for it. These games were Mogul Maniac, a skiing game with nine downhill courses; Surf's Up, a surfing game; S.A.C. Alert, a fighter pilot flying game; and Off Your Rocker, where players needed to follow a pattern of moves shown on the screen (Ahl, 1983).

In 1986 Bandai Namco developed the Power Pad (also sold as Family Trainer or Family Fun Fitness). The Power Pad consisted of a mat with eight buttons activated by the player using his or her feet. Nintendo later brought the rights and release it in 1988 along with the game *World Class Track Meet*. At least six games were released for the Power Pad, most of which were centred on a sports theme. None of these were a significant commercial success (Games Graveyard Website, 2007) and the Nintendo Power Pad was commercially very short lived.

Over a decade later, in 1998, an extremely similar product, called Dance Dance Revolution ® (DDR) was released in the video game arcades by Konami of Japan, and then later into the home console market. DDR also consists of a set of buttons pressed by the player stepping on them. The screen displays a set of dance steps matched to music, which the user is required to copy. DDR was a huge success and by the end of 2003 Konami had reported 6.5 million sales of the game (Game Spot Australia website, 2007). DDR now comes in many variants and is supported for most major gaming platforms.

In July 2007 Nintendo released the Wii Balance Board bundled with the Wii Fit software. Similar to the Atari Joyboard the balance board is designed to accurately measure the centre of balance of the user of the board and additionally can measure the weight of anyone standing on the board. By 2010 there has been over 30 software titles released for the Wii Balance board. There are numerous skiing and skate boarding based games which use the balance board, as well as some more original games such as Go Play Lumberjacks, which uses the balance board with the Wii motion sensitive controller to simulate “intense lumberjacking action.”(IGN Entertainment, 2009).

It is interesting to note that from 2008 there have been a number of exercise specific software packages released for the Nintendo Wii game console. EA Sports Active, Jillian Michaels' Fitness Ultimatum 2009, Golds Gym Cardio Workout, and Black Bean games New You, just to name a few. These packages move away from the gaming side of the Wii, and try to position the Wii as a piece of exercise equipment. According to Fabrizio Vagliasindi, Black Bean Games Head of Marketing, in relation to their newly release software entitled New You: Inside Out, "New You is not a game; it has been conceived as an interactive healthy lifestyle and workout video for the 21st century." (Wii Balance Board Games Roundup, 2009)

In September 2008, Bandai Namco the original developers of the power pad released a foot operated pad for the Wii called the active life mat. This mat looks and functions very similar to the original power pad. However being released nearly two decades later, the active life mat has been significantly more commercially successful, having sold over a million units in the first year (Dimola, 2009).

2.1.4 Other Physically Interactive Games

In 2004 Power Grid Fitness released the Kilowatt game controller. The controller consists of a metal bar that extends off the ground like an exaggerated joystick. The bar contains strain gauge sensors to measures the pressure exerted against it. In 2005 Power Grid fitness revamped the Kilowatt and released what is called the Exerstation, essentially a cheaper reduced version of the Kilowatt system. There appears to be few if any commercially available games which were specifically designed for the Kilowatt or Exerstation controllers.

There are also a number of dedicated single game exergaming systems. Radica have released a couple of sports oriented exergames that have fairly complex interfaces which are specifically tailored to the particular sport in question. Collectively called Play TV, they have released an American football game, a baseball game, a basketball game, a golf game and a snowboarding system. In early 2007 Electric Spin released Golf Launchpad, a golfing simulator.

2.1.5 Attractiveness and Effectiveness of Commercial Exergame Systems

An important outcome for exergaming systems is to achieve health benefits. We call this the *effectiveness* of the system. The other key feature for an exergaming system is to be fun. The system needs to make people want to play the game or games, in order to motivate the user to exercise. We call this factor *attractiveness*.

In the past the majority of commercial exergame development has come from the console game system manufactures. The exercise component of the system has been used as a selling point to sell what essentially are video games with an exercise component. The effectiveness component of the exergame system, the quality of the exercise regime instigated by the system, has generally been neglected.

We are also now seeing exergame type systems developed by exercise equipment companies. Generally this appears to be an afterthought added to existing equipment to drive additional sales. Simple games are being added to treadmills, rowing machines and exercise bike, or in some cases connections are added to allow use with existing game console systems. Limited thought is given to how the games fit with or motivate the exercise – the attractiveness side of exergaming.

2.2 Existing Exergame Research

Now that we have given an overview of commercial developments, we turn the focus to developments in exergame research. Some studies have been performed on commercial exergaming systems, while others have been done on custom built exergame peripherals.

2.2.1 Adding Motivation to Exercise

Saelens & Epstein (1998) connected a television, a VCR and a video game console to an exercise bike. The bike required cycling in order to activate the other equipment. The study found that when given a choice of activities, the children studied were prepared to undertake the physical activity, cycling the bike, in order to access the desired activities of television watching, videos or video games. This was despite the option of undertaking other activities, such as reading or drawing, without having to use the exercise bike. The study concluded that the use of desirable activities, such as television and videogames, could be used to promote less desirable activities, such as physical exercise.

Goldfield et al. (2000) performed a similar study. In this case there was no direct feedback from the physical activity performed. Subjects accumulated points on a pedometer by performing physical activities. These points could then be redeemed at a later point for desirable activities, such as television or video games. This study also demonstrated that children would be willing to undertake physical activity, in order to obtain access to television watching and video games.

IJsselsteijn, et al. (2004) studied the motivational effects of an immersive system and the use of bio feedback in the form of a virtual coach providing instructions based on heart rate readings. They used an exercise bike based exergame system for their study on 24 employees at the Philips Research laboratories in Eindhoven, The Netherlands.

Computer generated feedback was projected onto a 1.60m by 1.10m screen. During the non-immersive sessions, the software showed an abstract picture of a racetrack in bird's eye view, with a dot indicating the position of the biker. In this variant the users did not use the bike steering to control the bike, nor did the speed of cycling directly affect the speed of the dot travelling around the track.

In the sessions classed as highly immersive, the software displayed a detailed first person view of a racetrack. The track advanced in direct response to the player cycling and reflected the speed of the cycling. The subjects had to use the handlebars on the bicycle to steer and keep on the track. Both of these variations were used with and without a virtual coach appearing on the screen to give instructions and feedback based on the player heart rate.

The study concluded that "In the highly immersive environment, where the presence experience was stronger, participants reported more interest and enjoyment". However, they did not find that the virtual coach providing feedback based on heart rate readings added to the enjoyment of the system's users.

In 2003 a study was conducted at Massachusetts Institute of Technology looking into the motivational elements of applying a video game to an exercise (MIT Technology Review, 2003). A recumbent exercise bike was connected to a PC for use in this study. The study was funded by a $30,000 grant from Microsoft's iCampus initiative. The students involved developed a motivational computer game called CycleScore. It was not possible to locate any published material on the outcomes of the study, so we cannot review the findings in this thesis.

Glen Raphael of the *Videogame Workout* website however, reported on the study and quoted some of their findings based on the FAQ published at the CycleScore project web site (Raphael, 2005), which no longer exists and thus cannot be reviewed. One of the findings mentioned by Raphael was related to the use of existing commercial games for an exergame system. Apparently the research showed that existing commercial games are too complex to be used in an exergame setting. They found that racing games typically being used in exergame systems did not work extremely well in the context of exercise.

> "The problem is, the player is too aware of the fact that their pedalling corresponds directly to the speed of their virtual vehicle. They are constantly concerned about pedalling enough to win the race, which sounds good in theory, but in practice, it just leads to a tiring experience. Not super-motivational. We've found that if you disassociate pedalling from speed (and even movement), you're more likely to distract the player, increase motivation, but still create a solid exercise experience." – as quoted by Raphael (2005).

It is unclear what the basis is for this finding. We consider this to be a likely finding, but it is possible that this outcome may have been based on anecdotal evidence rather than any actual research.

Warburton et al. (2007) studied the health benefits of interactive video game exercise. Subjects were advised to attend training sessions 3 times a week, but were free to attend when they chose. The training sessions involved the riding of an exercise bike. Half of the subject rode a Gamebike and played PlayStation 2 video games during the exercise sessions. The other subjects rode a traditional exercise bike and were not involved in the playing of video games. The subjects who were in the exergaming group attended the training sessions significantly more often than the traditional training group.

The results demonstrated that the use of a video game appeared to be a motivating factor for people to train more often. The health benefits seen over the six week period of the study, appeared to map directly to the increased attendance of the video game group. This demonstrates that the goal of increased health through additional exercise, which is motivated by the use of videogames, is achievable at some level.

2.2.2 Energy Expenditure in Exergaming

In Luke (2005) masters thesis *Oxygen cost and heart rate response during interactive whole body video gaming*, the author did a detailed examination of the oxygen uptake of participants playing the EyeToy® Groove game for PlayStation2®. Participants were fitted with a mouthpiece connected to a metabolic analyser in addition to a heart rate monitor. These devices were used to collect data through several sessions of play. Luke concluded that the energy expenditure was enough to meet the requirements for moderate exertion and could therefore be used as a legitimate form of exercise.

The video game used in the study involved the player performing body movements and touching specific parts of the screen, in time to a selected song, to gain points. Luke concluded that the short periods of exertion, being roughly two and a half minutes, with sizable gaps between, did not make the EyeToy® Groove game ideal as exercise. There were short periods of exertion, being roughly two and a half minutes, with sizable gaps between. What this highlights is the need to ensure that in order to be a practical form of exercise, it is important that the games be carefully designed with this purpose in mind.

Lanningham-Foster et al. (2006) followed up on this study by examining the energy expenditure of activity promoting video games, compared to standard video games and watching television. They used the Sony EyeToy® in their study as well as a Dance Dance Revolution (DDR) pad. Their study concluded that there was a significant increase in energy expenditure for activity promoting video games, when compared to television or traditional video games. Their study also draws the conclusion that this could be used as a potential method to help combat obesity.

Hoysniemi's 2006 dissertation (2006) was on the design and evaluation of physically interactive games. In this study she asks important questions on how physically interactive games should be designed. She looks at the areas of entertainment, usability and suitability. The results were mainly qualitative and used three case studies for the research. Two of the case studies used camera and audio based interfaces. The first was a game aimed at children, where the body movement is used to control a game character. The second was a martial arts game where the user fights on screen characters by using full body motion. Additionally in both of these games, shouting is used to control some aspects of the game play. The third case study involved the Dance Dance Revolution game.

Hoysniemi looked at the use of peer tutors as an evaluation method for testing the usability of the game. She also examined the use of the Wizard of OZ methodology to prototype vision based games, and a methodology for describing the children's movements recorded during the prototyping.

Hoysniemi then collected feedback from martial artists who played a martial arts based exergame game. The results showed that it was possible to use low-level computer vision to generate an immersive embodied game play that could be intensive physical training. It is important to note that Hoysniemi also states that the martial artists who played the game found the biggest drawback with the interaction model of the game was the lack of physical feedback.

The third case study was an international survey of Dance Dance Revolution players. The survey covered their background, attitudes and opinions in relation to the game, in an attempt to examine, among other things, the social and physical effects of dance gaming on players' lives. Interestingly the study points out that two of the key reasons for people continuing to play DDR were fun and exercise. Also the study showed that there is an extensive social element to the popularity of DDR with a large socially interactive community of players both online and offline.

A study of Wii Sports in 2008 (Lauri Bausch, Jason Beran, Sara Cahanes, & Krug, 2008) showed that both the Wii Tennis and the Boxing simulations generated increased energy expenditure over non-active video games. The study concluded that "Depending on the duration and frequency an individual plays Nintendo Wii, they may be able to meet or exceed the minimum weekly energy expenditure threshold." And additionally "...Wii Boxing attained a relative intensity that exceeded the threshold to provide cardiovascular benefits ..."

In 2008 the American Council on Exercise (ACE) funded a study into the physiological responses of players playing Wii Sports (Anders, 2008). The report showed that playing Wii Sports was better than sitting down, but was nowhere near the energy expenditure levels of the actual sports activities. “Wii Boxing was the only Wii game tested that would be considered intense enough to maintain or improve cardio respiratory endurance as defined by the American College of Sports Medicine (ACSM)”.

In 2009 Alexa Carrol, graduate program student of University of Wisconsin, La Cross, was funded by American Council on Exercise to perform a follow-up study with the Wii Fit. Her study entitled "Physiological Responses and Exercise Intensity of Nintendo Wii Fit" was summarized in the November/December 2009 issue of ACE Fitness Matters Journal (Anders, 2009). The data also found that using Wii Fit, not unexpectedly, involved more energy expenditure than playing normal sedentary video games. However what was most notable about this study is that it found that Wii Fit, which was touted by Nintendo as a fitness program, performed worse in terms of energy expenditure than previously released Wii Sports.

The summaries of the two studies published by the ACE have been widely cited in the popular media. Unfortunately the two articles, which quote extensively from the researchers mentioned as having performed the studies, do not clearly reference the source material. It is not clear if the results from the original studies were peer reviewed or published independently.

2.2.3 Other Research in Exergames

Smith (2005) performed a pilot study on a number of different exergames, with the use of 3 different exertion interfaces. They tested the Cat Eye Gamebike, the Sony Eyetoy® and Konami's DDR pad, with a varied set of games. They identified four areas which they felt were important in order to maximize engagement and physical fitness:

- Warm-up and cool-down activities;
- Management of game load times;
- The integration of physiological measures;
- Dynamic game play adjustment.

A group of researchers from the University of Washington, in the United States of America have done some research into using technology to promote physical activity (Consolvo, Everitt, Smith, & Landay, 2006). They performed a pilot study where participants compete against other members of a group to see who was more active during a predefined period. This involved the participants wearing a pedometer connected to a PDA. The steps taken during the day were compared amongst members of the group, who all competed against each other. The study undertaken was based on two groups of 4 and one group of 5 females aged 28-42. They proposed four key design requirements for technologies that promote physical activity. These were:

- Give users proper credit for activities.
- Provide personal awareness of activity level.

- Support social influence.
- Consider the practical constraints of users’ lifestyles.

It can be seen that all of these design requirements should be considered in relation to the design of exergames.

Researchers with the University of Texas in conjunction with researchers from the Marshfield Clinic research foundation and the Mayo Clinic, have also commenced on similar research (Fujiki et al., 2007). The study is using accelerometers combined with PDA’s to measure activity performed during the day. The PDA displays the results in real-time on a computer generated race track. The race track shows the competing members of a group as animated figures on the race track, where activity dictates the distance covered around the track.

Lund et al. (2005) have developed a rubber tile based system for building physically interactive games, known as the PlayWare platform. In order to facilitate physical interaction, each tile contains a set of four different coloured light emitting diodes (LEDs), which can combine to generate eight different output colours, and the ability to produce simple sounds. A force sensing resistor is mounted in each tile to provide an input method, generally activated by being stepped on. Each tile also contains its own internal microprocessor and connection ports along the edges to allow the connection of the tiles, and to facilitate communication between the tiles.

The authors’ document two different games that were constructed for the system. One called *Color Race*, involved the participants moving around the tiles to press the sensor for the tile which is lit with a particular colour. As a tile of a particular colour is pressed, a new tile would light up with that colour. The participants raced against each other to be the first to press ten tiles of their particular colour. In the second game called *Ping Pong*, a coloured light moves back and forth across the tiles in a pseudo random manner. The participants needed to step on the appropriate edge tile in order to get the coloured light to move back towards the other edge of the tile arrangement.

Yannakakis et al. (2006) developed a game for the PlayWare tile platform called Bug Smasher. In this game the player needed to step on the lit tiles, which represented bugs, in order to squash the bugs. As bugs are squashed, more bugs appeared in a controlled manner. The authors experimented with the modification of the bug generation parameters, to determine which combination constituted the most enjoyable game. The games were evaluated by having players play two versions of the game with different settings, and then rate the two games against each other, indicating which game was more fun. They study mapped the changes in the bug generation algorithm, to three factors, challenge, curiosity and fantasy. It demonstrated that increases in the fantasy factor of the game made it more fun for all of the players, while the most enjoyable balances of challenge and curiosity were dependent of the particular individual player.

Mueller, Agamanolis & Picard (2003) have done some research on the social aspect of exergaming systems. They hold the belief that the addition of physical exertion to social interactions can help in the forming of social bonds, for example during the playing of sport. As a lot of social interaction is now occurring over long distance, they considered these interfaces lacking since there was no opportunity for exertion in the interaction. A system which allowed the playing of physically interactive games with others over a distance was designed and developed for the study. The study involved a game where video cameras tracked the motion of a ball that was kicked at a wall. This system was used to interactively play a breakout style of game with other players over a long distance. The feedback from players playing this game was then compared to players plying the same game, but using a keyboard based interface. The study did find that players reported a higher social bonding occurred using the physical exertion interface.

Tucker (2006) has developed a physically interactive version of Tetris. The system consists of a set of weights which are lifted by pulling down on either of two handles. The corresponding handle is pulled down with the left or right arm in order to move the Tetris piece left or right, while pulling both handles together results in the piece moving downwards. One important concept that Tucker expresses in his design of the system is the removal of any timing constraints. The normal automatic advancement of the Tetris pieces is removed from the system. Tucker explains how the slower paced games may be much more suitable for exercise based games.

Most existing exergames systems are based on aerobic exercise. Tucker feels that resistance based exercise, such as weight training, may be more suitable for the causal exerciser. These types of exercise are generally not performed against the clock and as such, when integrated into an exergame, require games where speed is not a factor. Within this study no evidence is presented to support the idea that resistance based exercise is more suited for exergames.

Tucker performed user testing of the system with 15 users and found that the user response to the system was overwhelmingly positive. While some facets of the game and control system were found to be slightly confusing, in general the players were successfully engaged by the system. It is interesting to note that they recorded the fact that many users expressed a desire for more multimedia feedback.

A study of video gamers playing Wii Boxing (Marco Pasch, Nadia Berthouze, Betsy van Dijk, & Anton Nijholt, 2008) concluded that there were significantly different playing styles resulting in different energy expenditure levels during the play. This study was in two parts. First part of the study consisted of interviews of four experienced game player. The authors conclude from the interviews that there are two different strategies involved in the play, which are associated with two different motivations for play.

The second part of the study used an inertial gyroscopic motion capture suit to track the movements of ten different players as they played Wii Boxing. From the motions of the players, the play styles were categorised into three distinct groups. These groups were loosely mapped to the identified motivations and strategies. The small sample size used in this study makes the classifications of the play types of limited value; however it does clearly demonstrate the notion that different players may play the same games in significantly different ways.

Muller et al has done significant research into the potential social interaction benefits which can be achieved through the use of exergames in a networked environment (F. Mueller, et al., 2003; Florian ‚Floyd' Mueller, 2007). Exercise as produced by an exergames system can be a means of promoting social interaction between individuals who are not co-located.

A three player exergame system called Table Tennis for Three was developed by Muller et al (2009). The equipment used for the exergames system resembles a standard table tennis board with the opposing side extended into the vertical position. Three players in different locations each use a similar system at the same time. Video footage of the players is projected onto the back board of the table tennis table. Superimposed on the video footage is a series of semi-transparent bricks. These bricks are progressively removed by the player by striking sensors in the back board with the ball during table tennis play.

This system was used to demonstrate that physical play can facilitate more social play, in comparison to button-pressing gaming and in addition showed the existence of a relationship between exertion and social play.

Using another system called Remote Impact – Shadowboxing over a Distance Muller et. al. (2008) further investigated the relationships between exercise within the context of an exergame and social interaction. The Remote Impact system consists of an interface which resembles a mattress placed vertically against a wall. Shadows of the both the local and remote player are projected on to the interface. The player strikes the shadow of the remote player while attempting to avoid having his own show struck by the remote player. The physical intensity of the game contributes to general fitness, weight loss, and stress relief at the same time it allows you socialize and create new friendships over a distance in an entertaining sportive way.

Muller et. al. (2010) looked the effects of design on the relationship between exertion and social aspects though the use of a system called Jogging over a

Distance. Jogging over a distance provide an audio communications link between two joggers. The Audio information was spatially located ahead, behind or next to the jogger based on the difference between the joggers' heart rates and target heart rates. The paper found evidence that the technology design can facilitate the relationship between social and exertion aspects and provides guidance for designers who want to facilitate social experiences by adding exertion to an interaction, or enable social aspects to existing exertion games.

2.2.4 Use of Biosensor Feedback

Buttussi (2007) has developed two physically interactive video games where the player heart rate is monitored. The game play intensity adjusts in order to maintain the player at the desired heart rate. One game involved the player doing squats to move a continuously firing space craft up and down in order to shoot enemy space craft approaching from the side. The second game involved the player doing jumps to the left and right to control a breakout style game. An initial subjective analysis of the system by eight players indicated that the games had the potential to motivate the player to perform more physical activity.

Nenonen et al. (2007) developed an exergame system which also uses heart rate feedback to control the game. No specific exercise was prescribed for this system. The players interacted solely though heart rate and the pressing of a fire button on a hand held controller. Any exercise which raised the heart rate could be used with the system. During this study, difficulty with the initial finger mounted heart rate monitor resulted in the requirement to have a person manually read and enter the heart rates into the system.

The study successfully demonstrated the ability to control a game using heart rate; however the sessions were all two to five minutes in length. It would be interesting to see how well the system work, with very limited control over the exercise, over longer sessions.

Stach, Graham, Yim, & Rhodes (2009) built an exergaming system based on the use of a recumbent exercise bike. They designed the system to use heart rate measurements as a scaling factor, in order to make people of different fitness levels equally competitive in a multi-player system.

The study indicated that the scaling worked well when the subjects were of different skill levels. When subjects were of similar skill levels and had close race results in unscaled competitions, the scaling tended to produce results which were less competitive, that is further apart. During this study the races were all around 1.5 minutes in length which is quite short when looking at heart rate responses. It would be interesting to see how well the scaling system worked on longer play sessions.

2.2.4.1 Commercial Product with Biosensor Feedback

In 1998 Amtex released a version of Tetris for the Nintendo 64 which worked with a biosensor. The game shipped with a heart rate sensor that clipped onto the ear of the player. Based on the player heart rate the game would either slow down or speed up. The game was only released in Japan and the biosensor component was not viewed favourably by reviewers. “Truth to be told, the biosensor is a neat little gimmick for health freaks, but it does not really add much to the whole gameplay experience. It's a cool extra, but we wouldn't want to pay extra to get it.” (Schneider, 1999).

2.3 Summary

From the existing literature we see that exergaming systems have the potential to help address the current obesity problem. Some motion at all is better than nothing; however we have seen that in some exergames the energy expenditure is quite low. If these games are seen by some people as a replacement for other physical activities, then the exergaming system can have a negative impact on health incomes.

Studies indicate that video games can be a motivator for increased physical activity, but there is no literature to indicate that long term it would have a significant influence on motivating people to exercise. The current anecdotal evidence indicates that some of the released exergame systems have a very short motivational period. We can speculate as to whether is potentially possible that the video game component of some exergame systems would be a de-motivator and discourage repeated play. Even though this gap in long-term studies has been identified, this thesis does not address it directly.

There appears to be no literature or studies in which different exergames as a whole have been compared. There are some studies which examine the energy expenditure of different systems, but they do not comment on the motivational aspects of the games in question. What our study attempts to do is to compare similar exergames by carefully controlling certain aspects of the system. The aim is to demonstrate some of the important factors in the design of exergames that can successfully help address the current obesity problem.

3 The Problem

From the existing literature, we can see that exergaming systems have the potential to help address the current obesity problem. Existing research has shown us that it is possible to make an exergaming system that causes enough physical exertion to be used as a legitimate form of regular exercise. The existing research also allows us to conclude that for some people, video games in the form of an exergame would be a significant means of motivating them to perform physical exercise.

In the past, the success of exergaming systems has been varied. Some systems have been relatively successful and others have not. The field is now at the point where we need to start building exergaming systems with the knowledge required to make the success and usefulness of the system, less of a hit or miss proposition and more of an understood quantity. Unfortunately there currently only exists limited research into how to design and develop exergaming systems. There is a clear need for some guidelines to be developed indicating how to build an exergaming system with a reasonably high chance of success.

In the course of this research we put forward a model for the development of exergaming systems. The model is tested to provide insight into the best methodologies to use in the successful development of exergaming systems.

3.1 Dual Flow Model

Having looked at the current state of research in the field has led to the conclusion that there are two key factors in the success of an exergaming system, namely, the concepts of effectiveness and attractiveness as introduced in 2.1.5. The most important outcome for exergaming systems is (arguably) to achieve health benefits. We call this the *effectiveness* of the system. The other key feature for an exergaming system is to be fun. The system needs to make people want to play the game or games, in order to motivate the user to exercise. We call this factor *attractiveness*.

3.1.1 Effectiveness

Effectiveness is the measure of how effective the exergaming system is in actually increasing or maintaining physical fitness. For healthy aerobic activity the American College of Sports Medicine (American College of Sports Medicine, 2006) recommends the following:

- Exercise 3 to 5 days each week
- Warm up for 5 to 10 minutes before aerobic activity
- Maintain your exercise intensity for 30 to 45 minutes
- Gradually decrease the intensity of your workout, then stretch to cool down during the last 5 to 10 minutes

In general, an exercise program must consider the mode or type of exercise, as well as the combination of duration, intensity and frequency. According to the American College of Sports Medicine, exercise can be performed for longer periods at lower intensity, or for shorter periods at higher intensity. Exact duration, intensity, and frequency depend on the individual. Additionally, the work-rate required to attain the required intensity of exercise depends on the physical capacity of the individual.

The intensity at which you exercise reflects the amount of oxygen your body uses to do an exercise, which can be used to calculate the number of calories you burn while doing it. In aerobic activity, such as walking, swimming or cycling, exercise intensity translates into how hard the activity feels to you. As a general rule, moderate-intensity activity is best. If you exercise too lightly, you may not meet your fitness or weight-loss goals. If you push yourself too hard, you may increase your risk of soreness, injury and burnout. Moderate-intensity activity decreases these risks and may even increase the odds that you'll continue your exercise program in the long run (Mayo Clinic, 2009).

The intensity of a particular exercise differs based on the individual involved. Not only does the intensity vary for different individuals, it also varies for the same person over time, as their fitness levels vary or they as they succumb to exhaustion.

For an exergaming system to be effective it must be able to adapt to changing requirements in exercise intensity. To maximize effectiveness, the system must be capable of providing the appropriate level of exercise intensity for the correct durations, as well as providing warm up and cool down periods - the exercise work rate must be correctly matched with the current physical capacity.

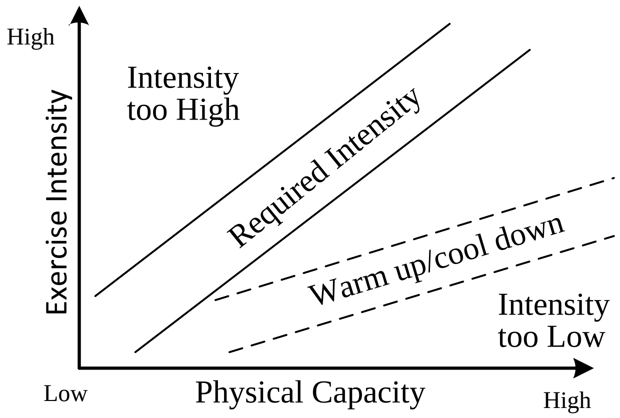

Figure 4 Control model for exercise effectiveness

As shown in Figure 4, we need to keep the intensity at the correct level for the individual through the control of the work rate. The physical capacity of the participant is essentially their general level of fitness. In the short term we see the physical state of the player deteriorate due to fatigue during exercise. The work rate may need to be reduced to accommodate this. Over the longer term, the normal physical capacity of the subject should increase as their general fitness level improves.

A key concept of intensity control is that the characteristics of exergame system players differ widely, and also change over time. Players could be nearly anywhere on the model shown in Figure 5. Building a one setting fits all system is very unlikely to be successful. The correct level of work rate must be set to suit the individual player at the current point of time. This cannot be done without careful monitoring and controlling of the parameters in the system.

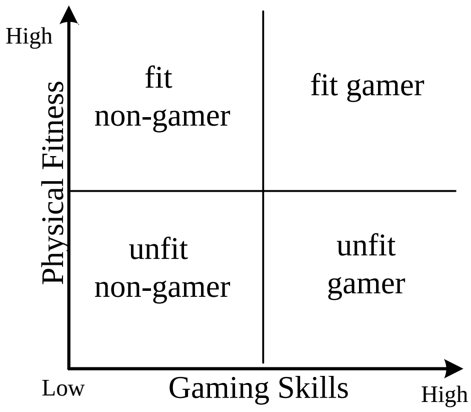

Figure 5 Player positioning on the control scales.

3.1.2 Attractiveness

Attractiveness is a measure of how much people want to play or use the exergaming system. This is essentially an answer to the question: how much fun is it to use the system? In a study of young adults aged 18 to 27, who play Dance Dance Revolution (DDR), a popular exergaming system, it was found that the top reason for playing was to have fun (Lieberman, 2006).

A key component of an exergaming system is engaging game-play. One of the central tenets of the exergaming concept, to provide additional motivation for exercise, is sadly disregarded if game-play does not marry with the fitness side of the exergaming system. In order to be successful, the game play of an exergaming system must be able to sustain the duration and frequency required to make the exercise effective. Game play that becomes repetitive after a short period is unlikely to provide additional motivation over the longer term required to make exercise effective.

In order to provide the appropriate game play, the question that needs to be answered is what makes a game fun? In the early 1980's, Malone (1980, 1982) carried out a number of psychological studies focused on what makes computer games fun. He identified three qualitative factors affecting the entertainment level of computer games; challenge, curiosity and fantasy. These factors were used by Yannakakis et al. (2006), to examine different variations of their games on the PlayWare platform. It demonstrated that increases in the fantasy factor of the game made it more fun for all of the players. However, the optimal balance between challenge and curiosity were dependent on the individual player. This idea that the attractiveness of a game is dependent on how it matches the player is also supported by the "flow" construct developed by Csikszentmihalyi in 1975 (S. Jackson & Csikszentmihalyi, 1999).

3.1.2.1 Flow

Flow is the state of maximum engagement in an activity. It is the equivalent to what is called in the sporting world "being in the zone". There are nine components of the experience of "flow":

1. The merging of action and awareness.
2. Clear goals (expectations and rules are discernible and goals are attainable and align appropriately with one's skill set and abilities).
3. Unambiguous feedback (successes and failures in the course of the activity are apparent, so that behaviour can be adjusted as needed).

4. Concentrating and focusing, a high degree of concentration on a limited field of attention (a person engaged in the activity will have the opportunity to focus and to delve deeply into it).
5. A sense of personal control over the situation or activity.
6. A loss of the feeling of self-consciousness (no feelings of self-doubt or self-concern).
7. Transformation of time (one's subjective experience of time is altered).
8. Autotelic experience (the activity is intrinsically rewarding - it is undertaken for its own sake).

The flow concept has been applied in many different domains, including several that relate to exergaming: sports, education and video games. Chen (2007) emphasizes the importance of maintaining flow within video games. In Chen's paper, he presents an outline of flow and then does a brief examination in relation to video games. His central theme in relation to flow in video games, is that to make skills and challenges balance out, different game players need to be offered different experiences from the video game in question. Chen (2007) sees the solution to this a matter of having choices within the game. However, he points out that it is more than just offering the users a choice; the choices need to be intrinsic to the game itself.

Sweetser et al. (Sweetser & Wyeth, 2005) present a modified version of flow, specialized to the video game domain, called "gameflow". The components of this model are:

1. Concentration - games should require concentration, and the player should be able to concentrate on the game.
2. Challenge - games should be sufficiently challenging and match the player's level of skill.
3. Player skills - games must support player skill development and mastery.
4. Control - players should feel a sense of control over their actions in the game.
5. Clear goals - games should provide the player with clear goals at appropriate times.
6. Feedback - players must receive appropriate feedback at appropriate times.
7. Immersion - players should experience deep but effortless involvement in the game.
8. Social interaction - games should support and create opportunities for social interaction.

The listed characteristics of flow (and gameflow) can be divided into elements that can be controlled directly by the game designer to affect player state, and elements that are simply artefacts of the flow state. For example: clear goals, direct and immediate feedback and balance between ability and challenge are elements that can be built into the game explicitly and tuned. Concentration, loss of self-consciousness, and a distorted sense of time are characteristics of the player that are present when the tuneable parameters have been set at the right levels. Nevertheless, the design of exercise based games needs to take both categories of elements into account.

Although flow is defined as a multidimensional construct of the nine dimensions mentioned above, Csikszentmihalyi has primary relied on the challenge-skill balance dimension as a key measure and predictor of flow (S. A. Jackson & Eklund, 2002). Csikszentmihalyi’s flow is very similar to the Individual Zones of Optimal Functioning (IZOF) Theory (McCune, 2006). IZOF theory studies optimal experience as a function of the interaction of performance and arousal. These ideas are both supported by one of the key laws of psychology, the Yerkes-Dodson law. The Yerkes-Dodson law demonstrates an empirical relationship between arousal and performance. It dictates that performance increases with cognitive arousal but only to a certain point: when levels of arousal become too high, performance will decrease (Teigen, 1994).

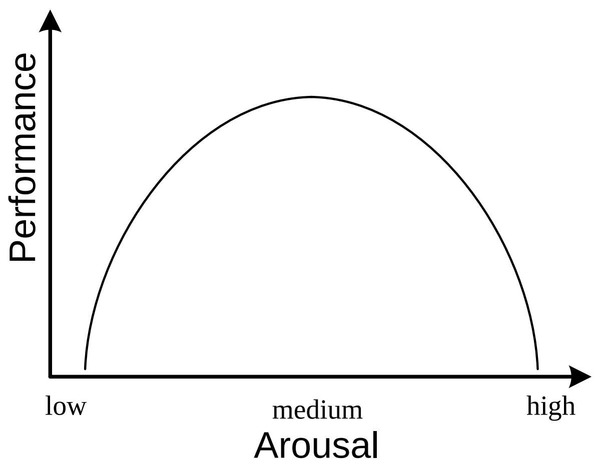

Figure 6 Yerkes-Dodson Law of psychology

The original flow model by Csikszentmihalyi as shown in Figure 7 is often used to explain the central skills versus challenge side of the equation.

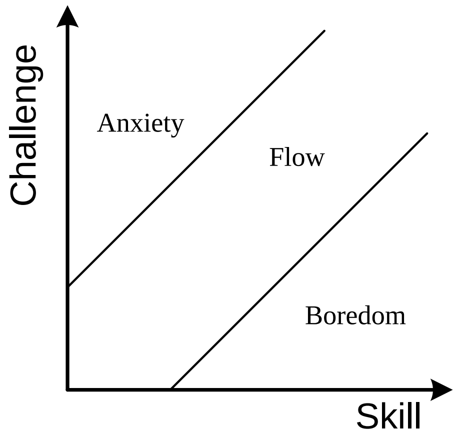

Figure 7 Early flow state model

The flow model demonstrates that in order to find flow, the level of challenge must be proportional to the level of skills. If the challenge is too high then anxiety will set in. If the challenge is too low then boredom will occur. The problem with this early model is that flow does not occur for low levels of skill and challenge, even if they are in balance. Csikszentmihalyi later postulated that the starting point for flow is when challenges and skills go beyond a person's average levels of skill and challenge. This resulted in a revised model shown Figure 8.

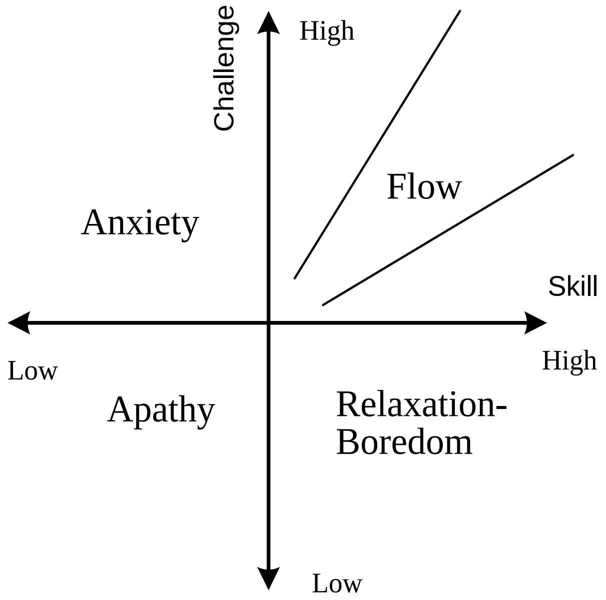

Figure 8 Model of the flow state (S. Jackson & Csikszentmihalyi, 1999)

3.1.2.2 Flow Measurement

There are several different methods used to measure flow. The experience sampling method (ESM), as related by Voelkl and Ellis (1988) involves the filling of self-reporting forms based on skills and challenges at periodic times. The user is periodically signalled in some manner to stop and record their feelings, or state, at the current point in time. This methodology does not fit well with an exergame system as it is based on recording feeling at exact times. It would be difficult to stop an exergame player continually, in order to get their temporal feelings during the middle of a gaming session.

The Flow State Scale (FSS) is a measure of flow in sports activities (Tenenbaum, Fogarty, & Jackson, 1999). It uses a 36 question Likert response format self-report, which addresses the nine key dimensions of the flow construct. They subsequently developed the Dispositional Flow Scale (DFS) which focuses on the frequency of the experience of flow. This is because Csikszentmihalyi has suggested that certain types of people are psychologically better equipped to experience flow, which can lead to individual differences in the flow experience (S. A. Jackson & Eklund, 2002).

The idea of matching challenge to skills can be applied to video games. “Games are boring when they are too easy, but frustrating when they are too difficult” (Hunicke, 2005). “Too much challenge and players got frustrated and quit. Too little challenge and players got bored and quit”. (Tolentino, 2008). As noted by Pagulayan, Keeker, Fuller, Wixon, & Romero (2007), challenge is a critical factor to the enjoyment of a game, and obviously can be highly individualized. Bailey & Katchabaw (2005) state that it is simply impossible for developers to deliver a game with an appropriate level of challenge and difficulty to satisfy all players using conventional techniques.

3.1.2.3 Dynamic Difficulty Adjustment

To maximise the attractiveness factor of an exergame, that is make it motivating, the level of challenge needs to be matched to the skills level of the player. In order to do this the challenge level of a game can be dynamically adjusted to correctly match the skills of the players. This process is what is known as *dynamic difficulty adjustment*(DDA). The correct application of DDA can be used to help the player achieve the flow state (Pagulayan, et al., 2007).

Dynamic difficulty adjustment has been increasingly recognized by the game development community as a key characteristic for a successful game (Liu, Agrawal, Sarkar, & Chen, 2009). There are many different ways to implement dynamic difficulty adjustment within a video game. It may be through the changes to the way computer characters behave, the number of enemies, the abilities of the player's characters, difficulty of puzzles or via various other factors within the game. The DDA can be applied continuously or at set points within the game, it may be overt or it might be quite subtle. There have been various commercial games which have implemented DDA, some successfully and some not so successful. Some DDA examples are discussed below.

The third person shooter Max Payne, by Finnish Remedy Entertainment, is known for its fairly successful implementation of DDA. The game very slightly adjusted the level of aim assistance you got, and increased enemy health slightly depending on your projected skill level and success (Tolentino, 2008). The term *Rubber Banding* is applied to one form of dynamic difficulty control (TV Tropes, 2010). Commonly used in racing games and some sports games, this technique involves adjusting the game so that regardless of the player skill levels, the player always remains in a competitive position relative to the game controlled opponents.

The Game Oblivion from Bethesda software is a single player role-playing game where players build up their character through the completion of different activities. The other computer-controlled characters within the game have their abilities scaled up according to the current level of the player. This was criticised by many players. According to Tolentino (2008), it significantly damaged your sense of growing power and progression.

Most existing work on DDA is centred on player performance, with the aim of increasing player enjoyment. Liu et al. (2009) looked at DDA from the point of view of the physiological signals produced by the player. They used biological feedback sensors to measure cardiovascular activity, electrodermal activity and EMG activity of subjects playing a particular game. They developed a satisfaction rating for players based on perceived challenge, enjoyment and perceived performance. Their study showed that the 15 subjects in the study had higher satisfaction ratings than when using the same game where the difficulty was controlled by player performance.

Unfortunately, when it comes to exergame systems it is generally not possible, or practical, to use biological measures to evaluate player satisfaction with the game. The act of exercising causes physiological responses of a magnitude that will completely mask physiological responses caused by the player mental or emotional state. For this reason currently we are limited to in game measurements of player performance when doing dynamic difficulty adjustment in exergames.

It is acknowledged that dynamic difficulty adjustment is important, but when done badly, it can be a negative impact to the enjoyment of the game. Many of the issues that people have with dynamic difficulty adjustment, such as feeling cheated or the ability to exploit the system though deliberately bad play (Adams, 2008), appear to be associated with overt difficulty adjustments which are visible to the player. A quality DDA implementation should not result in changes to the challenge levels which are obvious to the player.

For this study the DDA is kept fairly simple. It is deemed sufficient to show that the DDA improves the player enjoyment of the exergame. While perhaps not achieving the ultimate goal of perfectly balancing the skills and challenge, we intend to show that the result of our attempt to balance the skills and challenge produces a better outcome for our exergames.

3.2 Control System

In order to develop an exergaming system that addresses the two key factors of effectiveness and attractiveness, implementing the Dual Flow Model, we need to control two factors. We need to control challenge to produce the flow state, and additionally we need to control work rate to manage the intensity of the exercise.

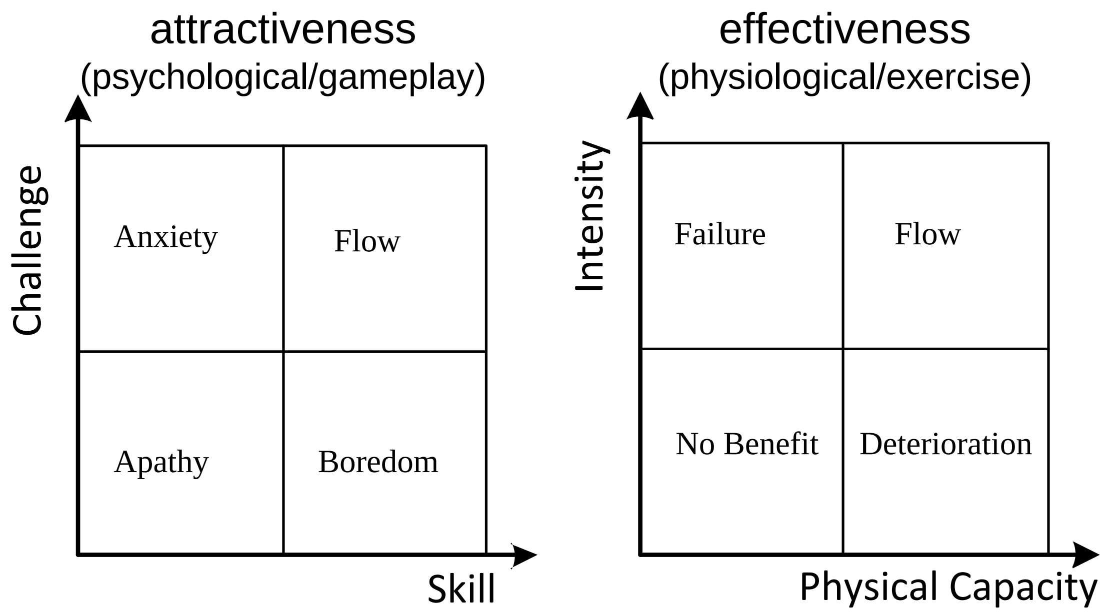

Figure 9 The Dual Flow Model for exergames. Challenge and skill need to be matched as well as intensity with physical capacity.

The Dual Flow Model, as shown in Figure 9, encompasses the two dimensions of attractiveness and effectiveness of the exercise. The attractiveness of an exergame can be modelled by the standard flow model from Csikszentmihalyi (1975). 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 physical capacity (the body's 'skill' in tolerating exercise), and intensity (the challenge of the exercise on the body). In the dual flow model, we also apply the concepts of the flow model from Csikszentmihalyi (1975) to the effectiveness dimension of exergaming.

3.2.1 Balance in Attractiveness

The left part of Figure 9 illustrates the standard skills versus challenge balance of the flow model, which can be represented by 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.

3.2.2 Balance in Effectiveness

The balance between intensity and physical capacity is represented in a similar four-quadrant balance model in the right part of Figure 9. If intensity and physical capacity 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 physical capacity 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 physical capacity exceeds the exercise intensity, there is also potential for the participant to enter a state of deterioration where the fitness level will drop.

3.3 Role of Feedback in the Dual Flow Model

The key requirements in the Dual Flow Model for exergaming are the balance between skill and challenge, and between physical capacity and intensity. Games that are not designed for exercise need only consider the skill/challenge balance. Commercially, such computer games try to achieve this balance through extensive play testing. Through play testing, levels of challenge are determined to suit the target audience. In exergaming this fixed matching of difficulty level to player capacity is less effective. Factors influencing success in an exergame involve not just the player reflexes and game experience (attractiveness), but also the player’s physical condition (effectiveness).

Tuning each successive level of an exergame to achieve a balance of player skill, level of general fitness, and current physical tiredness becomes problematic. The general assumption with traditional computer games is that the player’s skills increase with playing time and so difficulty level is increased accordingly. In exergames, while skills might also increase with duration of play, lengthy sessions at increasingly harder intensity will lead to exhaustion and failure. This difficulty of setting the right balance could be another reason why seemingly similar systems enjoy quite different levels of commercial success. One way to avoid this problem is to construct games with relatively simple mechanics that focus on the input device rather than the game. These simple games, such as Dance Dance Revolution, make it less costly to develop a wider variety of difficulty levels (e.g. choosing a different set of dance steps for a song) where one is bound to suit whoever is playing. Another option is to make the game adaptive to the player.

If it is desired for the game to be the centre of attention, rather than making the game appeal to the widest user base possible it becomes practical to somehow monitor the player's skill level, and modify the difficulty of the game adaptively. Thus we see that feedback plays a central role. Rather than just the simple feedback of clearly indicating success or failure to the player, feedback from the player relating to fatigue, exercise level, and boredom should be used to infer the player's current physical state and adjust the level of challenge accordingly. Experiments with the Bug Smasher game on the PlayWare platform (Yannakakis, et al., 2006), where player preference was deduced by the style of play is an example of one such feedback driven adaptive system, in this case on the psychological dimension.

3.4 Research Aims

The aims of this research are to test the validity of the proposed Dual Flow Model, with particular emphasis on the importance of the need to control both flow and exercise intensity for an exergaming system. The research covers the following three key ideas:

That the control of challenge levels to match skills provides improved motivation and indirectly leads to improved fitness outcomes.

The careful control of exercise intensity levels within an exergaming system leads to better fitness outcomes.

The application of control, to both the motivation and the exercise components of an exergaming system produce better fitness outcomes than control of only one of the factors.

In this research, we set out to show that exergame systems have two important factors; attractiveness and effectiveness. These two factors when managed correctly lead to better quality and more successful exergame systems. In this study we have developed an exergame system where we control the two factors of attractiveness and effectiveness. By varying the mechanism for the control of these factors, we produce four variants of the same system. Subjects will use each of the different systems. Using a series of self-assessment questionnaires and recorded play information, we then demonstrate the importance of the two factors.

In this research we have we have not actually tested for fitness benefits. Instead we have concentrated on attractiveness, relying on the proper design on the workout plus attractiveness to indirectly improve effectiveness.

The given aims also lead to a number of follow-up questions. Can we use the control of the challenge level to produce the flow state? Does the achievement of the flow state better motive the player? Does the additional motivation of the player produce better fitness outcomes? Does rigorous control of exercise intensity within the game session generate significantly better fitness outcomes compared to constant work rates? This research will help us work towards formulating answers to these questions.

3.5 Summary

The field of exergaming requires research into the successful design of exergame systems. In order to develop successful exergame systems we have put forward the Dual Flow Model. The model expresses the need to balance and control the two core parts of an exergame system; effectiveness and attractiveness.

The model postulates that effectiveness can be maximised by matching exercise intensity with the physical capabilities of the game player, and attractiveness can be maximised by matching game challenge with player skill. In this study, an exergame, which is based on the Dual Flow Model, was constructed. The system was designed so that the two key elements of the Dual Flow Model can be switched on and off. This will produce four different variants, or modes, for the system. The comparison of the subject's responses to the four different variants will allow us to test the assumptions of the Dual Flow Model. In the next chapter, we will look at how we built the exergame system.

4 Material and Methods

In this chapter, we will look at the design and development of an exergame system that implements the Dual Flow Model. First an overview of the game system will be presented. General designed principles and a design for exergame development will then be discussed. In the later part of the chapter, a discussion of the key parts of the design and its relationship to the different parts our exergame will be discussed.

4.1 The Study Exergame System

An exergaming system based on a Cat Eye Game Bike connected to a windows PC has been developed for this study. The game concept for the system used in this study is a classic 2D scrolling game. The player flies a helicopter that is boxed in above and below. The vertical thrust of the helicopter is linked to the cycle rate of the bike. The faster the player cycles, the higher the helicopter moves, and conversely the helicopter will drop down as the player cycling slows. The forward motion of the helicopter 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. This allows the game to have reasonably good control over the player cycling speed.

The player needs to adjust the height of the helicopter in order to stay away from the upper and lower boundaries of the play area. To encourage this, collectable items, in the form of round markers and letters of the alphabet, are adaptively placed in the level. The player collects the items by flying into them. When 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 different phrases.

Initially, we looked at allowing the player to attempt to influence the letters collected by using the steering controls of the bike in order to change the letters in the next sequence. Initial testing of the system showed that this made the game generally too complicated. It was difficult for players to control the up and down positioning correctly, while trying to determine letters required and adjust the upcoming letters to try and get the letters required. This functionality was removed for the trial in order to simplify the game play.

Sets of enemy characters, in the form of green aliens, fly through and attack the player. The player loses points by being 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 in order to shoot the aliens. Additional score is gained by shooting the aliens. Once the design was done, an initial version of the game was developed.

Figure 10 is a screen shot from the final system. The player helicopter can be seen to the middle left and is currently firing at the oncoming green aliens. The red brick like lines running across the lower part of the screen, form the floor and ceiling of the play area.

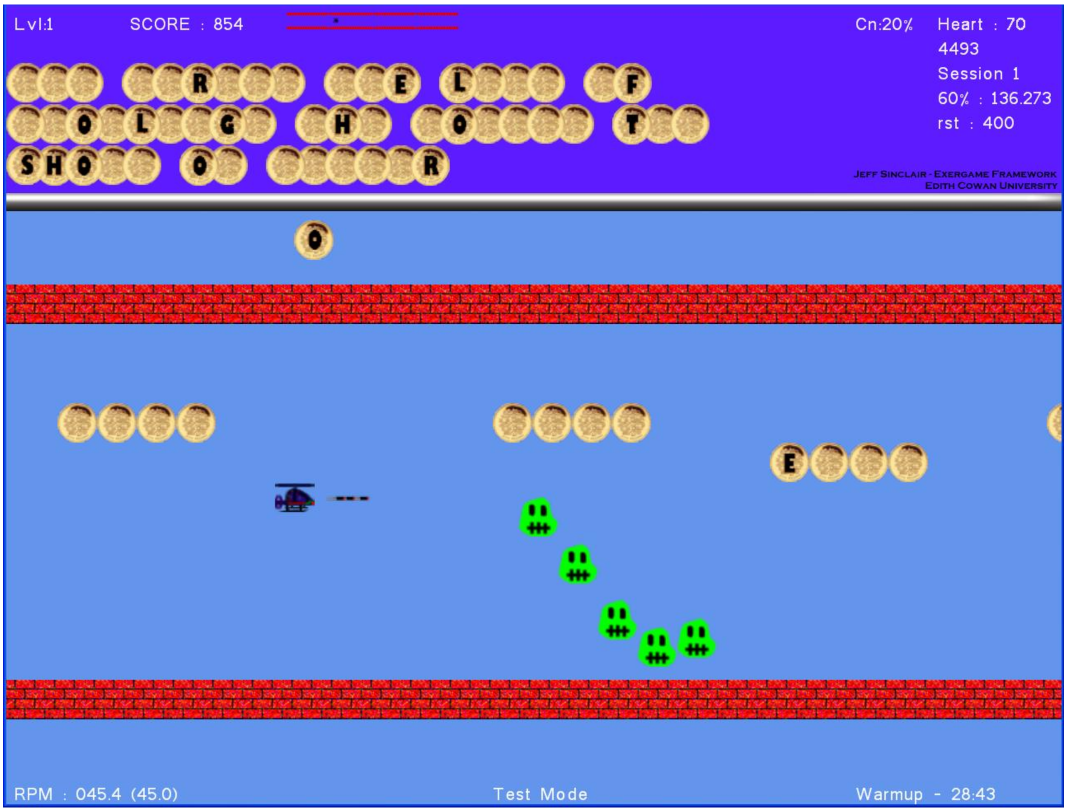

Figure 10 A screen shot from the exergame software.

In the top part of the screen the collected letters are displayed. The play area is also shown in miniature at the top of the screen to give players an indication of how far to the end of the level.

4.2 Exergame Design

To test the Dual Flow Model our exergame system will need to control the exercise intensity. The intensity at which someone exercises reflects the amount of oxygen the body uses to do an exercise and the number of calories burnt while doing it. In order to control the exercise intensity the system will need to monitor the intensity of the exercise workout.

4.2.1 Exercise Intensity Measurement

One of the best measures of exercise intensity is oxygen consumption (VO_2), measured in litres of oxygen per minute. Direct measurement of oxygen consumption is quite invasive and is not particularly suited to the exergame environment.

Three easier and commonly used methods of exercise intensity measurement are; heart rate; the rate of perceived exertion, normally using the Borg Scale; and the talk test, which evaluates your ability to carry on a conversation during exercise (Mayo Clinic, 2009). The need to continuously monitor intensity without undue impact on the game itself means that heart rate is the best practical measure of exercise intensity that is currently available for use with an exergaming system. Most commercial gym exercise equipment uses heart rate as a measure of exercise intensity.

Heart rate is correlated to VO_2 because the heart delivers oxygenated blood to the body. To deliver more oxygen, it must beat faster. Heart rate does not correlate as reliably to exercise intensity as VO_2, but does still provide a reasonably good measure of intensity.

Heart rate and its response to exercise depend on many factors. Even in the same individual, heart rate response depends on that person's physical state, including hydration, tiredness, the presence of caffeine or other drugs in the system, and the ambient temperature. A person's heart rate at a given intensity of exercise drifts upward over an exercise session (see 5.6.1.1). Over a longer period, changes in fitness alter both resting heart rate and response to exercise.

Considering all of these factors, for our study we have chosen to use heart rate as the measure of intensity during exercise. It is easy to measure with cheaply available equipment, and provides a pretty good indication of the exercise intensity being undertaken by the subject.

4.2.2 Game Modes

The system developed is designed so that it can run in several modes, allowing us to test the validity of the Dual Flow Model. The modes were designed around the two key components of the Dual Flow Model. The intensity control and the challenge control are alternately switched on or off in the different modes. By switching these components on or off, we generated the following four modes that the software can be used in:

Static (Mode S)

In this mode, the challenge or difficulty of the game increases gradually in a linear progression. The heart rate is monitored but only logged and does not affect the game. The workout intensity of the game follows a predefined pattern, based on the pre-defined plan calculated for the individual subject. The system is configured to achieve the desired heart rate at 70 RPM on the bike.

Intensity controlled (Mode I)

In this mode, the intensity is managed by monitoring of the player heart rate. The exercise intensity adjusts in order to achieve the desired heart rate of the player. The challenge or difficulty of the game increases in the standard linear progression.

Challenge controlled (Mode C)

The challenge or difficulty of the game is managed based on the success or failure of the player. If the player plays the game well, the game gets harder; alternately, if the player does not play well, the game gets easier. In this mode, the intensity follows the pre-defined plan and does not adjust based on heart rate.

Full Control (Mode F)

In the full control mode, both the games mental challenge and exercise intensity are both managed, in alignment with the Dual Flow Model.

The four different game modes can be summarised as follows in Table 1.

Table 1 Four different exergame modes generated by alternately switching the intensity control and challenge control on or off.

		Exercise Intensity	
		Intensity Steady	Intensity Controlled
Game Challenge	Challenge Linear	Static mode **(Mode S)**	Intensity controlled **(Mode I)**
	Challenge Dynamic	Challenge Controlled **(Mode C)**	Full Control **(Mode F)**

In addition to the 4 game play modes, the system has a fifth special mode where the game is not played. The intensity of the workout is managed based on the predefined plan. During this session, the subject maintains the correct RPM's to keep a marker centred in the screen, see Figure 11.

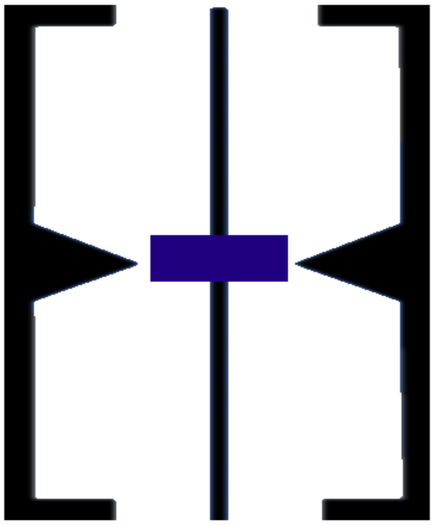

Figure 11 Exergame System RPM Marker used to keep subjects cycling at the correct rate. The blue marker (centre) moves up or down based on the RPM of the player. The player must focus on keeping the marker in the centre between the two arrows.

The heart rate is monitored and recorded in this mode but is not used to influence the intensity of the workout. This mode was used in setting up the system and also allows us to compare workout sessions using the game, with sessions where the game was not used.

In the remaining part of this chapter the exergame system, the design and how it was constructed are described in detail.

4.3 System Design for Dual Flow Model Exergame

The previously discussed Dual Flow Model indicates the need to control the exercise intensity as well as the need to manage the game difficulty. In this section, we discuss our system design for an exergame system based on the Dual Flow Model.

In order to build an exergame based on the Dual Flow Model, the game software component of an exergame system (Figure 1 c), can be broken down into the following four modules:

a. User Management Module
b. Exergame Control Logic Model
c. Game Play engine
d. Exergame Control Adaptor

The modules interact as illustrated in Figure 12.

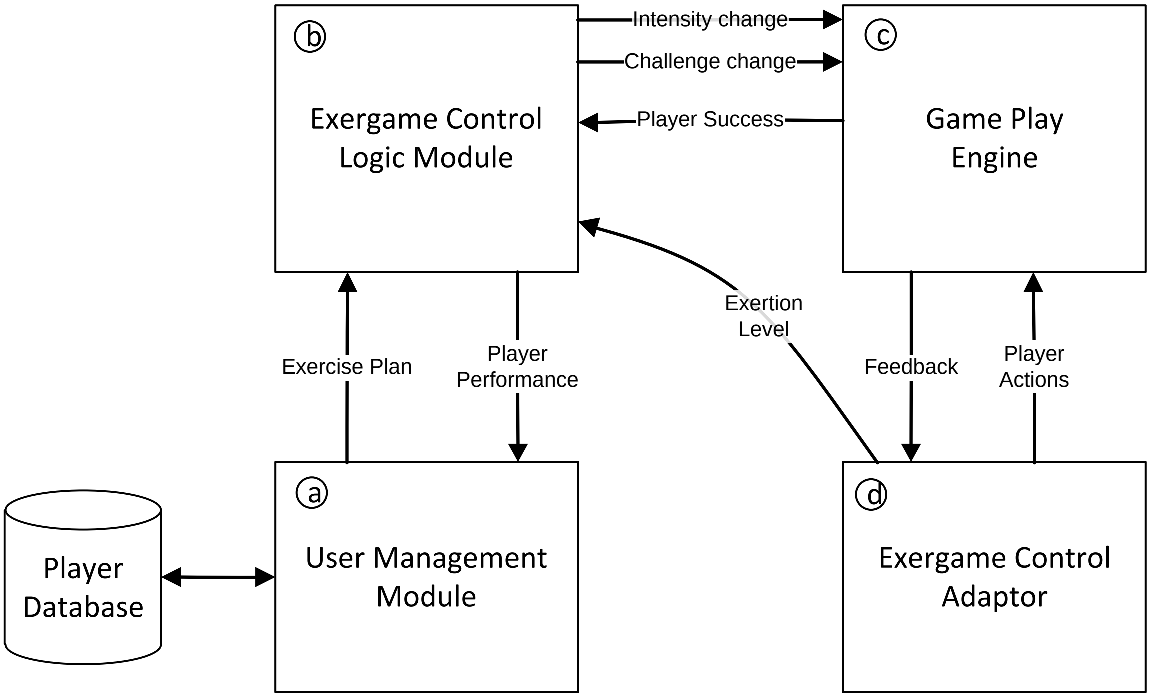

Figure 12 High level exergame system design showing the crucial components of an exergame system based on the Dual Flow Model.

Each of the sections of the Dual Flow Model based exergame system design is discussed in detail below. A description of the purpose of each module and how we implemented it for our exergame system is described.

4.3.1 User Management Module

In order to manage the interaction with each user of the exergame system it is important to know something about the user. This module, see Figure 12 a, is where user details are entered and the appropriate level of exercise required for the player is calculated. The module takes into account a number of factors to produce an exercise plan for the user. Our goal for this study is to have the player undertake modest exercise at about 60 - 75% of maximum heart rate, which is the appropriate amount for general fitness maintenance (McArdle, Katch, & Katck, 2007). This level of exercise is commonly referred to as *conversational exercise,* because it is not intense enough to prevent the participant from conversing with someone else during the exercise.

The module allows selection of the target intensity, as a percentage of maximal heart rate, for the workouts.

4.3.1.1 Maximal Heart Rate

In order for us to determine the target heart rate, we first need to know the maximal heart rate of the player. While ideally this would be a clinically measured value, for simplicity it is an estimated value. There are a wide range of general formulas for the estimation of maximal heart rate. The best known of these is 220 minus age. Robergs and Landwehr (2002) did a review into the history and origin of this formula. The 220 minus age formula is attributed to Fox, Naughton, & Haskell (1971). However it is indicated that the formula presented, 220 minus the subjects' age, was not formulated from original evidence. The original paper (Fox III, et al., 1971) was a review of research pertaining to physical activity and heart disease. Upon review of the data presented by Fox, et al. (1971), Robergs & Landwehr (2002) conclude that the data does not actually support the equation of 220 minus age.

Robergs & Landwehr conclude that while there is quite a range of different formulas for the prediction of maximal heart rate, there is not any that is particularly accurate. They determine that the formula by Inbar et al. (1994),

$$\text{Maximal Heart rate} = 205.8 - (0.685 * \text{age}) \tag{1}$$

is the most accurate, but it still has an error of ± 6.4 b/min. Despite this level of error we can still make use of this formula in our exergame system. In our exergame system we are attempting to find a reasonable level for our subject to exercise at. Since we are demonstrating the results of controlling the heart rate, and we are only looking for moderate exercise, the accuracy of the heart rate levels selected using the formula by Inbar et al. (1994), will be sufficient for the purpose of our study.

4.3.1.2 Desired Heart Rate Calculation

The selected percentage of maximal heart rate is used to calculate a desired heart rate for the player’s workout based on the Karvoen method (American College of Sports Medicine, 2006) as follows:

$$\begin{aligned} &\text{Target Heart Rate} \\ &\qquad = (\text{Heart Rate Reserve} * \text{Intensity}) \\ &\qquad + \text{Resting Heart Rate} \end{aligned} \tag{2}$$

Heart Rate Reserve is the difference between the resting heart rate and the maximal heart rate, calculated based on Inbar et al. (1994); effectively the range that heart rate can travel through. The intensity element is the desired percentage of maximal heart rate that we selected for the subject.

During the study, the resting heart rate was measured by taking the average of the last minute of readings, while the subject sat resting for five minutes on the exercise bike. This value was calculated once on the initial introductory session. This appeared to be reasonably accurate, however in hindsight it may have been useful to validate this measurement by taking a reading prior to each of the game sessions. There exist a number of short-term factors which can affect the resting heart rate. Some examples are current exhaustion level, time of day, prior intake of chemicals such as caffeine and nicotine, and the persons current emotional state. As we will see in later chapters, there were a number of subjects in the study who had starting heart rates that differed between the sessions.

In this study, we do not measure the long term health benefit of our exergame system. We are demonstrating that we can control the intensity in such a way as to get the subject working close to the set heart rate. A better setting for the desired heart rate might be more important when looking at long term health outcomes.

4.3.1.3 Module Inputs

As shown in the high level design, Figure 12, the player performance is fed into the player management module. Ideally this module should keep some historical records related to the skill and fitness levels of the player. This would allow the player to start the next game at an appropriate challenge level, rather than needing to wait for the system to adjust to his or her current skill level. Due to the short nature of the study and various time constraints, the history side of this module was not implemented for this study.

4.3.1.4 Module Outputs

This module is used to produce an exercise plan for the subject in question. Details about the player, such as age and maximal heart rate are stored in the plan. The warm-up, cool-down, exercise periods and intensities are all stored in the plan for the subject. In order to maximise the utility of the plans produced by the planning module, the plan information is serialized out to an XML file.

XML is a set of rules for encoding data electronically. By following these standardised rules, it is easier for the files to be interpreted by other software systems. In most modern computer languages there exists support for the handling of XML data. For each user of the system, a separate XML file containing details of their exercise plan is produced. This set of XML plans is what constitutes the Player database shown in Figure 12.

4.3.1.5 Player Identification

Due to the nature of this study, it was important that we do not identify subjects and that they remained anonymous. The system randomly generated a three digit number for each player when their details were entered into the system. We planned to use several of the exergame systems in the trial. To avoid any confusion the identifier assigned to each user needed to be unique across all the systems. In order to do this, each exergame installation was assigned a unique single digit identifier, which was prefixed on to each user's identification number. This allowed for easy identification of the system that the subject ID was generated on. If the user details needed to be transferred from one system to another, there was no risk of the user ID clashing with an existing ID in use on the new system.

The difficulty with using ID numbers is that they are difficult for people to remember. If during the trial a subject forgot their identification number, we needed a simple way to know which plan was associated with the user. For this reason, we created a mapping in the system between the user name and the users ID. This way the plan could be loaded by for an individual by name, but the plan information, logging and output were all recorded by user identifier.

4.3.2 Exergame Control Logic Module

This module is, in essence, the brains of the system; see Figure 12 (b). This module uses a number of algorithms to adjust the game to fit the Dual Flow Model as defined earlier. The aim is to manage the intensity and difficulty of the system in an effort to keep the game interesting while meeting the identified exercise goals.

4.3.2.1 Module Inputs

There are three inputs into this module as follows:

1. **A defined exercise plan.**

   This is developed by the user management module. This plan would indicate the desired exertion levels and time periods, including warm up and cool down. This would be loaded into the module at the start of the game play.

2. **The current exertion level of the player.**

   As covered in 4.2.1, we have chosen heart rate as the measure of exercise intensity for our system. We continuously feed this value from the exergame control adaptor into the control logic module.

3. **The success of the player in terms of game play.**

   In the model, we are not concerned with the absolute skill level of the player but rather the skill level of the player compared to the current level of challenge. What this means is that we can measure the skill level of the player in terms of how well they are currently succeeding in the game. This simplifies the process of measuring the skill of the player. A positive player success is used to indicate that the player skill is above the level of the challenge of the game. A negative value for the player success is an indicator that the player has a skill level which is below the challenge level of the game.

4.3.2.2 Module outputs

The module produces the following two outputs:

1. **Intensity change.**

   A positive value indicates that the exergaming system needs to increase the intensity of the current exercise being undertaken. A negative value would indicate that the current intensity is too high and needs to be lowered.

2. **Challenge change.**

   A positive value indicates that the challenge within the game needs to move up to a higher level to match player skill, while conversely a negative value would indicate the need to reduce the current level of challenge.

We now examine in detail how intensity and difficulty change are controlled by this module.

4.3.2.3 Intensity Control

The effective gravity operating on the player's helicopter character is altered by the game to act as a means to control the players work rate. If the player is cycling too hard (in terms of their target heart rate) then the gravity is reduced. The player is then forced to reduce the cycling rate to avoid crashing into the game area ceiling, and maintain the collection of markers for scoring purposes. If the player is cycling too slow and working below their target workout requirements, the gravity effect in the game is increased. This means the player will have to cycle harder to maintain the helicopter in the central area of the game screen and avoid crashing into the bottom of the game play area.

In our system, we use a proportional integral derivative (PID) (Sclater & Chironis, 2001) control loop as the feedback mechanism to control the gravity affecting the Helicopter. The PID control loop is a commonly used feedback control mechanism used in process control. The three components of the controller, proportional, integral and derivative are calculated based on the error in the current reading or Process variable (PV), when measured against the desired reading called the setpoint (SP). The Manipulated Variable (MV) is set based on the error in the current readings.

For our system:

PV = the current player heart rate.

SP = the desired player heart rate.

MV = the gravity affecting the player craft, and hence the heart rate.

The error between the actual and desired value is determined as:

$$\mathrm{e(t) = \ error\ (SP - \ PV)} \tag{3}$$

and K_p, K_i and K_d are tuning constants.

The new gravity is then determined using:

$$MV(t) = P_{out} + I_{out} + D_{out} \tag{4}$$

The *proportional* term, P_{out} makes a change to the output that is proportional to the current error value.

$$P_{out} = K_p\, e(t) \tag{5}$$

The *integral* term, I_{out} determines the reaction based on the sum of recent errors, and

$$I_{out} = \ K_i \int_{o}^{t} e(\tau)d\tau \tag{6}$$

The *derivative* term D_{out}, determines the reaction based on the rate at which the error has been changing.

$$D_{out} = \ K_d \frac{d}{dt} e(t) \tag{7}$$

4.3.2.4 PID Loop Development and Tuning

For our exergame system we used the standard symmetrical PID loop as above. However we initially implemented an asymmetrical PID loop. In this subsection we discuss the asymmetrical PID loop and its eventual rejection in favour of the less complex and more common symmetrical PID loop.

Based on Warner & Cox (1964) the heart rate response to exercise is thought to be asymmetrical; the heart rate in response to exercise will rise faster than it falls. In the case where the managed variable rises at a different rate to the rate that it falls, as in player heart rate, an asymmetrical PID loop can be used (SPLat Knowledge Base, 2009). An asymmetrical PID loop (aPID) was developed on this basis, using a different set of constants $K_p, K_i \; and \; K_d$, when the error is negative, or change in error is negative as opposed to positive.

$$K_p(t) = K_{pp}\, , K_i(t) = K_{ip} \;\; | \; e(t) \; \geq \; 0 \tag{8}$$

$$K_d(t) = K_{dp} \; | \; \frac{d}{dt} e(t) \; \geq \; 0 \tag{9}$$

$$K_p(t) = K_{pn,}\, K_i(t) = K_{in} \;\; | \; e(t) < \; 0 \tag{10}$$

$$K_d(t) = K_{dn} \; | \; \frac{d}{dt} e(t) < 0 \tag{11}$$

According to King (2011), there are 117 published methods for tunning PID loops however they all have flaws and limitations. They conclude that in the process industry “The majority of tuning is completed using experience and trial and error.” The constants for our PID loop were selected and tuned using a manual tuning process based on the prior experience of the researchers. The use of the Virtual Body Simulation software (see Chapter 5) allowed for a quick turnaround in the testing of changes to the parameters. We were able to adjust the parameters and test them reasonably easily.

Eventually we tuned the loop variables to a level where we achieved a level of control that we felt was appropriate for our exergame system. When we tested the control loop with human subjects, and the control system worked as we expected; bringing the subject heart rate to a reasonably steady state and keeping it centred there. Unfortunately it had a tendency to keep the heart rate centred approximately 5 beats lower than the desired value (See example Figure 13).

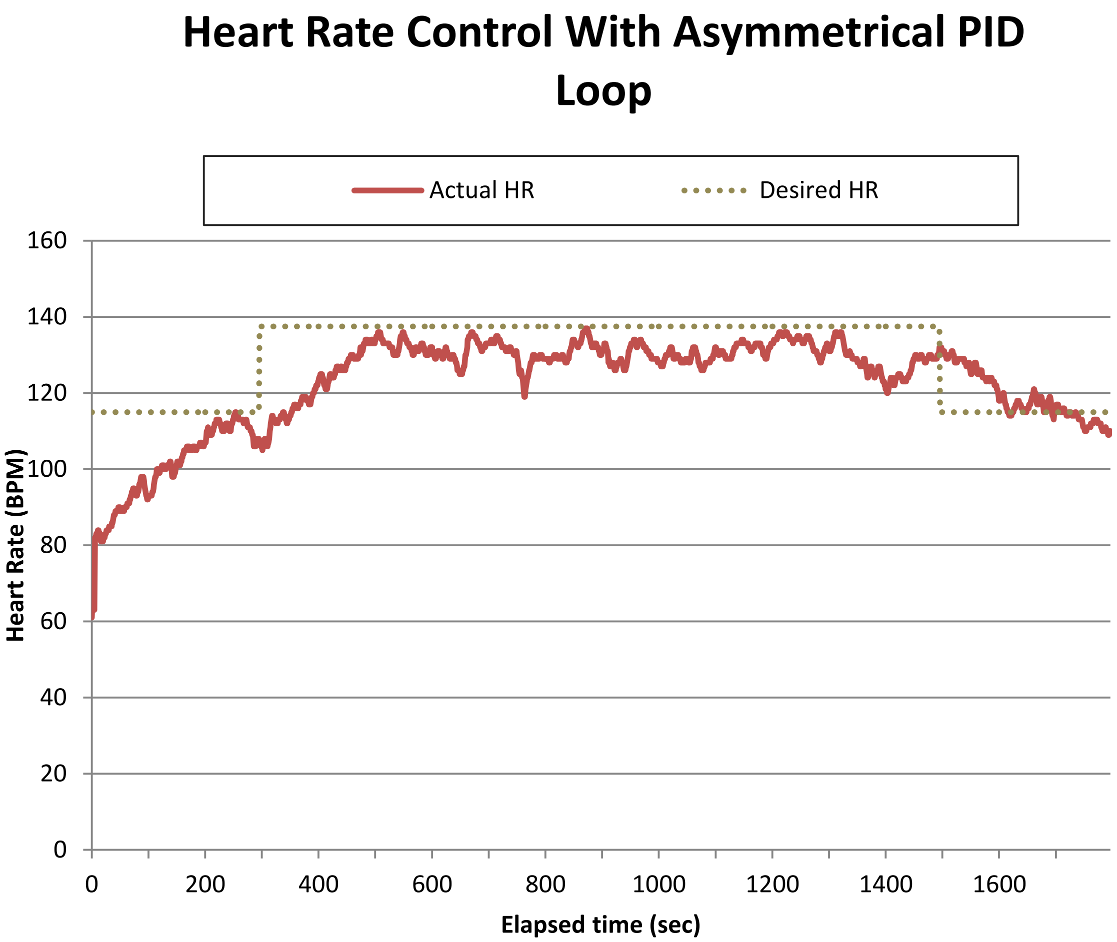

Figure 13 Low heart rate response of subject while playing exergame with initial flawed asymmetrical PID control loop.

The resulting low heart rate results were unexpected because the simulation did not show the same behaviour. Upon review of our simulation software, we realised that the lack of noise in the simulation was a potential factor in causing different results from the actual observed results. Introduction of a reading noise component into the simulation software caused the simulations to match the observed results.

Further investigation with the Virtual Body Simulator revealed that the asymmetrical nature of the PID loop was holding the managed variable low. With the measurement of heart rate, there is a fair degree of variability in the readings. When the heart rate was fairly flat, due to normal variability in heart rate, the value of the heart rate derivative was constantly fluctuating, giving negative and positive derivative values in roughly even amounts.

The derivative component of a PID loop has a tendency to amplify any measurement noise (King, 2011). In our initial control loop configuration the derivative component in the case for the negative error (Equation 9) was smaller than the derivative component on the positive error (Equation 11) as shown in (Equation 12).

$$K_{dn} < K_{dp} \tag{12}$$

This configuration was because of our assumption regarding the asymmetrical nature of heart rate response; that heart rate would rise quicker than it would fall. The asymmetrical weighting on the derivative component results in greater magnification of the negative change in error, causing the heart rate fluctuations to result in a lower than optimal controlled values.

The initial lack of the noise component in our simulation software had initially failed to reveal the issue with the derivative values. Introducing an appropriate level of noise into the simulation of our heart rate response immediately showed us that the PID controller setting would hold the heart rate values low.

Re-tuning of the loop constants indicated equally good performance could be achieved when the constants were identical for the negative and positive errors in the managed variable. Thus the asymmetrical nature of our PID loop was removed and a standard PID loop was used resulting in better controlling outcomes (see Figure 14). The asymmetrical nature of the heart rate response was found to not have a significant impact on the controlling when using a standard symmetrical PID loop.

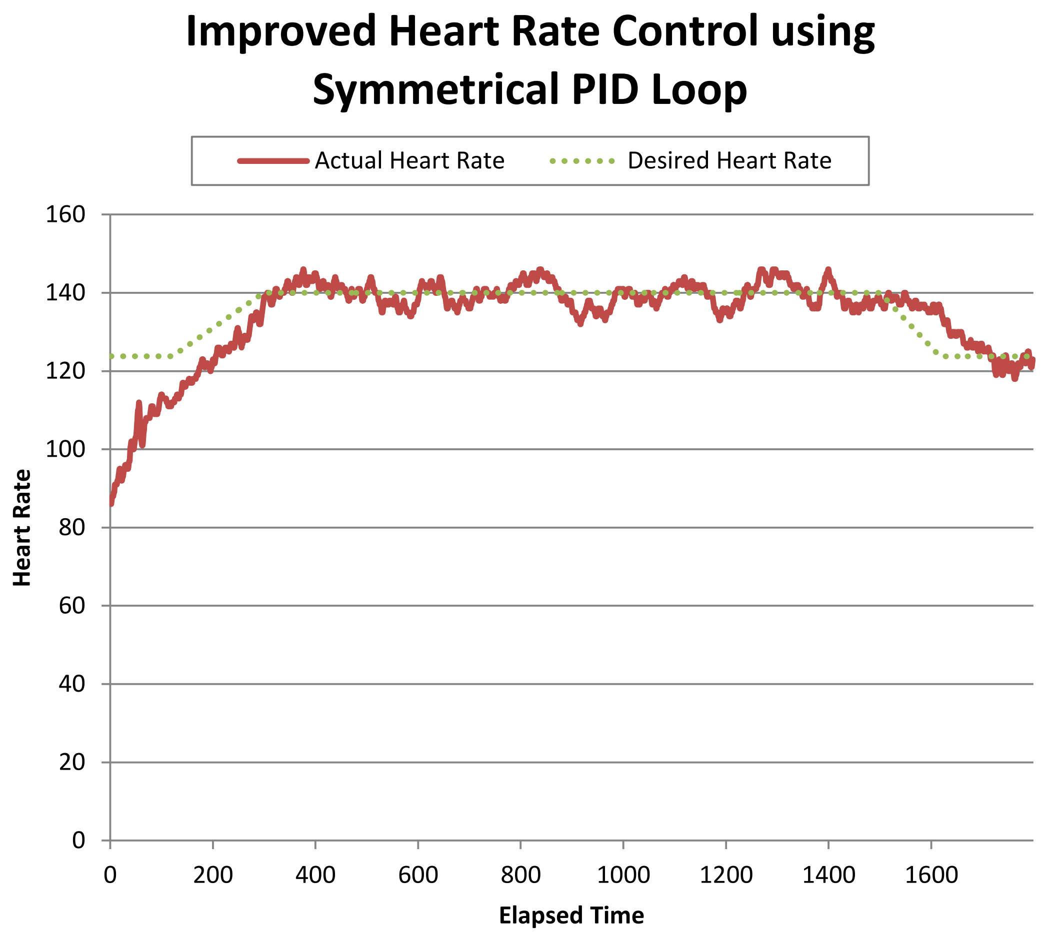

Figure 14 Improved heart rate response control.

4.3.2.5 Challenge Control

The calculation of the game challenge is more complex than the intensity control because there is not a simple linear mapping. The challenge of the game is modified at the end of each level of play based on the success of the player over the level. There are several factors in the game, which are measured and can be combined to determine a success rating for the player. The factors measured are as follows:

1. The percentage of the markers 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 were collected.

Each of the above factors is measured, and then passed into the control logic module as the player success parameters shown in Figure 12. The module uses a Fuzzy Logic system to work out the amount by which to alter the current level of challenge.

4.3.2.5.1 Fuzzy Logic

Fuzzy logic is an automated reasoning method that simulates the human ability to reason using multiple, inexact concepts. Fuzzy systems have been found to be well suited for control applications. Fuzzy logic is a mathematical means of evaluating a set of vague conditions. It is based on the concept of the fuzzy set.

Formal Set Theory

In formal mathematical set theory, for any set and element in a given universe, the element either belongs to the set or belongs to the complement of that set. There is no concept of partial membership. An element cannot belong to both a set and its complement. This is referred to as the law of excluded middle. Imagine we divide a group of people into two groups; tall people and the complement set, people who are not tall. In formal set theory we would need to make a cut-off point and define exactly where tall started. For example, we could define the cut off at six feet tall and say everyone six feet tall and over is tall. All other people are not tall. Everyone can be placed into the set. There is no ambiguity. A person is either six feet and over or not. This is the basis formal set theory which forms the basis for a lot of computer processing. In formal set theory we give elements a value of zero, not having membership, or a value of one, having membership to the set.

Fuzzy Sets

In the real world, it often does not make a lot of sense to have an absolute cut off value. Instead of having a crisp cut off value we can define smoothly varying curve that passes from not-tall to tall. We call this a membership function and it gives us a value anywhere from zero through to one, which indicates the degree of membership that an item has to the particular set. In Figure 15 we see a classic sharp edged membership set for the set of tall people. In this case, the person is either tall or not tall.

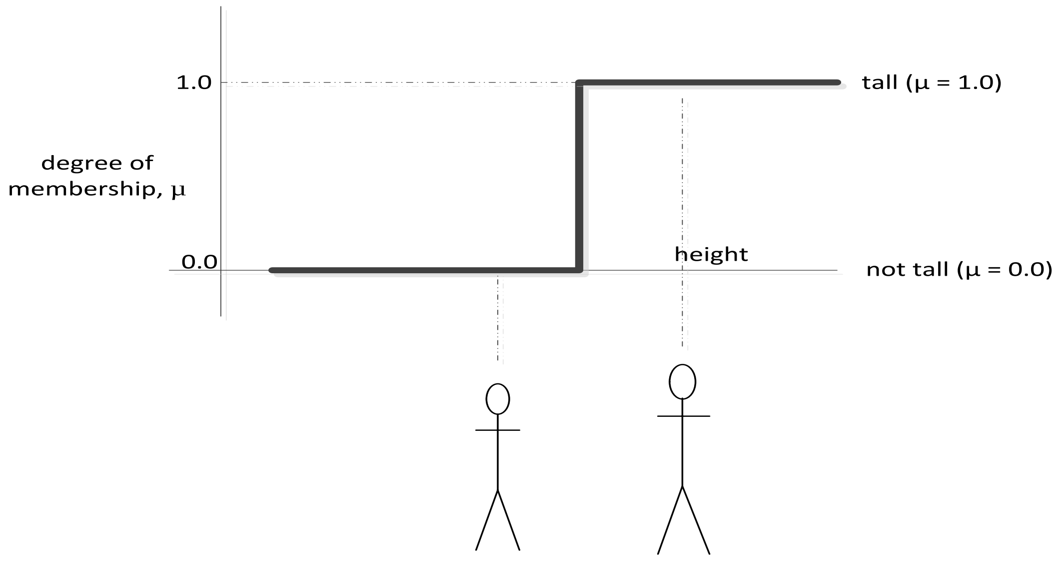

Figure 15 Crisp membership function for the set of tall people using classical set theory.

In Figure 16 we see a continuous membership function for the set of tall people using fuzzy set theory. There is a continuous range of values from 0 to 1 which indicate the degree of membership to the set of tall people.

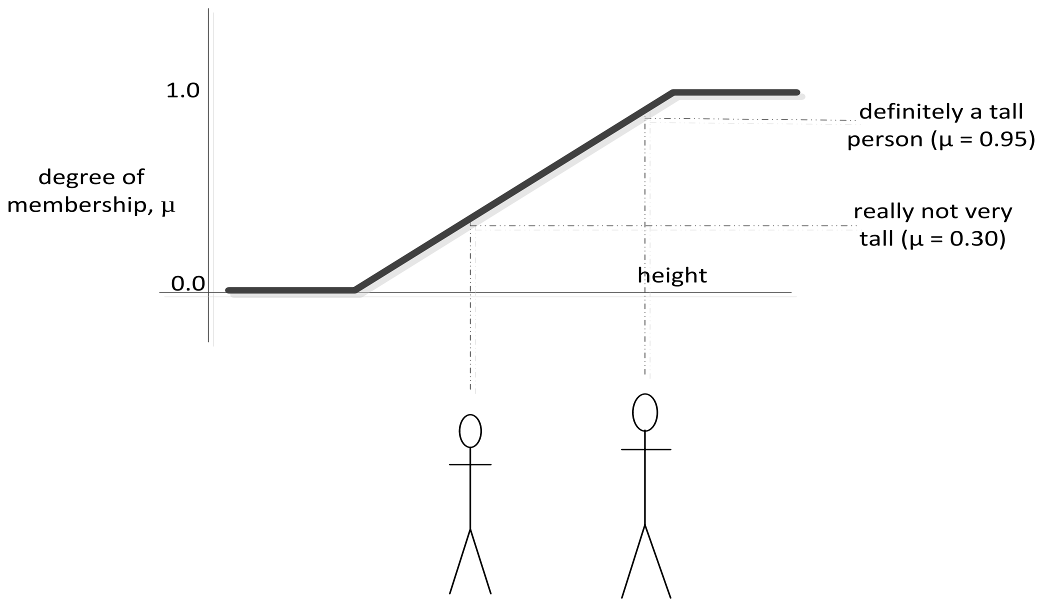

Figure 16 Continuous membership function for the set of tall people using fuzzy set theory.

Fuzzy sets can be used to evaluate a number of inexact conditions to produce a result on which we can base some actions.

Fuzzy Inference

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. A number of rules are applied to one or more fuzzy sets which are inputs, to produce one or more fuzzy sets as outputs. Formal or classic set theory has a set of logical operators which can be applied to evaluate a collection of sets. These operators have equivalents in fuzzy logic maths. The operators AND, OR and NOT, all have equivalents that can be applied to the fuzzy sets. These operators can be applied with a set of *if then* type rules to generate an output. For example:

If service is good then tip is average

In this rule the fuzzy set *good service* is used to determine if our output, the value of a tip, should have membership of the set *average tip*. Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision.

Fuzzy Logic Library

In order to control the challenge of the game, a third party open source fuzzy logic library called fuzzynet (Kaluzhny, 2009) has been used. The freely available library developed, by Dmitry Kaluzhny, is available as C# source code for the Microsoft .Net platform. It provides support for fuzzy inference in both Mandani and Sugeno methods (Kaluzhny, 2009). The library was reasonably easy to integrate and use. Initially there was some difficulty getting the software to correctly read and process the rules developed. It was discovered that a fault in the library software caused it to halt when certain rules were encountered. The library source code was examined and a clear logical error was identified in the code. This error was corrected and no further issues have since been encountered.

The library has not been updated since October 2008 and it appears that it is no longer being maintained by the author. No response was forthcoming in relation to the reporting of the previously mentioned error.

Game Control

The fuzzy control system for our exergame was developed based on the methodology described in Negneveitsky (2005). We create a “linguistic variable” to represent each of the input factors. For each of these factors a linguistic variable and a group of fuzzy sets and linguistic values have been developed. The module uses a fuzzy control system to process the inputs and determine the changes required to modify the game challenge. Fuzzy control systems are suited to handling situations where the logic is expressed in vague and inexact terms. This matches with the ambiguous nature of player success within a video game.

The exergame was initially tested with linearly increasing challenge. The challenge control functionality was disabled. During this testing we were able to generate some values and determine the normal ranges of our input variables. Based on the recorded results of our initial play testing, we generated suitable linguistic categories, known as a "fuzzy sets", for each of the variables. For example, the percentage of markers collected, has five linguistic categories - very low (VL), low (L), medium (M), high (H) and very high (VH). We then defined fuzzy sets for these categories, shown in Figure 17.

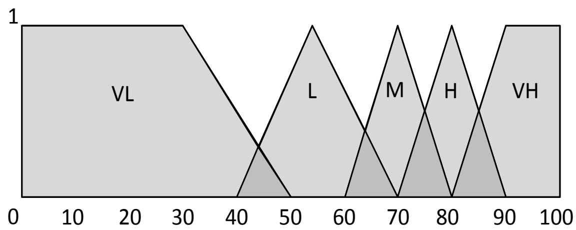

Figure 17 Fuzzy sets for percentage of markers collected

Fuzzy sets were designed for all of the input variables. A set of rules (see Appendix C) was developed, which was applied to the inputs to produce a change in difficulty for the player. For example one of the rules was:

if *PercentMarkersCollected* is low then *GameChallengeChange* is *SmallReduction*.

Rules were generated for the inputs and their categories. The fuzzy system combines the recommendations from all the rules to determine a suitable change in difficulty for the player.

The control logic part of an exergame required extensive fine tuning. The appropriate values for the fuzzy sets and rules needed to be calculated in order to find the optimal control settings for the game play challenge.

4.3.2.5.2 Game Challenge

The fuzzy logic system was used to return an indicator which indicated if the challenge level needed to be increase or deceased. Based on this indicator, the game challenge was increased through the use of three key mechanisms:

1. The speed of the game, essentially the forward speed of the helicopter.
2. The placement of the markers; reductions in the number of straight lines and more random placement of markers.
3. The pattern of the aliens and the propensity for them to move towards the player.

4.3.3 Game Play Engine

The game play engine, see Figure 12 (c), is the core of the video game itself, and manages the game play. In order to apply the Dual Flow Model to an exergame, the system needs to be able to vary two key aspects of the game play; the intensity of the workout involved, the effectiveness, and the level of challenge, the attractiveness. This module provides the game that generates the varying levels of difficulty and exercise intensity. The modular nature of this component provides a mechanism for development of many different games for the platform, without the need to redevelop the core exergaming components of the system.

One of the more difficult aspects of the actual game play is the ability to accurately control both exercise intensity and game challenge independently. The perfect game would have the two components seamlessly blended together from the player perspective, while being totally independent from the game control perspective. Exergame system users may have different levels of skill and fitness; For example, there may be video games players with low levels of fitness, in contrast to regular exercisers who may have limited video games exposure.

4.3.3.1 Controlling Challenge

Because the skills of the player are not known at the onset of the game, the game will need to start at some default level of challenge. The challenges in the game will then increase or decrease as the game progresses and the player’s current skill level can be more accurately determined. For the determination of what the current player’s skill level is, and how to raise or lower the challenge, a fairly detailed knowledge of the game in question is required. The period of time over which the player’s skill level is measured also needs to be considered. Because the player skill levels will be regularly changing, the current skill level of the player will need to be regularly re-evaluated.

4.3.3.2 Controlling Intensity

The fitness levels of the player will also not be known. The game play engine should not need to be overly concerned with the intensity levels, since there is a specific module designed to provide the custom exercise plan for the individual. What the game needs to be concerned with is the ability to control the intensity of the player's exercise, in order to match that prescribed by the control module. As mentioned earlier the difficulty is in increasing the intensity of the workout, without overly affecting the challenge of the game.

4.3.3.3 Game Mechanics

The exergame designer needs to determine the mapping between the game player's physical actions and the game play. The exercise that the subject undertakes needs to affect the game is some meaningful and controllable way.

As mentioned in Chapter 2, (MIT Technology Review, 2003) indicated a belief that the obvious direct pairing of the pedal speed with game motion speed did not work well in an exergame and should be avoided. We are in agreement with that finding, that the direct association is not likely to produce the best outcome. For the exergame system developed in this study, we avoided that mapping and focused on using some other mapping for the player cycling speed. In the case of our system the bike speed translates to vertical positioning of the player craft.

4.3.3.4 Music

As mention earlier Yim & Graham (2007), indicated that music in an exercise game was important and that it should have music that is upbeat. In our exergame system we used music to clearly differentiate the different segments of the workout; warm-up, workout and cool-down. A slower more peaceful tune was played during the warm-up and cool-down. During the workout portion of the game play a fast paced energetic sound track was used.

4.3.4 Exergame Control Adaptor

As mentioned in 2.1.1, the Cat Eye Gamebike was chosen as the exergame control adaptor in our exergame system. We chose the Gamebike from Cat Eye, mainly due to its price and availability. The Gamebike works as a PS2 controller, which we used with an adaptor to work with a PC. The Gamebike also comes equipped with a heart rate sensor and inbuilt 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. Furthermore, the Gamebike is quite wide in the centre frame and as such has pedals that are further apart than normally encountered on a bike.

Figure 18 Standard unmodified Cat Eye Gamebike (Cat Eye Company Ltd, 2002).

The Cat Eye Gamebike was originally designed as an adaptor kit for standard bicycle (see Figure 2.) The game bike is now sold essentially as the adaptor kit pre-installed on a supplied exercise bike (see Figure 18). 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 was to be controlled via the PC for our exergame system. An 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. On later versions of the bike, a USB connector was used in preference to a RS232 connection, see section 4.3.4.1.4.

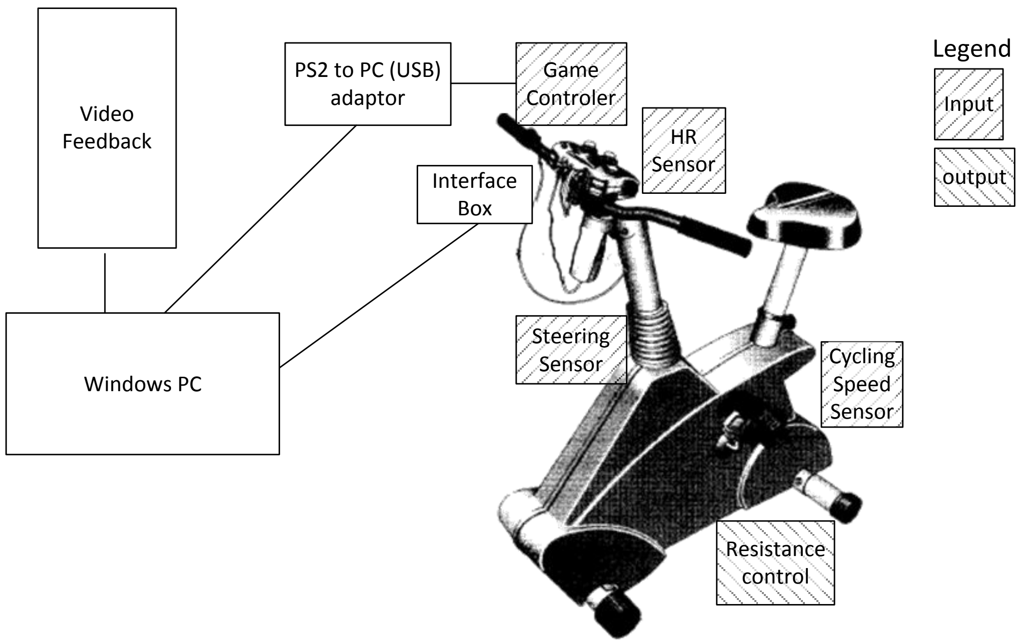

Figure 19 Modified Gamebike system overview

The modified Gamebike has two connections to a Windows PC. One connection is used to provide the player actions. There are three key inputs through this interface. The cycling speed, the steering direction and the handle bar fire button. The other connection to the PC is used to receive information about the player's physiological state, in this case through the monitoring of heart rates to provide a measure of exertion level for the exergame control logic module. This connection is also used to output resistance control back to the bike from the game play engine.

4.3.4.1.1 Heart Rate Sensor

The bike was equipped with a wireless Bluetooth receiver. The receiver is used to pick-up heart rate signals from a standard Bluetooth heart rate device such as the chest strap sensor. For our Gamebike, the receiver was removed and an off the shelf circuit board (see Figure 20) was mounted in a separate plastic box (see Figure 21) and attached onto the front of the bike behind the controlled (see Figure 22 and Figure 23). 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 centre of the steering column on a plastic mounting bracket.

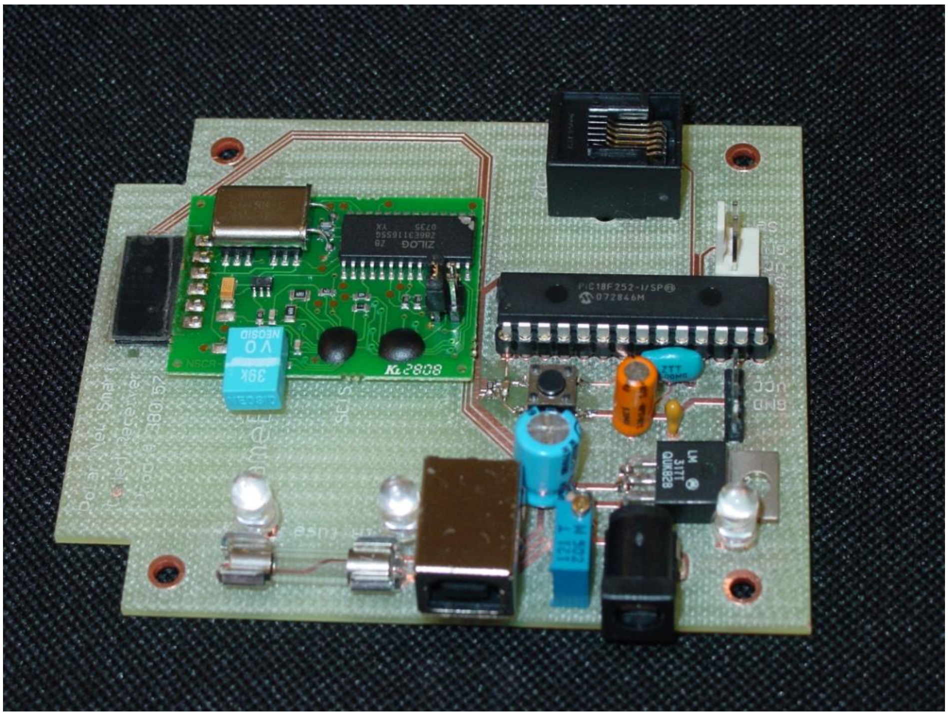

Figure 20 Control board for PC interface to wireless heart rate receiver and resistance control.

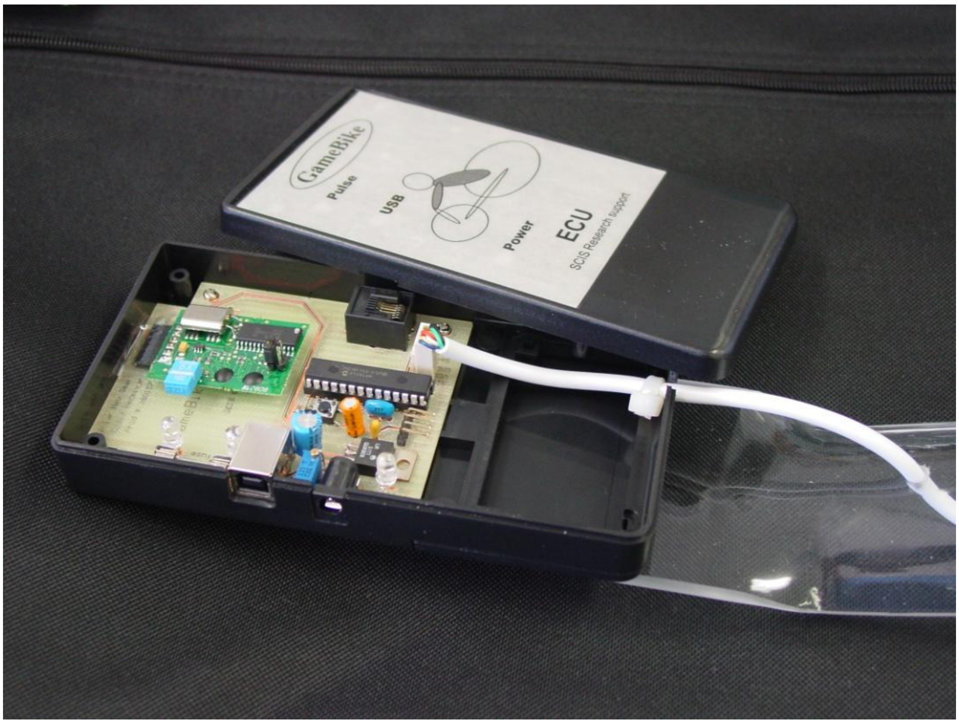

Figure 21 Gamebike control box with control board.

Figure 22 Heart Rate sensor box front mounted on bike handlebars.

Figure 23 Close up of Heart Rate sensor box front mounted on bike handlebars.

4.3.4.1.2 Resistance Setting

The front mounted plastic box also houses the control interface for setting the bike cycling resistance. The bike flywheel is run in a 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, shown in Figure 24 and Figure 25.

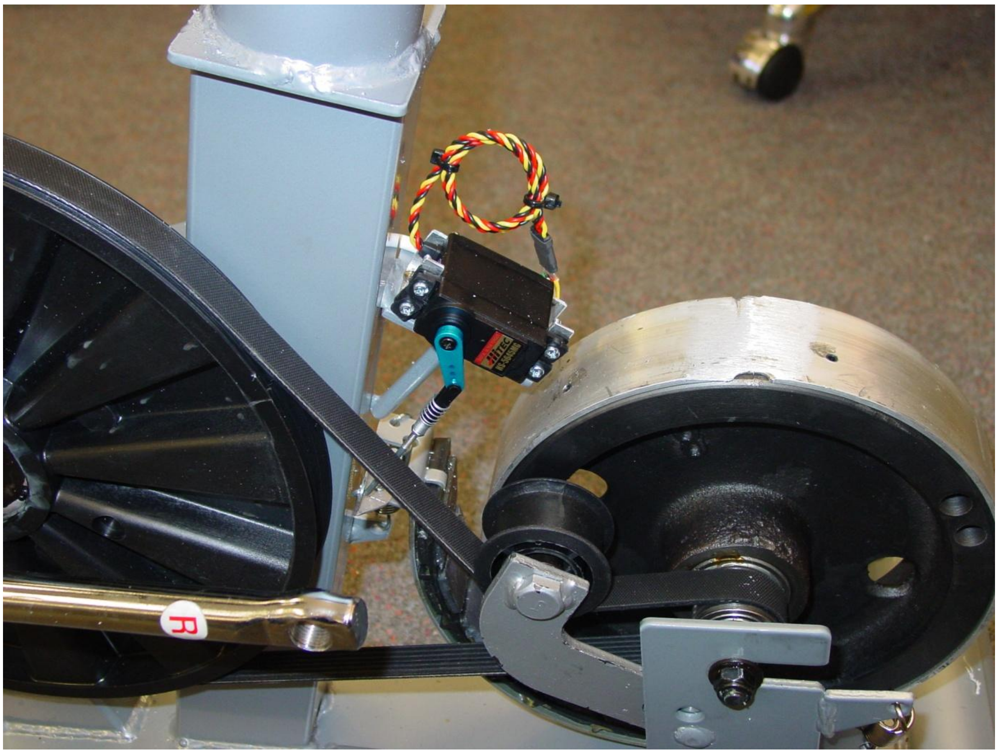

Figure 24 Bike resistance control - the servo motor (centre) pulls up on the spring loaded metal shoe holding the magnets, in order to bring the magnets closer to the flywheel and increase the resistance.

Figure 25 Modified Gamebike with the plastic cowlings, pedals and game control pad removed.

4.3.4.1.3 Game Controller

The Cat Eye 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 PS 2 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 / 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.

4.3.4.1.4 Bike Interface Software

To allow easy development of applications for the Gamebike, a simple application was written to manage the interface with the serial communications (COM) port. The application monitors the appropriate COM port for heart rate readings, and writes these values out to a text file. The text file can then be read by other applications, in this case the exergame software, to retrieve the heart rate values. The application also monitors a local file which contains the resistance settings for the bike. If the value in the file is changed, the new value is written out to the COM port to set the resistance on the bike. The use of the flat files for the interface to the application means that the bike interface could be easily accessed from a range of different software environments. This interface management application was successfully used as a bridge to programs written using the torque game engine and using the Microsoft XNA platform. Several games were also written which were successfully able to read the exercise bike heart rate sensor, and set the resistance of the bike.

Later on when further Gamebikes were obtained, the new models were fitted with a USB connection rather than the older serial port. As a short term measure, to enable the utilization of the existing software based around using a COM port, a driver was used to map the USB to a COM port. The Leadtek GPS USB to UART bridge driver was used to allow the USB devices to be represented in Microsoft Windows as a standard COM port. By using this driver, the existing software with the file based output and input, could be used without modification until software could be written to directly access the USB device. This setup was used for the exergame system in our trial.

One issue found with the use of the flat files is that if an error occurred and the bike software stopped updating the heart rate reading in the file, the exergame software would continue to use the last reading, without any idea that the readings were not being updated. In order to prevent this, the last write time of the file also needs to be monitored, in order to ensure that the file was indeed being updated.

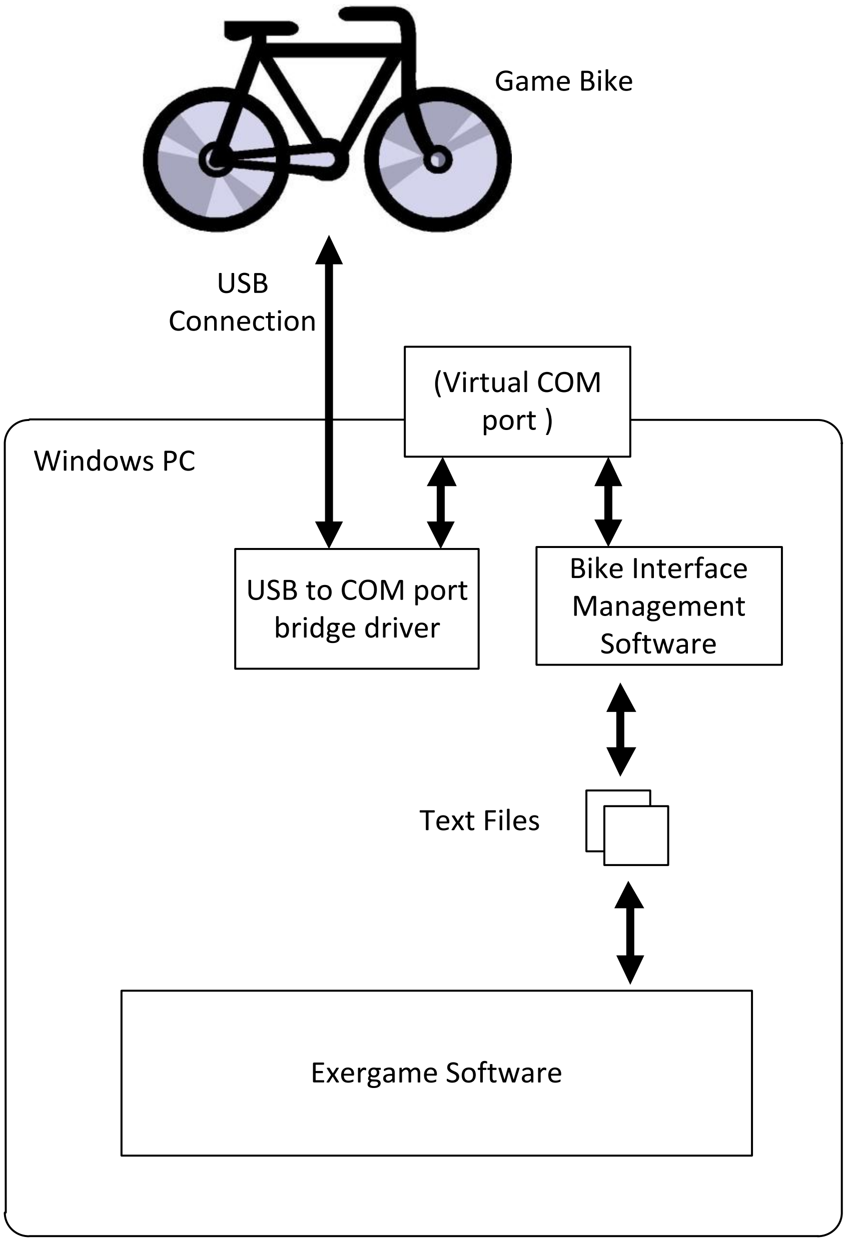

Figure 26 Gamebike heart rate and resistance text file interface

4.3.4.2 Input System

In an exergame, the input systems are concerned with the actual physical motions actions and state of the player. This includes voluntary actions such as button presses and other physical movements, as well as involuntary measurements such as heart rate or skin conductance levels.

In our exergame system we treat the bike sensor inputs as a Joystick controller under windows. The XNA Game platform was used for our game development, (See 4.4). XNA was initially developed with a focus on Xbox game development. XNA does not inherently provide any PC joystick support, and only has built in support for the Xbox 360 controller. In order to access the Joystick under windows from the XNA platform the Managed Direct-X libraries are used. Direct-X is the name of a collection of API's provided in windows to directly access the hardware such as the video, sounds and joysticks. These low level APIs are difficult to use from within the managed code of the XNA platform. The Managed Direct-X library is a .Net wrapper around the Direct-X libraries. The latest version of the Direct-X libraries currently supported by managed Direct-X is version 9, which is what has been used for our exergame.

The Managed Direct-X library provides a module called DirectInput, which is used for user input from the keyboard, mouse or joystick. The generic *Device* class forms the basis for all the access to the input. The Device class allows the setting of a semaphore which is used to signal a state change in the device. The semaphore used in our case is what is called an *AutoResetEvent*. A thread can be asked to wait for the particular semaphore to become signalled. As soon as a thread has been released by the event it is automatically reset, and can be used again to wait for the next event. When a state change occurs the application then needs to read the device state and take appropriate actions.

A separate thread in the application is used to wait for and process the Joystick state changes:

```
While (Game Running)
{
 Wait for joystick event semaphore.
 Get joystick button states
 Process joystick buttons.
}
```

Some direct input devices do not automatically trigger the event for a state change. For these devices, the code must poll the joystick to cause the triggering of the state change event. In the case of our Gamebike, polling for event changes was required. In order to maintain flexibility, the polling of the device was done in a separate thread from the state change processing. In our exergame, a dedicated thread is set up to call the XNA joystick poll function every 10 milliseconds. When the poll function is called, the associated event handlers are triggered to handle the state changes.

4.3.4.2.1 Pedal Motion Measurement

The pedal motion of the Bike is seen as repeated presses of the fire button. The Gamebike triggers a button press every half rotation of the pedals. A timer is used to measure the time between button presses in order to calculate the speed at which the bike is being peddled. Every time a button press associated with the pedals is received the timer is read and then reset to wait for the next button press associated with a further half rotation of the bike pedals. The player cycling rate (RPM) is calculated by dividing 1 minute by the elapsed time, multiplied by the number of button presses generate per revolution, in our case 2 presses.

$$rpm = \frac{1}{\Delta \mathrm{t} * \mathrm{p}} \tag{13}$$

where Δ t is the time interval between consecutive button presses, and p is the number of button presses triggered per revolution of the pedals, in our case 2.

The problem with this is that when a user stops pedalling or slows down, we receive no event changes for an extended period. This means that if we only calculate based on the joystick events, the cycling speed stays high after the user has stopped pedalling. In order to counter this, when the current timer exceeds the length of the elapsed period between the previous two presses, the speed is constantly recalculated based on the currently elapsed time. This causes the speed to reduce until the next event is received.

```
if ( current elapsed time since last event
                         > last gap between events )
{
 Last gap between events = current elapsed time.
 Recalculate speed.
}
```

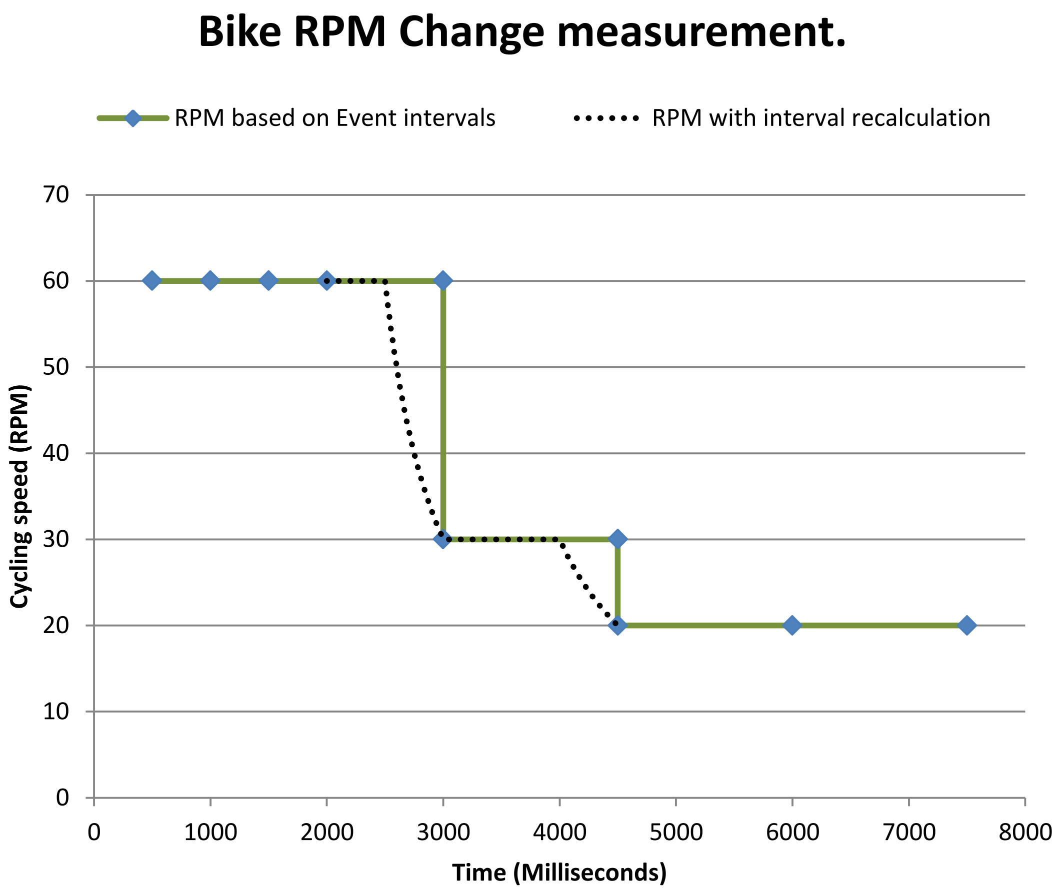

Figure 27 shows the problem with the measurements based only on joystick events. As cycling speeds get lower, the change in time interval for different speeds becomes lager and the issue is more pronounced.

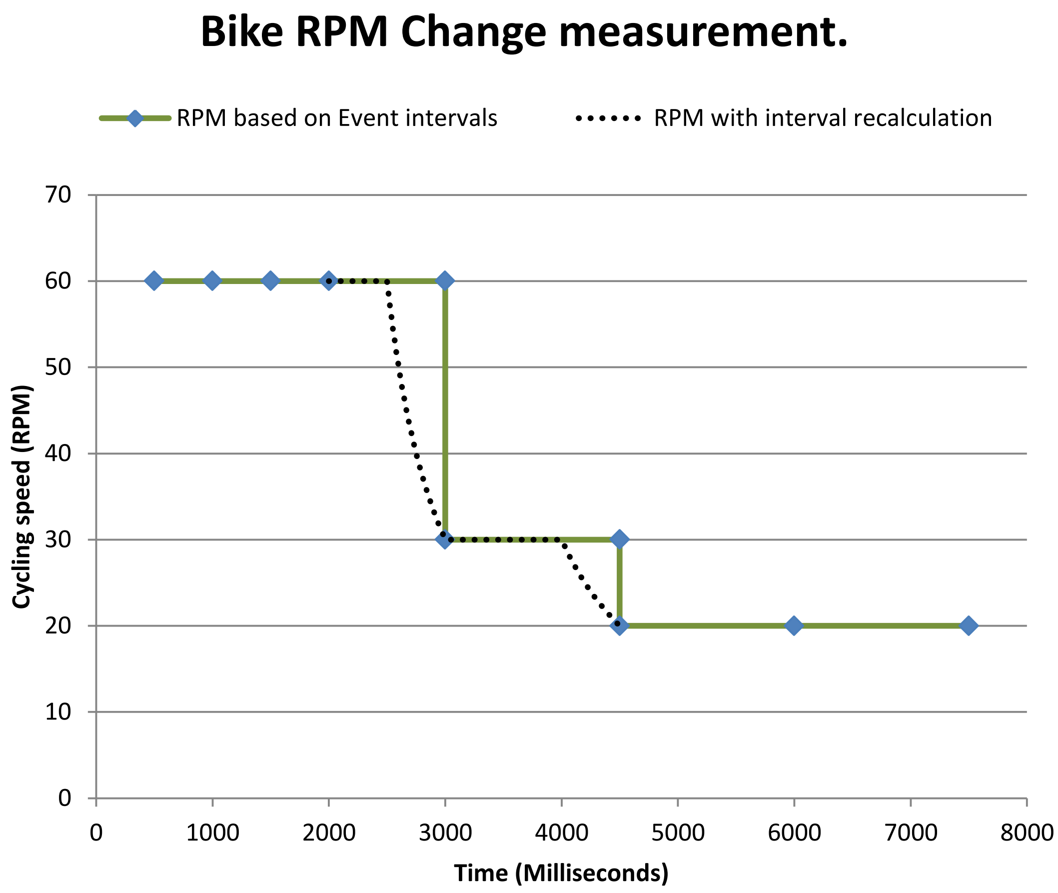

Figure 27 Contrast between RPM calculated solely on events against continuous calculations.

4.3.4.2.2 Measurement Noise

If the player is cycling at 70 RPM then there are 140 button presses per minute. This is one press every 428 milliseconds. It was found that with the polling process and other activities happening on the PC the timing accuracy of the button press timing was not very high. Also sometimes a double press was recorded, or a press was missed. This caused fairy erratic changes in the calculated cycling speed. In order to reduce the effect of these errors, a number of different strategies were tested.

The averaging of readings over a period was tested, as well as using timings over several presses, rather than the time between consecutive button presses. Both of these methodologies had undesirable side effects. In various configurations, they resulted in either sluggish responses to changes in speed, or jerky movement control.

4.3.4.2.3 Noise Reduction Solutions

In the final release several small dampening strategies were adopted, which when used together worked reasonably well. The current cycling speed of the player in the game is tracked separately to the speed calculated from the Gamebike button readings. The game update loop is called by the XNA framework every 60^{th} of a second. In each cycle of the update loop, the current player cycling speed is adjusted by 1% of the difference between the current player speed, and the calculated speed from the device.

This may appear to be quite a lot of lag, but the high update rate and the game context made this work quite well. In the two charts, Figure 28 and Figure 29, we chart a simulated curve where the player physical cycling rate goes from 0 to 70 RPM in 7 seconds. Within the game, the player speed would approach 70 RPM shortly after 10 seconds. The second chart shows the same data but with a sensor noise of approximately ± 20%. We see that within the game, with this amount of noise within the processing of the physical button presses, a smooth curve of player speed is still generated.

In Figure 30 we show the results of using 10% of the difference in value between the game reading and the actual sensor reading. Here it tracks much quicker, but we can see the noise being reflected in the game reading value.

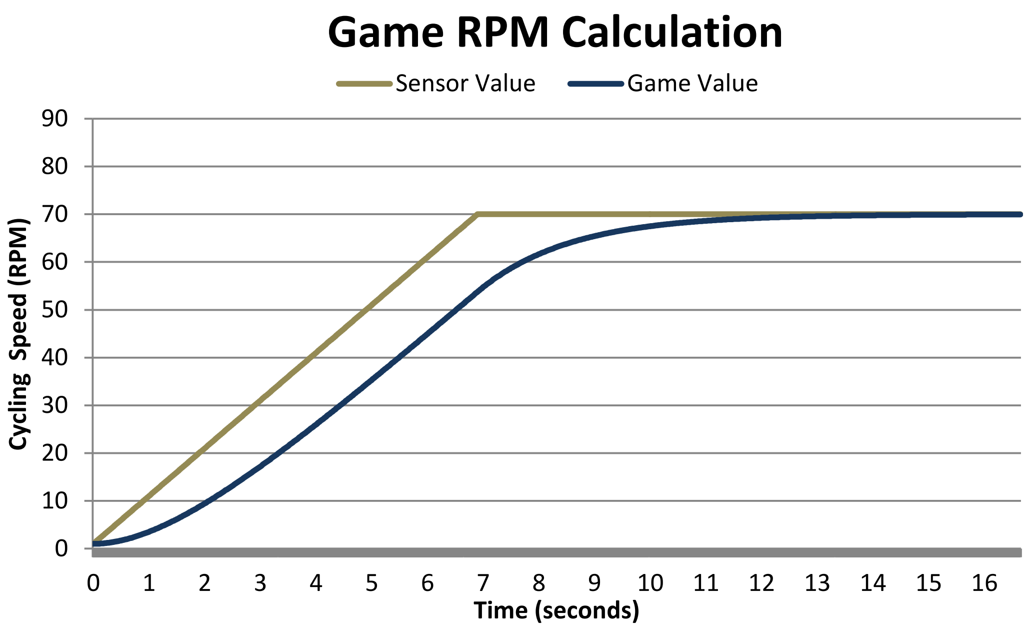

Figure 28 Player goes from 0 to 70 RPM in 7 seconds with no sensor noise.

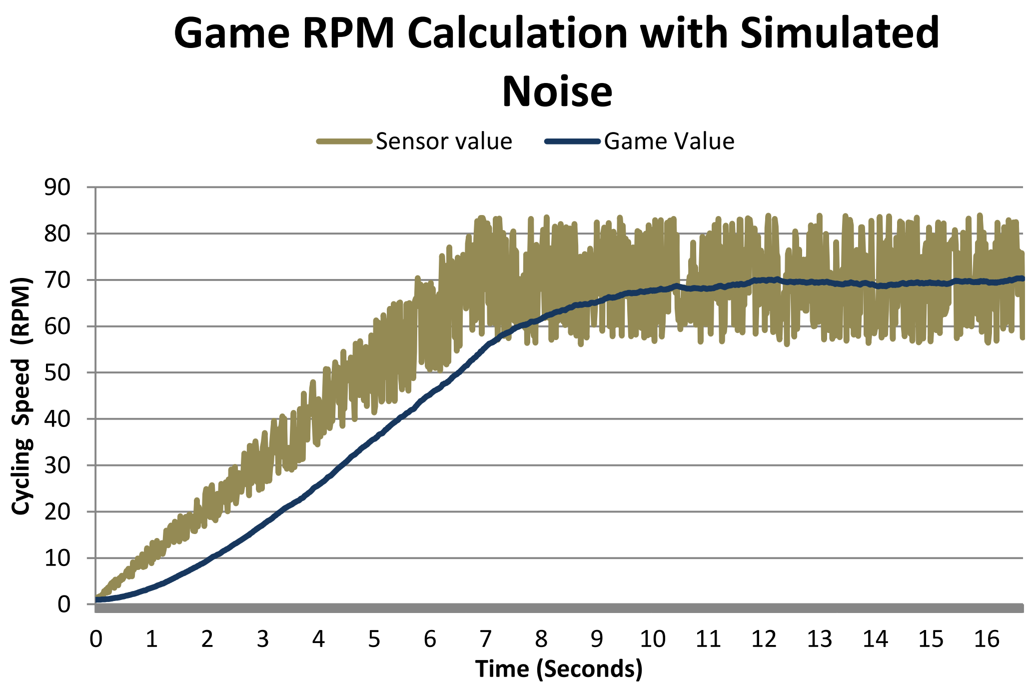

Figure 29 Player goes from 0 to 70 RPM in seven seconds with ± 20% sensor noise

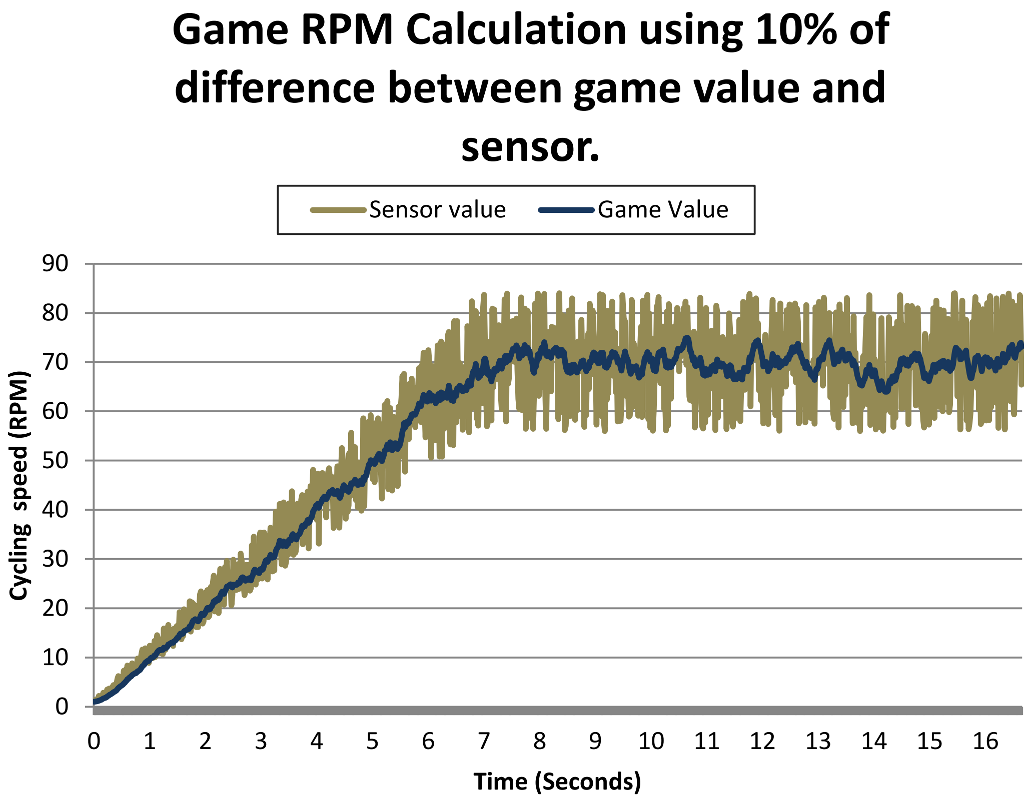

Figure 30 Player goes from 0 to 70 RPM in seven seconds with ± 20% sensor noise. In this case, the Game Value moves 10% of the difference between the previous game value and the sensor value. Here we can see the noise in the game calculated value, which is then reflected in a jerky movement of the craft on the screen.

The actual pedal speed reading noise, within the game setup, was not anywhere near 20%. The existence of the lag in the control is not perfect, but further attempts to reduce the lag resulted in jerky motions within the game. In the context of the game, the trade-off of responsiveness in exchange for a smooth motion was considered to be a better option.

In addition to this filtering, in order to prevent spikes, button press intervals of less the 150ms are ignored as they represented impossibly high cycling speed. The change in player cycle rate is also restricted to changes of no more than 0.5 RPM per game loop.

4.3.4.3 Output of Feedback System

Feedback is used to provide the game challenges to the player and as the mechanism to generate higher intensity exercise. Feedback provided in an exergame can be direct or indirect. An example of direct feedback would be increasing the resistance of the particular exercise device being used. An example of indirect feedback may be increased game speed, which would then result in increased work rate for the player.

4.3.4.3.1 Feedback in the Trial System

In the exergame developed for the trial, we do not vary the bike's resistance settings during play. The resistance setting is calculated and set for the play during the initial session and then held constant for the rest of the session. The key feedback for the player within the game, in terms of the exercise, is the gravity effect on the in-game character. In terms of challenge in the game, the game speed, and the placement of the markers are the key driving factors.

Figure 31 Final exergame system set up and ready to go.

4.4 Development, Testing and Tuning

In this section we discuss the software tools used in the development of our exergame system.

4.4.1 Game Development Software

Microsoft's XNA game studio (Microsoft, 2009) has been used as the development platform for the exergame in this study. XNA is a set of tools and libraries for the Microsoft .Net Managed runtime, which takes care of standard video game functionality. It is designed to support multiple different gaming platforms, currently the XBOX, the Zune media player, Windows phone 7 and windows PC. The XNA framework provides low level routines for processing of the hardware initialisation, graphics rendering and audio playback. It also provides a base class upon which to build game logic on. This class provides a timing loop which is executed in precise intervals. This frees the user from having to manually keep track of elapsed time in order to provide regular smooth game play.

The XNA graphics pipeline uses a proprietary format graphics file. XNA provides a tool in Visual Studio to provide for the creation of the graphics for use with the XNA run time. In order to produce the graphics for our game, the free Paint.Net application was used to produce Portable Network Graphics (PNG) files which could then be converted into the proprietary XNB format used by the XNA runtime.

The initial development of the exergame system was started using XNA version 3.0 on Microsoft Visual Studio 2008. Later the XNA platform was upgraded to version 3.1. The game is written entirely in C# for the Microsoft Windows® .Net 3.5 platform. The source code files were managed using the open source version control system subversion. The graphical subversion client TortoiseSvn was used to interface with the subversion source code repository from the development windows workstations.

4.4.2 Logging

Logging within any software is important during the development process. It allows the developer to understand what has occurred within the software after it has executed. This helps in the fixing of faults and problems within the software.

Additionally, because the software being developed in our case was for research purposes, after an exergame session is complete, we want to be able to review the subject's performance and actions, as well as the performance of the control mechanisms. During execution our exergame software logs the user's current state and actions every second. This includes the cycling rate, heart rate, desired heart rate, and other game based variables like aliens shot. A full list of the variables logged is included in Appendix F.

4.4.3 Testing and Tuning

Development of any game that requires physical exertion is difficult for a number of reasons. Having the developer perform all of the physical activity required in playing the game is limiting due to problems with exhaustion. Once the tester has reached even a low level of exhaustion, it is difficult to produce more useful testing for some period. Additionally, since we were using an exercise bike as the exergame controller for our system, there was the added inconvenience of continually getting on and off the bike to switch between testing and developing.

Players of different levels of fitness will exhibit different response characteristics. This means different responses types need to be tested. Having a set of testers on hand which cover the required range of different characteristics and physical capacity levels is not easy to achieve.

To overcome these problem a software simulation package known as the Virtual Body Simulator was used to aid in the software development (Sinclair, Hingston, Masek, & Nosaka, 2009). The Virtual Body Simulator allows the testing of an exergame without the need to perform the required physical exertions. The software sits between a standard game controller and the computer to act as a translator. Some mappings are used to convert the motions of a normal controller into appropriate input form the exergame controller, along with the appropriate biological feedbacks, in this case heart rate response. The development of the Virtual Body is covered in detail in Chapter 5.

4.4.4 Building the Exergame System

After the game was designed, an initial playable version of the exergame was developed in which the workout and game challenge levels were fixed. After the initial game mechanics were developed, the focus switched to getting the workout levels set correctly.

Using the Virtual Body software, the intensity workout control was introduced and a usable heat rate control system produced. The heart rate response simulation of the Virtual Body was then used in conjunction with the Game Control model to refine and tune the PID controller used in the game control. A game play simulation was used which set the player automatically at the correct RPM to stay locked in the centre of the play area. For testing purposes this allowed us to perform tuning where the game control module has perfect control of the player workout.

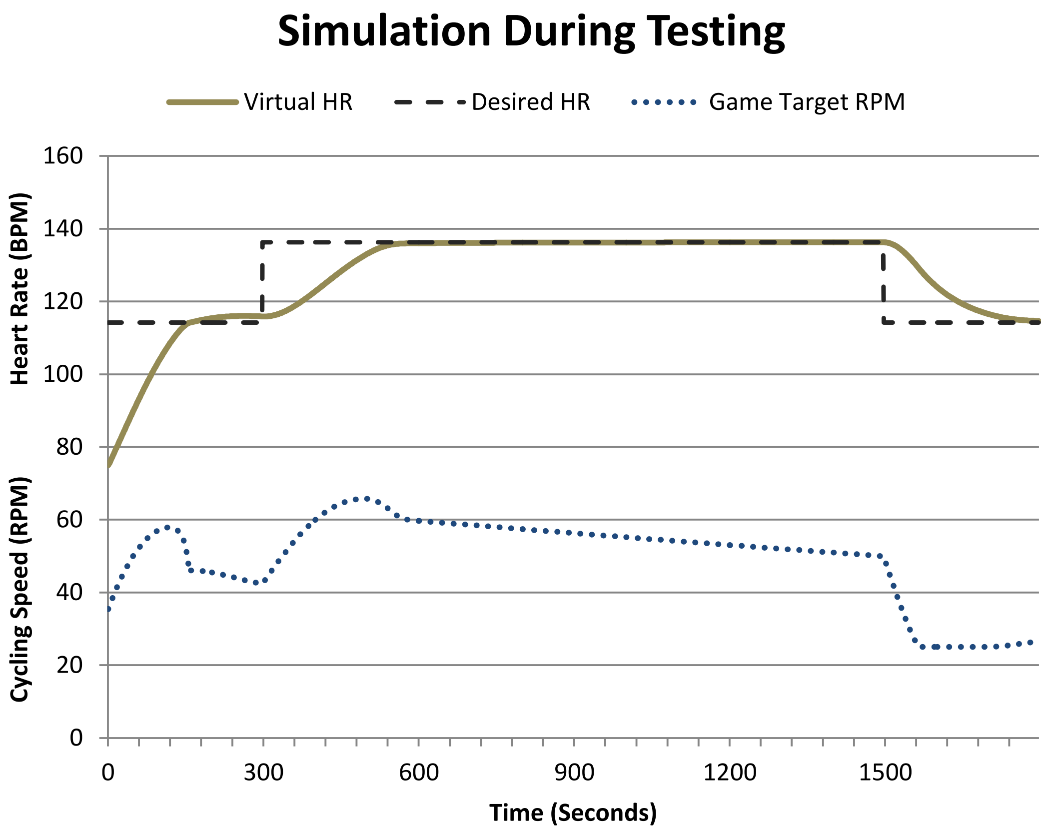

Figure 32 PID control of simulated heart rate

In a real game situation, the player RPM's would be fluctuating up and down above and below the desired RPM. However, it is a reasonable assumption for testing that the error, the difference between where the system wanted the player to be and where the player actually was, would average out to be close to zero. Using this process, the PID loops were tuned to provide good heart rate control responses when run against the Virtual Body Simulation software, as shown in Figure 32.

Once the controller was tuned successfully to fit the simulated heart rate, the game was play tested again. This time using the Virtual Body to provide physiological responses to the exergame, but combined with normal player erratic RPM rates. After some additional tuning, the intensity control for the final system was complete.

Testing and development of the game challenge was a similar process. The game was designed and developed with the difficulty setting rising at a constant rate per level. This is a normal pattern for many video games. The rules were run and the generated results used for recording purposes, but not utilised in the game control.

From the recorded results, the fuzzy sets and the rules were adjusted and tuned until reasonable results were produced. The fuzzy logic control system was then enabled to allow further testing and tuning for the final game control system.

4.5 Summary

In this chapter we saw that that we designed and developed an exergame system based on the Dual Flow Model. The system applies the attractiveness side of the Dual Flow Model by using a fuzzy logic controller to dynamically match the difficulty of the game play with the individual player's skills. The effectiveness attribute of the Dual Flow Mode is managed by monitoring the player heart rate, and using a PID control loop to match the player exertion to the correct level. Next we need to look at how we formulated and executed a study of the Dual Flow Model using the exergame.

However, first in Chapter 5 we will look at in more detail the software called the Virtual Body Simulator, which was built during the course of this research. This software was developed in order to aid in the testing of exergames and in particular the exergame system used for this thesis. In Chapter 5 we discuss this software and the development of a successful mechanism for simulating heart rate responses.

In Chapter 6 we then look at the setup of the trial performed for this study. After we have performed the trial and had subjects use the software in the different modes, we can analyse the data to see how it fits with the Dual Flow Model in Chapter 7

.

5 Virtual Body

As we saw in chapter 4, the exergame system designed for this research uses heart rate as a measure of exertion, and as a means of applying the effectiveness attribute of the dual flow model. In order to use heart rate in our research, we required some tools to allow us to develop a heart rate based software system.

In this chapter, we look at the heart rate response model called the Virtual Body. The Virtual Body model was developed during the course of this doctorate as a tool to aid in the development of exergames systems. In our development we required a means to simulate heart rate responses to exercise in a exergames environment. There currently existed no appropriate model for the simulation of heart rate responses, so we were required to devise our own model of heart rate response. The model developed worked well, and the software packaged developed proved to be effective in speeding the development and testing of the exergame software which was used in this study.

Developing any software requires significant testing, adjustment, and refinement, particularly in the later stages. Video games in particular, require testing by both developers and potential users to find defects in the software and to tune and balance game play. In developing an exergaming system, the exercise component adds a significant extra dimension - developers must also test for safety and effectiveness. This all leads to the requirement for more play testing and more play testers.

Gathering data on physiological responses is an important part of exergame testing. For example, for an exergame to be a safe, effective form of aerobic exercise, it must meet recommended exercise guidelines. As mentioned previously, for healthy aerobic activity, the American College of Sports Medicine (American College of Sports Medicine, 2006) recommends the following:

- Exercise 3 to 5 days each week
- Warm up for 5 to 10 minutes before aerobic activity
- Maintain your exercise intensity for 30 to 45 minutes
- Gradually decrease the intensity of your workout, then stretch to cool down during the last 5 to 10 minutes

Extensive testing is needed to ensure that the game meets the desired exercise requirements, and it requires observing how the exercise affects the player. The amount of physical exertion required for this testing becomes a limiting factor. Combining the physical activities of game play with the rest of the software development process is inconvenient, tiring, and time consuming.

To overcome this problem for our study, a system to simulate both the exercise a player normally undertakes during game play, and its effect on the body, has been developed. By remapping the exertive game inputs to less strenuous actions, and modelling body responses to exercise, we can accelerate exergame development.

As a secondary benefit, the system could also be used to evaluate a game for a range of players with different physical characteristics. A database of player physiological characteristics can be set up in order to test exergame systems against a wide range of potential players. This database can test different iterations of the same game or entirely different games (based on similar physical activities), with less need for actual human testers. A further benefit of simulating physiological responses, rather than measuring them for real human players, is the ability to compare different exergames for effectiveness using identical player data. Comparing different games using real test subjects can be difficult because an individual's physical responses can vary in both the short and long term, and can additionally be influenced by outside factors. For our purpose of aiding software development we only consider modelling of heart rate response in people without significant health problems.

5.1 Adding a Virtual Body

To remove the need for physical exertion when testing an exergame, we need to virtualize the physical-exertion components of the system. Ideally, we would automate the entire human-interaction part, but automating player responses to each part of the game is impractical, especially as the game undergoes design and development changes. What we can do is replace the physically demanding controller with a standard game controller that does not require the same level of physical activity. Let us recall the standard exergame components as described in Chapter 1.

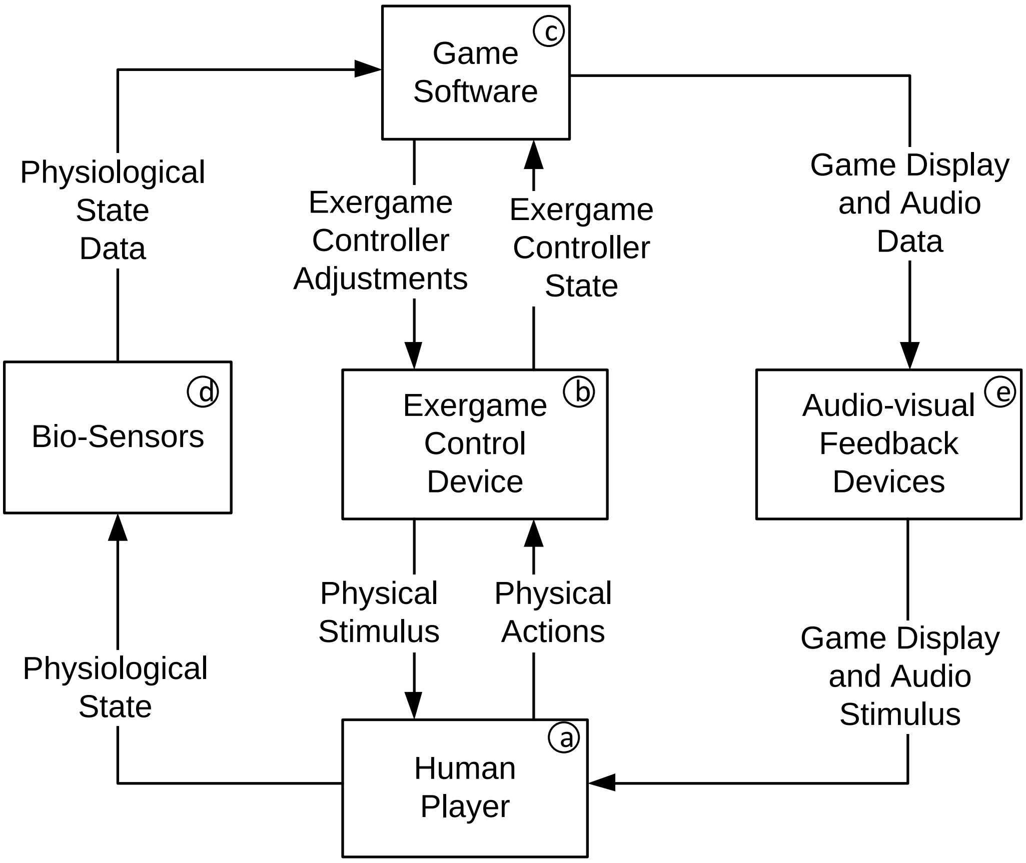

Figure 33 A standard exergaming system, showing the system components and interfaces.

We can modify the standard exergaming system, shown in Figure 33, by introducing virtual components that replicate the required functionality, as Figure 34 illustrates. The virtualized parts of the system are shaded in the figure for clarity. We want the game software to remain unchanged because that is the core system that we are attempting to test. The human player no longer provides actions directly using an exergaming controller but uses a standard game controller to play the exergame. The standard controller's output is then passed to a virtual controller that simulates the control device that would normally be used.

Because the player no longer performs the physical activities normally associated with the game play, we must replace any biosensors that the game uses with software that generates simulated sensor data. The system in Figure 34 includes a player physical state emulator, which calculates the player's normally expected state on the basis of the player's simulated physical actions. The virtual biosensors then use the player's physical state to generate the required simulated sensor data.

Our new system has two configuration databases. One contains the simulated player's physical characteristics. We can modify the player characteristics to test against a wide range of player types. The other database has information about the characteristics of the physical controller the exergaming system normally uses. This data helps map standard controller actions into simulated physical actions.

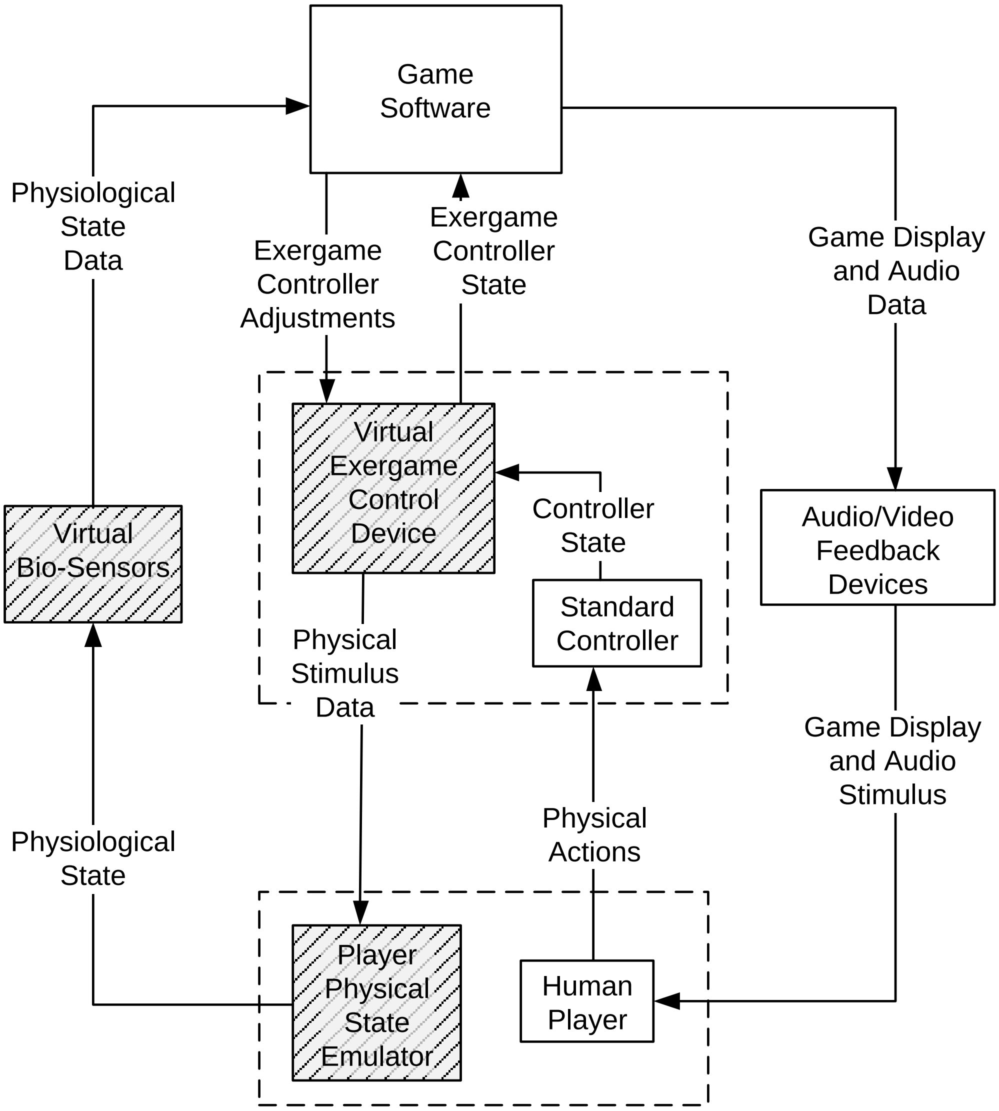

Figure 34 An exergaming system with emulation. Note the extra shaded components added to Figure 33, providing simulated data as required.

There are three key functions that the Virtual Body Simulation software needs to perform:

1. A means to play an exergame game using a standard joystick controller, while simultaneously reading the game joystick motions and converting them to exertion measurements, which can be used to generate physiological data.

For flexibility this needs to be done while still interfacing the exergame as a standard videogame controller.

2. A mechanism to convert joystick motions of one type, as appropriate for hand held play, into other joystick inputs, those appropriately representing the inputs produced by the physically demanding exergame controller.
3. A means of generating physiological responses from physical exertion data.

5.2 Exergaming Control Devices

A game controller input consists of axes and buttons. An axis is a controller movement that outputs a value within a range. A control movement of this type could require effort to move the control from one value to another. An example would be turning a steering wheel or lifting a weight to a certain height. Axis-type controls can also require maintenance energy expenditure. An example of this is an accelerometer. Force is required to produce a reading and also required to maintain a reading.

Buttons on a controller represent a digital state: on or off. Buttons can also be used to indicate an event has occurred. In the case of our Gamebike, regular button presses are used to represent the rotation of the pedals. The controller presents a button press for every half turn of the pedals.

Two key energy expenditure values are associated with buttons. There could be energy expenditure in pressing a button (or turning it on) and in maintaining the button's "on" state.

5.3 Virtual Exergame Controller

In order to replace the exergame controller, with a less physically demanding game controller, we need to assign some energy expenditure values to its movements. These values are representative of the physical activities which would normally be performed when using the normal exergame controller. We assign a value in joules to each movement that expends energy. There are several types of movements and ways we can assign energy values to these movements, depending on the energy expenditure needed for the device we are modelling.

In our Virtual Body application, we support the assignment of two polynomial expressions to each axis of movement. One represents the energy in joules required to get from one setting to the next. The other is the energy in watts required to maintain the current setting. Our Virtual Body software also supports the assignment of a joule value for a button press. We can also assign a value in watts to a button to indicate the energy required to keep the button on.

Accurately calculating the energy expenditure of exergame players can be a difficult task. The energy expenditure required to turn the pedals on the bike at a particular resistance setting can be measured. This value remains the same for all players. However, this value does not equate to the full energy expenditure of the subject. The actual amount of energy expended by the bike rider may be influenced by a number of factors such as leg length, sitting position, and body mass.

For other exergame controllers, players can expend energy in many ways that the game inputs cannot measure. For example, in a foot-pad-based game, the player’s skill level will significantly affect the energy expended for each move. Larger steps will require more effort than smaller, more precise steps (Masek, Hingston, Carrigy, Collins, & Nosaka, 2009). The same is true for systems using accelerometers, such as with the Wii. In some games, short, sharp movements could have the same game play effect as larger, less efficient movements, but expend different amounts of energy. We need to carefully calibrate the software for each emulated physical-input device. We need to know what the actual energy output is for various actions. For some exergaming devices, finding the correct measurements can be complicated.

5.3.1 Gamebike

For this study, as described in section 4.3.4, we used a modified Cat Eye Gamebike Pro; a steerable, variable resistance exercise bike that can be used with the PC using an adapter kit. The bike functions as a standard PC USB device, using the Human Interface Device class. The cycling action translates to a series of repeated button presses on a standard controller. The steering action translates to movement on one of the controller's axes, and there is a button on the handlebars.

5.4 Virtual Exergame Control Software

On a Windows PC-based system, many exergame control devices interact with the game software through the standard Windows game controller interface. This is the case with the Gamebike. The Virtual Body software is designed to remap a Windows game controller port to a virtual game controller, which then interfaces with the game software.

What this means that you can replace the controller with any standard Windows game controller. The game software does not require any modification, which means you are potentially able to use the Virtual Body with standard commercial exergame systems. However, simply replacing the controller would not be sufficient for our purposes. We need to record and process the player's actions so that we can model his or her physical state.

To implement a virtual exergame control device, we used a software package called PPJoy (Westhuysen, 2003). PPJoy is a driver for the Microsoft windows operating system which creates a virtual parallel-port joystick. A software package for mapping a physical device to the virtual parallel port joystick is freely available from the software service company Assembla (assembla LLC, 2008). This software package has been developed for use with flight simulators in order to interface custom-built aircraft cockpits and instrument panels. Many flight simulator enthusiasts build elaborate I/O systems, which use the software to map into the flight simulator software via a virtual parallel-port joystick.

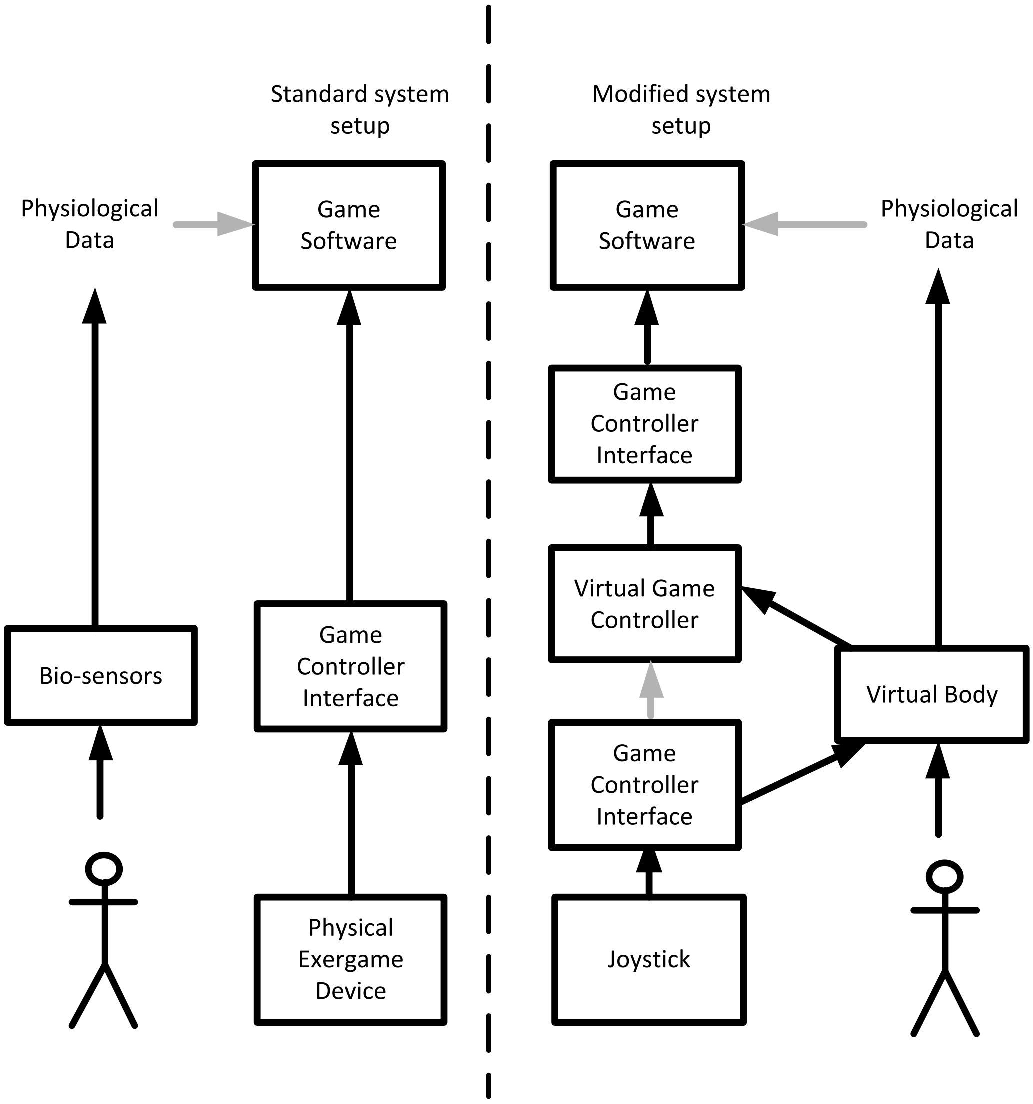

Figure 35 The setup of the Virtual Body compared to a normal exergame. The movements of the controller are re-routed into the Virtual Body software. The Virtual Body software can then process the data to produce physiological responses as well as appropriate game control inputs.

In a normal exergame the Physical exergame device produces outputs which are sent to the normal windows game controller interface, the left side of Figure 35. The game software then reads the game controller motions and systems through a standard interface such as Microsoft Direct-X.

In our modified setup, the right hand side of Figure 35, a standard joystick is used as input into a game controller interface. The Virtual Body has been built using the Microsoft .Net platform. It uses Microsoft's Managed Direct-X API to read from the game controller interface. It then performs any appropriate re-mappings required to match the data to the required physical exergame device.

For example, in the case of the Gamebike, cycling is presented to the PC as a series of button presses. When using the Virtual Body and a standard joystick we allow the user to press and hold a single button. This single button press is translated into a series of presses, with a slider on the joystick being used to manage the rate at which the button presses are delivered. The new data is then written to the virtual joystick. The Exergame software then read the virtual joystick as a normal joystick.

In Figure 36 we see a configuration screen for the virtual player. In this case, a Logitech Attack 3 joystick is being used a substitute for the exertion interface. It has three axis, X, Y and Z, plus 11 buttons. The Logitech Attack 3 has no POV/Hat switches. In the figure, we can see button 1 being mapped to the virtual controller.

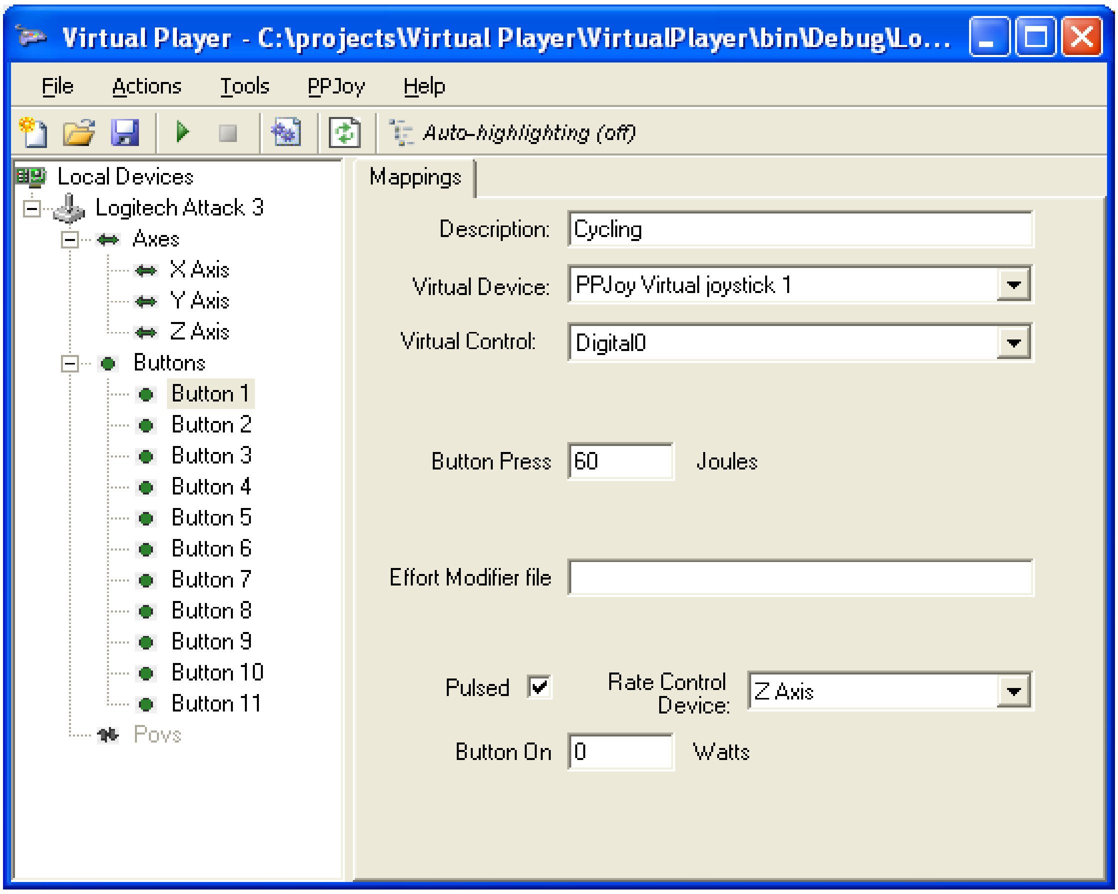

Figure 36 Virtual Body configuration screen showing the mapping of the normal cycling to a button press on the attached standard Logitech joystick. The pulsed check box allows the player to press and hold the button, but have this passed forward to the game software as a continuous sequence of new button presses.

When the Virtual body was first developed it was refined and tested with an existing experimental exergame system called Bike World.

5.5 Using the Virtual Body in Bike World

Bike World is a simple exergame for two players connected over a network. Players use a modified Gamebike to move around a virtual world and fire explosive arrows at each other. Although the game is simple, it’s fun to play, easy to learn, and provides moderate exercise.

In the game, pedalling the bike corresponds to forward movement. We have thus mapped the frequency of presses as an indicator of cadence- the speed in RPM at which the pedals are rotated by the cyclist. To calculate the player’s virtual work, we must assign energy values to each action. So, we assign a fixed number of joules to a pair of consecutive button presses. Power output on a bicycle depends on how hard you push on the pedals and how fast you pedal. If you push harder or pedal faster, you expend more energy. Although we could program the resistance level on the Gamebike, for this game the resistance was set at a constant level. This allows the use of cadence alone as a proxy for work rate.

Figure 37 shows two players playing Bike World. The player on the left is using the modified Gamebike as a controller, so he is actually sweating, physically pedalling, and steering the Gamebike. He has a heart rate sensor strapped to his chest and must stay in range of the heart rate receiver. The player on the right is resting comfortably, using a normal game controller to simulate pedalling (holding down a specific button and using the joystick to control the cadence). He steers with the joystick and fires arrows using another button. The Virtual Body system is providing simulated heart rate data based on the virtual work that he is doing.

Figure 37 One player uses his real body (left) and another player uses a Virtual Body (right) to play a game of Bike World.

5.6 Emulating the Player's Physical State

The simple Bike World program does not use physiological feedback. Biological feedback is used by the exergame system developed for the study in this thesis and simulation of this data was an important goal for the development of the Virtual Body Simulation. Even when the Virtual Body software is used on a system that is not using physiological feedback it is still crucial to have this information. The software developer needs this data to verify that any changes he or she has made are on the correct track. During development, it is important to ensure that the workouts required by the software, are not too hard or too easy.

The physical exertion data generated by the game play is transferred to another part of the system to produce the simulated physiological effects of a Virtual Body. This data can be used to make the system work with any exergaming systems requiring biofeedback. For example, the software could calculate heart rate such that it can provide input into systems measuring heart rate. Ideally, the Virtual Body would also be able to respond to excessive exercise in the same manner that a player actually exercising would.

In simulating how physical activity affects a game player's physiological state, we could attempt to model many physiological effects and measurements. As mentioned in Chapter 4, oxygen consumption (VO_2), is a good indicator of exercise intensity but not ideally suited to being measured in exergames. Heart rate, while not quite as good as oxygen consumption, is easier to measure and suited to use in exergames systems. For the Virtual Body system, we produce simulated heart rate data as an indicated of the intensity of the exercise being performed by the subject.

5.6.1 Simulating Heart Rate Response to Exercise

We use configuration data to model players with different heart rate response characteristics. However, because the response varies between exercise sessions, if we used the system to predict expected responses for a real player in the loop, the model would have to recalibrate itself for each new exercise session, perhaps using configuration data as a starting point. Figure 38 is a plot of measured and simulated heart rates for an exercise session undertaken on a Gamebike.

In this session, we fixed the bike's resistance at a moderate level. The subject cycled using an interval pattern, interspersing 5-minute periods at a fairly constant cadence of 60 revolutions per minute with rest periods. In the figure, the lower dashed line is the cadence, which is approximately proportional to the work rate. The dotted line is the measured heart rate. We can visually pick out several key features of the heart rate response and combine these with prior knowledge to propose three principles:

For a given exercise intensity,

- There is an equilibrium, a steady-state heart rate that relates linearly to the intensity level.
- At a given exercise intensity, the instantaneous heart rate moves toward this steady-state rate at a rate that's proportional to the difference between the instantaneous and the steady-state rates.
- The steady-state rate increases over a period of exercise (see 5.6.1.1).

These principles are in general accord with known features of a normal heart rate response (Wilmore & Costill, 1994). We have, however, made some simplifying assumptions. The heart rate response to exercise generally differs between anaerobic and aerobic exercise, generally coinciding with the anaerobic threshold, the point at which lactic acid starts to accumulate in the muscles (Conconi, Ferrare, Ziglio, Droghettie, & Codeca, 1982). The point at which this deviation occurs varies among individuals, is protocol dependent, but generally occurs at around 85% to 90% of maximal heart rate (McArdle, et al., 2007). For our study, we are interested in aerobic exercise and will be focused on exercise at around 60% of heart rate reserve. This is well below the anaerobic threshold, so we ignored the differences in heart rate response after the threshold in our simulation of heart rate responses.

Additionally, based on Warner & Cox (1964), the mechanism for increasing heart rate when exercise intensity increases, differs from that for reducing heart rate when intensity drops. The change in heart rate occurs at different rates; however for simplicity we use the same rate for both directions. Our results indicate that these simplifying assumptions are reasonable.

We need to operationalize our general principles as a set of formulas. We have not found an equivalent set of equations in the literature that we could use for this application. Some related formulas exist, but none fit our needs. For example, we could potentially estimate heart rates from the ACSM's VO_2 calculations because there's a reasonably linear relationship between heart rate and VO_2. The following function estimates oxygen uptake required for leg cycling:

$$\begin{aligned} VO_2 = {} & \text{Load(work rate)/body mass} \\ & + \text{Unloaded Cycling} \\ & + \text{Resting Oxygen Uptake} \end{aligned} \tag{14}$$

where Unloaded Cycling is the oxygen needed to move the legs against zero resistance.

However, this function is specific to cycling, applies only to steady-state conditions, and requires data that would be difficult to measure.

Warner & Cox (1964) developed a model for the simulation of heart rate responses to direct stimulation of the sympathetic and vagus nerves. The sympathetic and vagus nerves are used in regulation of the heart rate during exercise. In order to produce their model Warner & Cox performed heart rate measurements while performing direct electrical stimulation of the nerves in a number of dogs. While their heart rate response modelling is similar in nature to what we are attempting, the modelling performed on the heart controlling nerves does not directly translate into heart rate response to exercise. We require for our purposes, a simpler higher level modelling of heart rate response to exercise.

We offer our own set of empirical equations based on broad principles. We assume that doing a unit of work increases the steady-state heart rate and that this effect decays with time (like radioactive decay) see Equation 15.

Suppose that we have a measurement of the instantaneous work rate w(t). For example, with an exercise bike we might calculate this from cadence and resistance force. We define the discounted accumulated work d(t) at any point in the session as:

$$d(0) = 0, \text{ and}$$
$$d(t + \Delta t) = w(t) \times \Delta t + \delta \times d(t) \tag{15}$$

where Δt is the time step and δ is the discount rate (that is, the decay rate). We then calculate the steady-state heart rate for a given work rate *w* as

$$ehr(t) = rhr + a \times w + drift \times d(t) \tag{16}$$

where *rhr* is the pre-exercise heart rate, a is the relationship of the increase in the heart rate above the pre-exercise rate to work rate, and *drift* is a constant that determines the size of the cardiac drift. Finally, we update the heart rate from one calculation to the next using

$$h(t + \Delta t) = h(t) + \alpha \times \Delta t \times (ehr(t) - h(t)) \tag{17}$$

where α determines how quickly the person approaches the steady-state heart rate. So, we have five parameters - δ, rhr, drift, a, and α - that we can use to fit the model to a particular person.

To determine the model parameters, we use an optimization algorithm, as we describe in the next section. We provide a detailed verification of the success of the model in later sections. Here Figure 38 shows a representative example of how the algorithm performed for one subject. The upper solid line in the figure shows the simulated heart rate calculated using this model. In this case, the simulated data fits the real data rather well, suggesting that the model captures the important features of the response to exercise in this case.

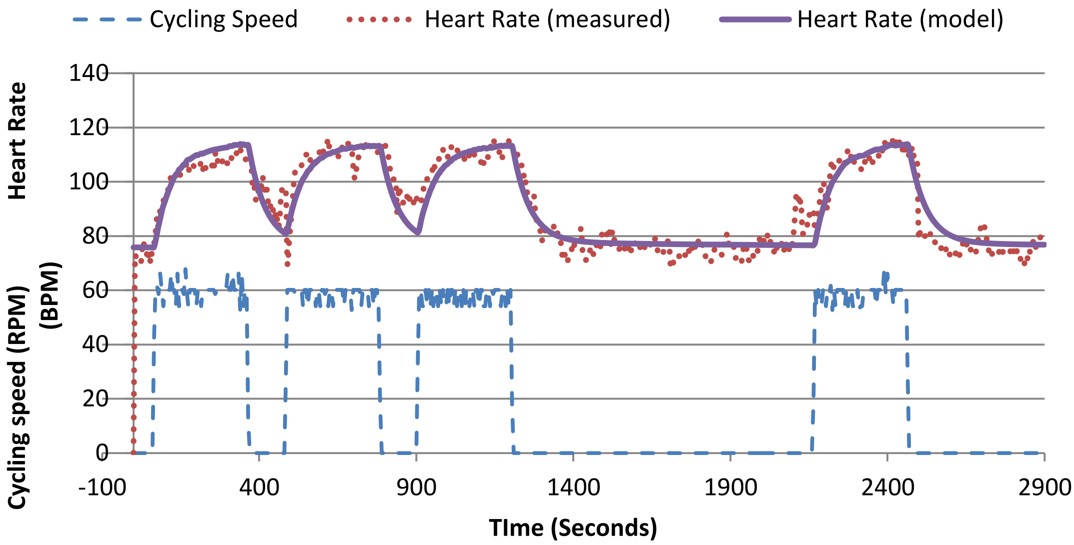

Figure 38 Simulated and measured heart rate responses for a subject with a fixed resistance level, and periods of 5 minutes at approximately 60 revolutions per minute, interspersed with rest.

5.6.1.1 Cardiovascular Drift

During continued exercise at the same intensity, after approximately 10 minutes, heart rate will continue to slowly drift upwards (McArdle, et al., 2007; O'Brian, 2003). This is known as cardiovascular or cardiac drift. There are a number of different explanations offered for the cause of this drift.

As the human body heats up, blood flow to the skin is increased to promote cooling. This results in a shift in fluids from blood plasma to the skin tissue – an increase in cutaneous blood flow. This results in a decrease in pulmonary arterial pressure and reduced stroke volume in the heart. To maintain cardiac output at reduced pressure, the heart rate must be increased (McArdle, et al., 2007; O'Brian, 2003).

Cutaneous blood flow is a commonly given explanation, however Coyle & Gonzalez-Alonso (2001) claim that the evidence for this is lacking. Other explanations for cardiovascular drift include dehydration, fatigue and reduced preload of blood into the heart before contraction.

Regardless of the exact cause of cardiovascular drift, Wingo et al. (2005) assert that it is related to reduced maximal oxygen uptake and increased metabolic intensity. This supports the use of changes in heart rate to reflect changes in intensity.

5.6.2 Calibrating the Heart Rate Response Model

To simulate the heart rate response for a specific player using a specific exergaming input device, we must do two things:

- The input to the heart rate calculation is a stream of (real or virtual) work-rate data, w. We must map input signals from the exergaming control device to calculate work.
- We also need suitable values for δ, *rhr*, *drift*, *a*, and α. In other words, we must calibrate the model to fit each player. We can then use the formulas described earlier to calculate the heart rate from the stream of work-rate data.

Here, we illustrate this calibration for the Gamebike example. The physical exertion required to operate the Gamebike has three components.

1. A constant baseline of effort required just to sit stationary on the bike, keeping balance and maintaining normal breathing.
2. The effort for the specific player to cycle without any resistance set, unloaded cycling.
3. The effort required to drive the pedals against a given resistance at a given cadence.

For this application, we incorporate the first component, the constant baseline of effort, into the pre-exercise heart rate, by using the resting heart rate to represent the pre-exercise heart rate when the player is seated on the bike.

Based on the ACSM formula for leg ergometry (physical work activity) (ACSM, 2006), the effort to pedal with a given resistance will much larger than the second component, the energy cost of the unloaded cycling. As a result of this, we have ignored the second component in our equation, because, compared to the third component it will have a negligible impact.

To simplify matters, we set a constant resistance level, so the only variable is cadence. We follow this up in our trials by also using a constant resistance which is calculated and set on a per subject basis. With these assumptions, the work rate is directly proportional to the cadence, so we have used cadence as a proxy for work rate.

The requirements for a model-calibration method depend on the application we have in mind. Our heart rate response model has at least two potential applications. Our primary application is to provide simulated heart rate data for exergame testing. Second, in exergames where we want a feedback loop to manipulate the player's heart rate (for example, to keep it within some upper and lower limits) by changing the work rate (for example, by changing the resistance level on an exercise bike), we'd like to be able to predict the effect of a change in work rate.

For the first application, we can do the calibration offline and store the results in the player characteristics database. It's not that important if the calibration is valid only for a particular session as we can store multiple profiles. For the second application, the model must be accurate for each session. So, we want a method that lets us recalibrate the model during play, preferably with no noticeable effect on game play.

5.6.3 Genetic Algorithm

Keeping in mind these possible applications, we opted for a method that we can use to recalibrate the model in real time during actual play, if desired. Using sample data such as that shown in Figure 38, we used a genetic algorithm (GA) to search for values for δ, *rhr*, *drift*, *a*, and α that minimize the mean squared difference between the measured heart rate and the predicted heart rate.

GAs are an optimization method modelled on natural evolution (Goldberg, 1989). The GA represents an iterative process where each iteration is called a generation. A population of potential solutions (genomes) is maintained. The genomes are subjected to variation (mutation and crossover) and selection (removing lower-quality solutions) during each iteration. We stop our run after a defined number of generations, at which point the GA should have generally found a high quality solution.

For the GA, we initially used a genome consisting of five nonnegative real values (representing the model parameters). A GA with the following properties:

- Gaussian mutation, adding a random value from a Gaussian distribution to each element of an individual's vector to create a new offspring.
- Linear fitness scaling – the scaled fitness of an individual in the population is linearly related to the unscaled fitness.
- a population of 250, and
- Run length of 500 generations.

An alternative approach would be to measure *rhr* (the pre-exercise heart rate) separately and use the GA to determine the other four parameters. However, this would require interrupting the normal game play. So, we opted to attempt to fit all five parameters, including *rhr*, directly from in-game data.

5.6.4 Initial Results

Initial attempts with this setup produced variable results. For some data sets, each time we ran the GA, it reliably found similar parameter values that fit the data well. However, for other data sets, the GA occasionally (approximately 10 percent of the time) found parameter values giving a better fit. When this happened, the value of δ was approximately 0.99 for the better-fit cases, and near 0 for the poorer fit. The GA could not reliably locate this superior set of parameter values.

We fixed the value of δ to 0.99 and used the GA to search for good values for the other four parameters. (We also tried 0.995, with similar results.) The GA then gave reliably good results over all the data sets, with similar parameter values each time it ran on a particular data set. However, we still saw a good deal of variation in the parameter values between data sets.

Table 2 shows the GA results for one data set, similar to the one in Figure 38, but with periods of 70 revolutions per minute instead of 60. Figure 39 shows the simulated heart rate data these parameters generated.

Table 2 Parameter values returned by 15 runs of the genetic algorithm.

Run	rhr	a	α	Drift
1	75.260	0.636	0.095	0.0032
2	75.642	0.676	0.078	0.0026
3	76.330	0.634	0.092	0.0029
4	76.466	0.659	0.087	0.0025
5	73.907	0.615	0.102	0.0040
6	75.877	0.654	0.088	0.0028
7	75.368	0.644	0.093	0.0031
8	74.416	0.635	0.094	0.0035
9	76.184	0.666	0.084	0.0025
10	76.092	0.645	0.091	0.0029
11	75.240	0.632	0.097	0.0033
12	75.191	0.647	0.089	0.0031
13	74.341	0.626	0.096	0.0036
14	75.104	0.619	0.098	0.0035
15	75.923	0.637	0.092	0.0030
Mean	75.423	0.642	0.092	0.0031
Std. dev.	0.763	0.017	0.006	0.0004

For another data set with the same subject, resistance level and cadence, recorded on a different day and with longer intervals of exercise, the GA found these values:

rhr = 75.39, $a = 0.375$, $\alpha = 0.218$, and *drift = 0.006.*

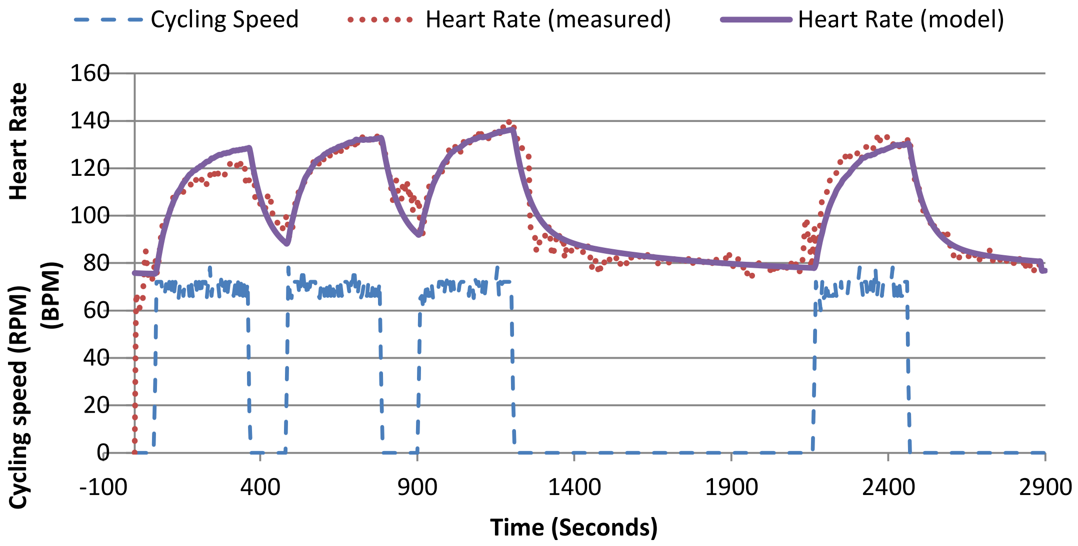

Figure 39 Simulated and measured heart rate responses for subject, with a fixed resistance level and 5 minute periods of cycling at approximately 70 revolutions per minute, interspersed with rest. As in Figure 38, and despite the higher exercise intensity, the simulated and measured heart rates match well.

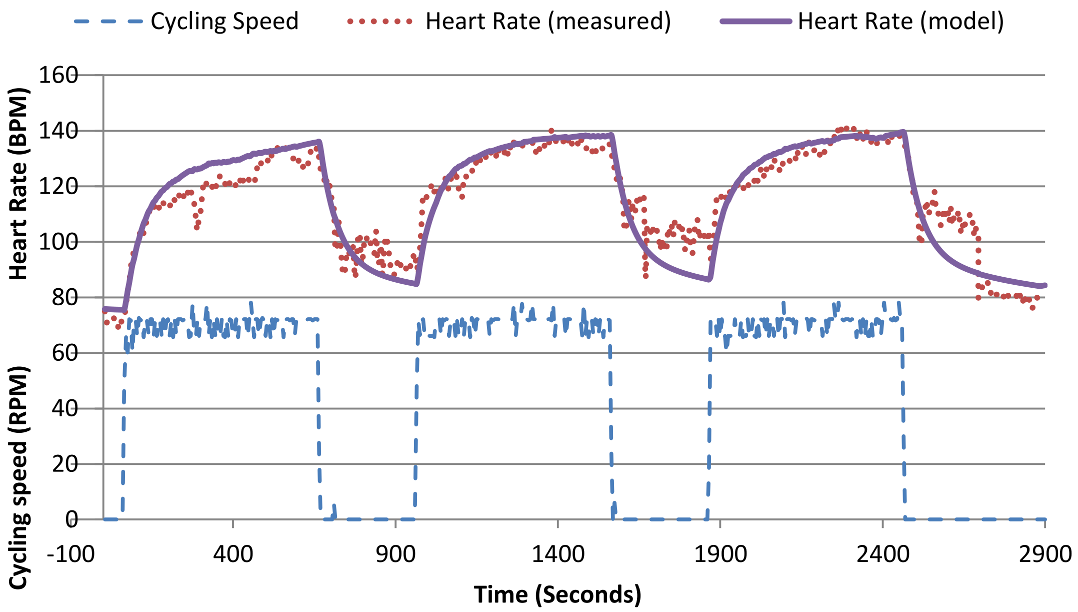

Figure 40 Simulated and measured heart rate responses where the simulated data is calculated using parameters fitted to a different data set.

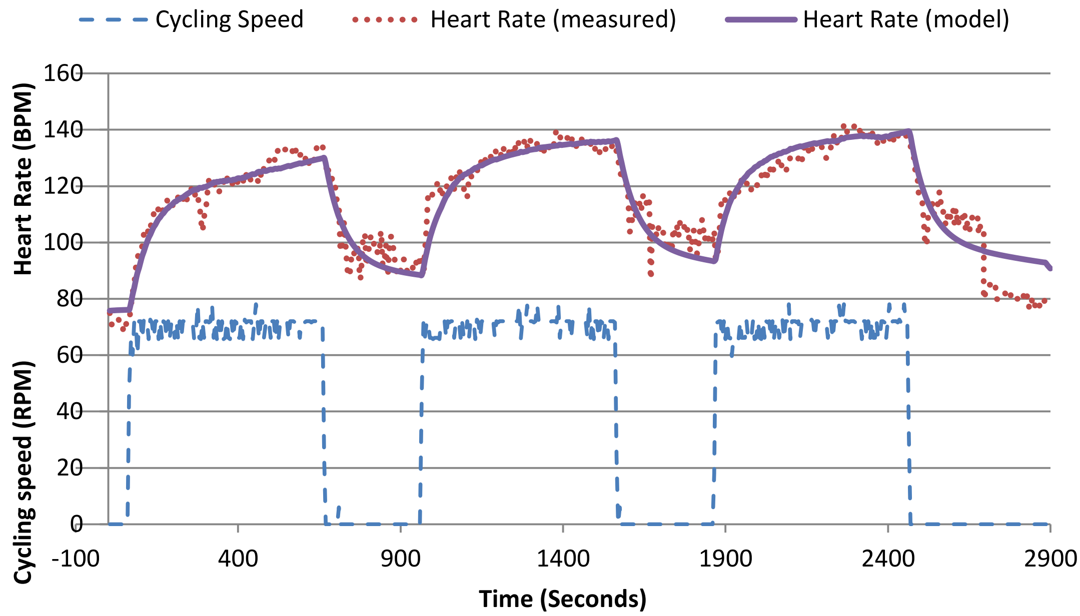

Figure 41 Simulated and measured heart rate responses where the simulated data is calculated using parameters fitted to the same data set. Comparing Figure 40 and Figure 41, you can see that although the prediction model is more accurate within the same exercise session, the fit is still reasonably good between exercise sessions.

Figure 40 shows the simulated heart rate data generated using the means from Table 2 (that is, the simulated data uses parameters derived from a different data set). Although the fit is reasonable, we obtained a better fit using the parameters derived from the data set itself, as Figure 41 shows. The visual difference is not significant, but the fit is definitely better in objective numerical terms. In the first case, the root mean square is 7.36, and in the second 6.75.

5.6.5 Heart Rate Measurement Accuracy

During the study, we used a polar Wearlink chest strap. The manual for this device lists an accuracy of "± 1% or ± 1 bpm, whichever larger". However, the manual states that this accuracy only applies in the steady state. Testing by Burke & M. V. Whelan (1987) indicated that when bench testing several different heart rate monitors their results were good within 2-3 bpm, however when used on subjects jogging at slow speed on a tread mill “typically 20-70% of the readings given by the machines had errors of greater than 20 bpm”.

Boudet & Chaumux (2001) in laboratory testing found that 98% of values were within ± 3bpm. The heart rate monitors are also known to do filtering and smoothing of the real data when in transition. The exact nature of this smoothing and filter is proprietary information and the exact effect this has on accuracy is difficult to judge.

In real word exercise situations, measurement of heart rates is not exact. There are a number of physical considerations which can also add to the difficulty of getting an exact reading; for example, difficult getting a good electrical contact and electromagnetic interference.

For our purpose of simulating the exercise response of subjects playing an exergame, we conclude that ±5% is a sufficient level of accuracy.

5.7 Exergame Trial Data

After the development of the exergame and the trial performed for the study, we were able to take the trial data from our 21 subjects and verify the Virtual Body against this data. Each subject undertook 5 different sessions on the bike, on different days.

During the trial the exergame system was used in 5 different modes as discussed in section 4.2.2

- Non-game – where the user had to keep a mark centred on the screen.
- Static mode (Mode S) – Statically pre-planned workout intensity with linearly increasing game challenge.

- Intensity controlled (Mode I) – Dynamically controlled workout intensity with linearly increasing game challenge.
- Challenge controlled (Mode C) – Statically set workout intensity with dynamically controlled game challenge.
- Full control (Mode F) – Dynamically controlled workout intensity with dynamically controlled game challenge.

In these sessions the player played our exergame, which generates significant variance in the cadence of the player, rather than the interval pattern used in the earlier data sets. The data generates a good fit. For this data set, a higher data sampling rate of reading every second was used, which produced generally improved results compared to those of Figure 40 and Figure 41.

The outcomes as shown in Table 3 were reasonably good. For most subjects the RMS error of the session was only 3 or 4 beats per minute. There are some cases where the error was significantly higher, being in the double figures; Subject 4102 session 4, 4567 session 1, and 4771 session 3. The cause of these higher values is discussed in the next subsection.

Table 3 Heart rate RMS error of formula over each session.

Subject	Modes				
	Non-game	S	C	I	F
1076	5.009	4.532	4.157	3.856	4.521
1134	3.967	4.417	3.171	5.142	3.494
1377	5.956	4.547	4.086	3.330	3.532
1464	2.901	2.533	2.625	3.209	3.135
2457	3.015	2.986	4.008	3.562	3.048
2565	2.801	2.587	3.621	3.750	2.517
2810	4.282	3.568	4.414	4.005	5.134
2830	4.287	3.702	2.869	2.562	3.560
2866	4.198	4.012	3.990	3.195	3.962
4102	3.520	3.138	12.166	2.730	3.310
4228	3.432	2.958	3.460	2.866	2.872
4386	4.353	4.520	4.439	3.339	3.241
4446	3.174	2.451	3.095	3.785	7.319
4496	3.193	5.549	4.066	5.118	3.521
4501	3.105	2.487	2.834	2.725	2.410
4567	10.565	3.356	3.323	3.793	4.303
4623	3.589	5.200	4.506	3.296	2.603
4771	3.934	14.028	4.178	3.827	4.717
4881	3.609	3.342	4.552	4.375	3.703
4882	3.189	3.396	4.015	4.659	3.571
4982	3.503	3.347	2.672	3.605	3.751
Mean HR Difference	4.075	4.126	4.107	3.654	3.725
Std. dev.	1.628	2.377	1.904	0.704	1.057

5.7.1 Data Irregularities

The initial thoughts regarding these abnormal values were that they were merely aberrations caused by the mechanism of the genetic algorithm failing to find the appropriate settings. However, repeated subsequent running of the tuning process across these sessions returned matching results with RMS errors which differed by less than 0.1%.

Close examination of the data set used for these three sessions eventually revealed the cause behind these abnormally high error levels. Due to the nature of mechanical systems used in measuring the RPM of the Gamebike, a spike in the RPM measurement occurred occasionally. When this occurred, the software would record a jump in the RPM to a level of around 10,000 RPM. The RPM would then quickly return to normal, but would take 5 or more seconds to return to the correct levels. Each of the three sessions in Table 3, which were identified as having the high error level for the Virtual Body, corresponded to the sessions during which there was a spike in the RPM measurements. Table 4 is an excerpt of the RPM readings for subject 4567 during session 5. We can see that the RPM being around the low 60's suddenly jump to nearly 10,000 before dropping back to correct levels.

Table 4 RPM measurements over 14 second period of the first session for subject 4567.

Time	768	769	770	771	772	773	774	775	776	777	778	779	780	781
RPM	63.28	65.76	5018.9	9492.24	5341.74	2968.97	1666.15	926.5	521.36	310.07	183.18	112.1	67.75	53.52

A filter was applied to the data from the sessions in order to remove the anomalies in the data. The previous value for the RPM was retained when the RPM jumped by more than 50 RPM within the second. The value was repeated until the current readings returned to within 50 RPM of the repeated value.

Table 5 Smoothed RPM measurements over 14 second period of the first session for subject 4567.

Time	768	769	770	771	772	773	774	775	776	777	778	779	780	781
RPM	63.28	65.76	65.76	65.76	65.76	65.76	65.76	65.76	65.76	65.76	65.76	112.1	67.75	53.52

This process removed the 3 previously identified spikes in RPM measurement as well as three other spikes in RPM which were singular 2 second spikes of about 60 RPM.

The filtering system was then also applied to the heart rate monitoring in order to identify and remove errors in the recording of the heart rates. Any jumps of more than 25 beats per minute within a second, were filtered out of the data in the same manner as before. There were approximately ten places in the data where we encountered a several second spike or drop in the recording of the heart rates. After the filtering, we re-ran our previous modelling.

Table 6 RMS Error of formula over each session after data filtering.

	Mode				
Subject	**Non-game**	**S**	**C**	**I**	**F**
1076	4.158	3.800	4.491	4.489	5.058
1134	5.167	4.004	4.466	3.425	3.344
1377	4.073	5.889	3.551	4.465	3.439
1464	3.217	2.907	3.117	2.650	2.487
2457	3.916	3.085	3.584	2.862	2.987
2565	3.609	2.524	3.821	2.688	2.751
2810	5.092	3.541	3.286	4.368	3.678
2830	3.698	3.570	4.290	2.825	2.645
2866	3.997	3.953	4.182	3.961	3.179
4102	3.375	2.838	3.536	2.707	3.181
4228	3.410	3.155	3.449	2.900	2.942
4386	4.415	4.421	4.313	3.302	3.166
4446	3.036	3.789	3.596	3.235	2.438
4496	3.474	3.182	5.553	4.083	4.724
4501	2.495	2.412	2.725	3.101	2.806
4567	3.818	3.315	4.342	3.299	4.099
4623	4.562	5.354	3.560	3.367	2.751
4771	4.719	3.725	4.062	4.166	3.807
4881	3.674	4.312	3.683	4.222	3.392
4882	4.126	3.500	3.364	3.151	4.669
4982	3.577	3.734	3.428	2.709	3.659
Mean HR Difference	3.886	3.667	3.829	3.427	3.391
Std. dev.	0.645	0.821	0.602	0.632	0.723

When examining the results of the model, e.g. Table 3, we saw that the model could potentially provide a means to spot errors and anomalies in the data. For exergames this functionality might be useful in order to spot anomalies in the data collection after the fact, or on a real time basis provide a validation of the data collection. Anomalies could be an indication of failures with the hardware or monitoring systems, sudden changes in environmental conditions, or even potentially medical complications with the subject which might need addressing.

5.7.2 Consistency within Sessions

To test the predictive ability of our model, the sessions were calibrated using only the first 10 minutes of data from the sessions. The model was then used to calculate the heart rates across the entire 30 minute sessions. As we see in Table 7, in most cases the magnitude of the RMS error did not get significantly bigger. 85% of the values show less than three beats larger RMS error than when we used the whole session data to calibrate (see Table 6). This indicates the model is performing satisfactorily.

Table 7 RMS error for all sessions where the first 10 minutes was used to generate the parameters for the remainder of the session.

	Mode				
Subject	**Non-game**	**S**	**C**	**I**	**F**
1076	6.208	5.248	4.776	4.654	5.398
1134	10.916	4.085	4.618	3.560	4.175
1377	4.869	7.167	5.802	4.583	3.759
1464	3.503	3.168	6.646	4.074	2.768
2457	10.472	3.595	5.269	3.827	3.395
2565	4.165	2.655	4.208	3.971	4.188
2810	13.337	5.637	5.072	4.439	4.662
2830	4.666	5.199	6.554	3.098	2.614
2866	6.296	6.812	7.019	7.117	4.796
4102	5.181	3.079	3.871	4.853	4.097
4228	4.154	7.250	5.289	3.148	3.110
4386	4.844	14.180	31.908	3.398	5.297
4446	7.468	4.585	4.940	5.747	3.165
4496	11.159	4.994	13.019	7.376	6.873
4501	2.584	2.731	3.331	3.777	3.483
4567	4.272	3.989	4.775	3.471	5.177
4623	5.159	8.410	4.783	3.684	2.763
4771	10.327	4.198	6.519	4.654	3.900
4881	8.065	4.877	5.723	5.604	4.548
4882	5.488	20.186	4.452	4.366	5.501
4982	6.401	5.460	5.933	3.988	4.224
Mean HR Difference	6.644	6.072	6.881	4.447	4.185
Std. dev.	2.887	4.015	5.908	1.141	1.057

There are some sessions in which the model calibrated only over the first ten minutes does not fit very well. This was mainly due to the lack of heart rate response variation during the first ten minute calibration period. In some of the sessions after the first ten minutes of the session the subject heart rate has not plateaued. This means that the ten minute time period is insufficient to get a good variation in heart rate response. As an example, we can see in Figure 42 and Figure 43 that for these sessions, the heart rate of the subject is almost continually rising during the first ten minutes of the session.

For these sessions, the calibration performed by the GA when using just the first ten minutes of the session, did not have sufficient variation in heart rate response to produce values for the model which worked over the entire session. Furthermore, note that all of sessions with an average error of 8 beats per minute or higher, in Table 7, are in the non-game mode, and the non-intensity controlled modes S and C. The reason for this is that these modes are the modes which generate the least amount of variation in heart rate response. From this we can see the importance of ensuring that a suitable data set is used to calibrate the model.

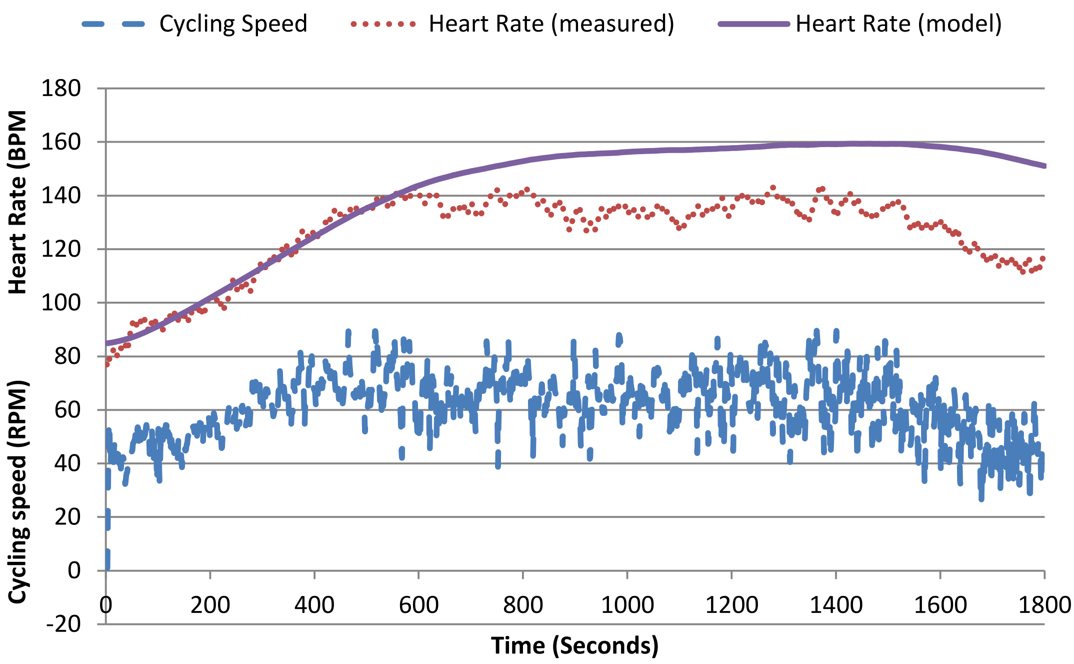

Figure 42 Simulated heart rate response for subject 4882, session 5 exergame play cycling session. The model for this session was calibrated on the first ten minutes, which in this case is not adequate as the heart rate response is almost exclusively in the upward direction.

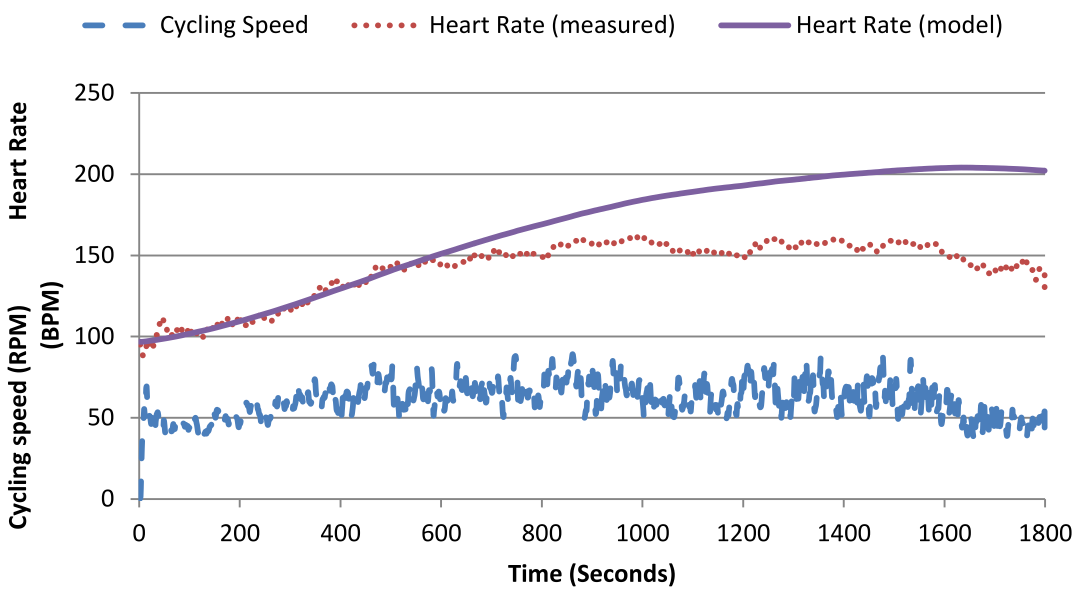

Figure 43 Simulated heart rate response for subject 4386, session 1. The model for this session was calibrated on the first ten minutes, which in this case is not adequate as the heart rate response in almost exclusively in the upward direction.

5.7.3 Consistency Within Subjects

For our session data, we checked the consistency of the model within subject by calibrating the results from one session and using it to model each of the other sessions for the subject. For each subject the parameters produced by the GA earlier were applied to each of the other sessions by that subject.

Table 8 RMS error from using the model for each session when calibrated against the other sessions for subjects 2830

		Session				
		12th Oct	13th Oct	14th Oct	19th Oct	20th Oct
Session Used for Calibration	**12th Oct**	3.698	10.445	5.383	4.862	8.996
	13th Oct	10.469	3.570	12.667	11.265	4.305
	14th Oct	4.723	12.819	2.645	2.810	10.432
	19th Oct	4.654	11.817	3.193	2.825	9.396
	20th Oct	9.458	5.221	11.545	10.186	4.290

We can see from the data in Table 8 that the formula produces the best result for the data in which the parameters are tuned for. This evidence suggests that stored parameter values are completely adequate for our primary application of exergame play testing but that recalibrating the model for each exercise session would be preferable when using simulated data in a feedback loop.

For the subject used in Table 8, subject 2830, there were two sessions that resulted in very similar calibration parameters. The session on the 14th October and the Session on the 19th October both fit the model well see Figure 44 and Figure 45. Two of the remaining sessions for this subject, as shown in Figure 46 and Figure 47, did not fit so well.

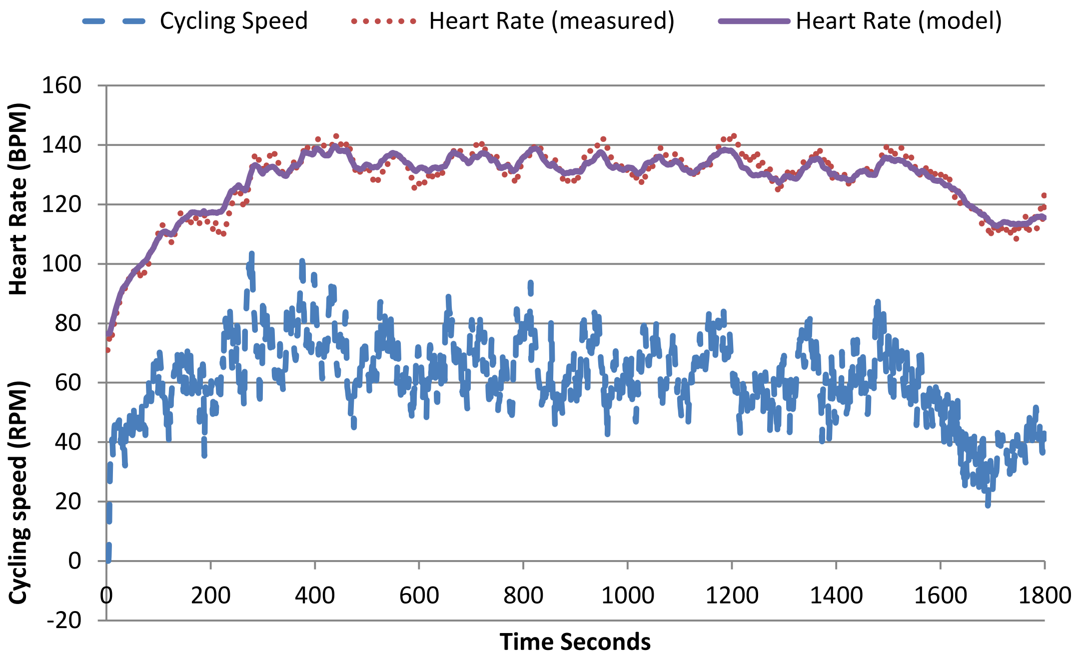

Figure 44 Subject 2830 modelling for the session on 14th October using the same session for calibration.

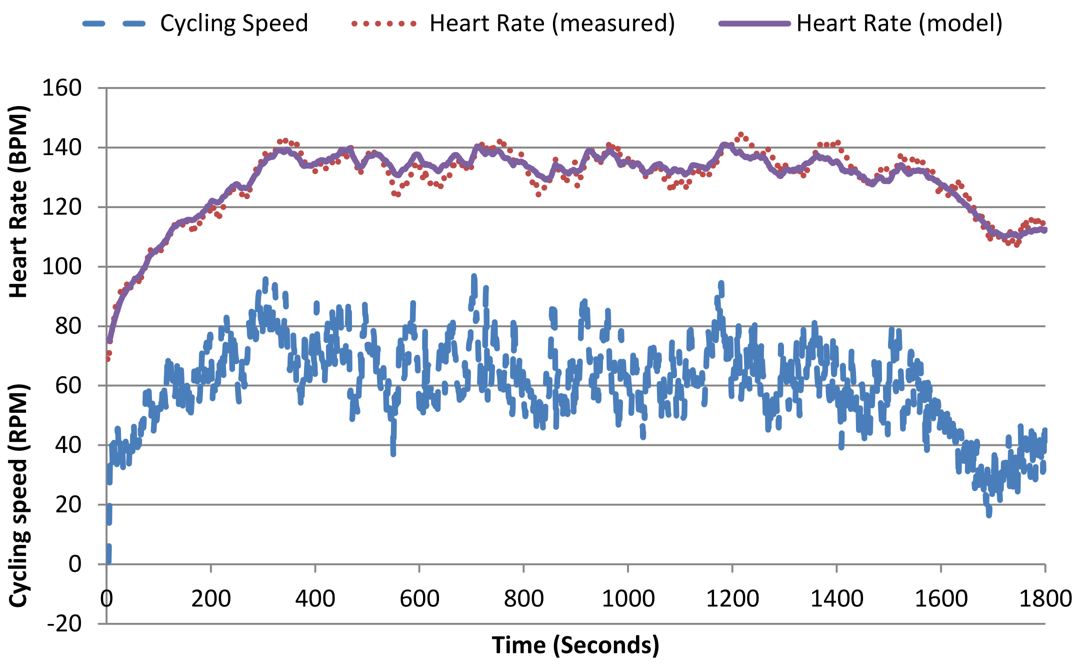

Figure 45 Subject 2830 modelling for the session on 19th October using the same session for calibration.

For the sessions by subject 2830 on October 13th, see Figure 46, and October 20th, see Figure 47, the subject started the session with a heart rate which was elevated above the starting point of the two other sessions, shown in Figure 44 and Figure 45. The model always starts the calibration from the point where the subject is assumed to be at rest; having a resting heart rate. There is no allowance in the model for starting the simulation at any point other than at complete rests. If not, and the heart rate of the subject is already elevated at the start of the simulation, the results will differ from that of the real subject heart rate. The model will have produced results lower than the actual physical reading because of the already raised heart rate.

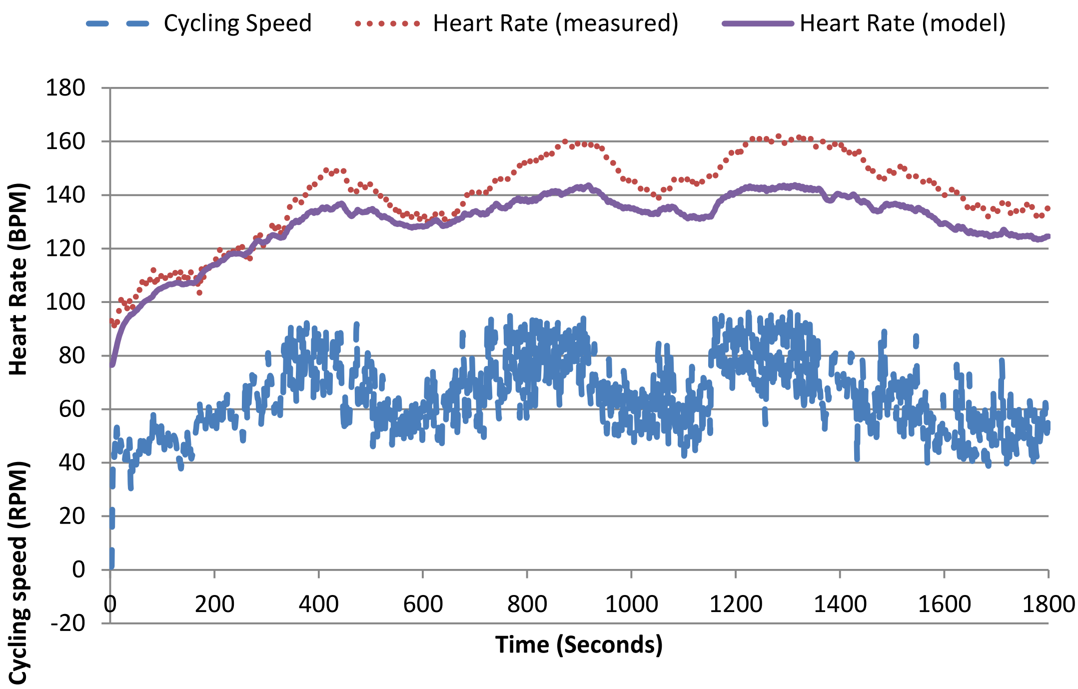

Figure 46 Subject 2830 modelling for the session on 13th October using the same session for calibration. Model has difficulty where player heart rate does not start at rest.

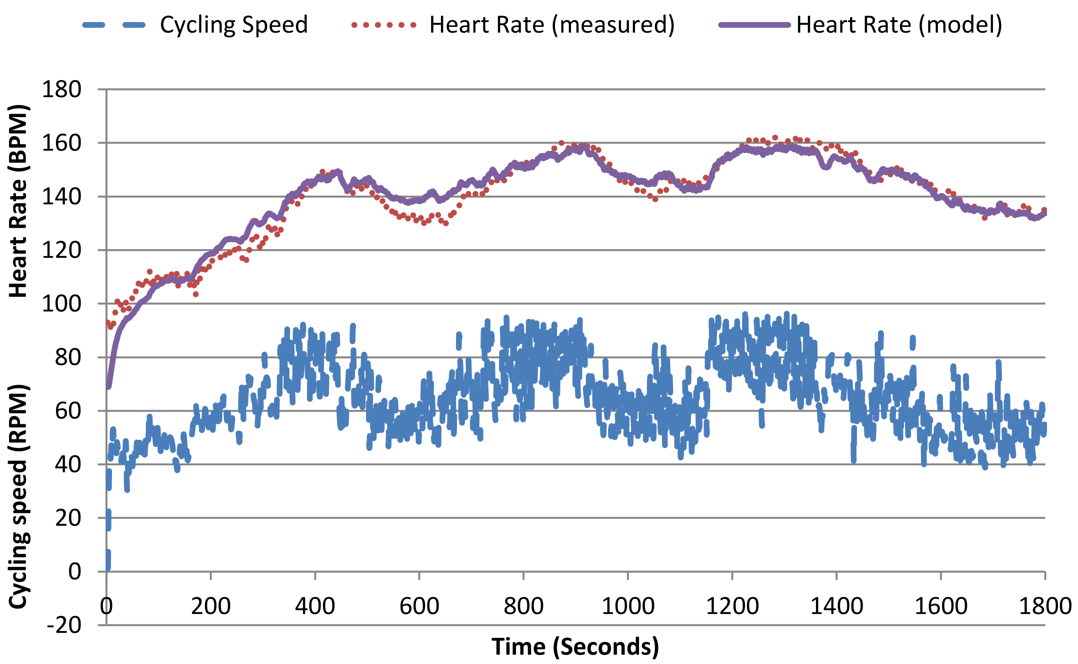

Figure 47 Subject 2830 modelling for the session on 20th. Model calibrated with session starting at rest remains low when run against a session which, does not start at the same level, and potentially has residual work remaining in the system.

To further test the model we can calibrate against a full session and check the fit with the other sessions. This analysis was performed across the five sessions for each of the 21 subjects. In Table 9 we can see that the results were varied.

Table 9 Results from calibration on one session, used to predict heart rate response over a different session.

Subject	Mean RMS Error	Standard Deviation
1076	7.45	1.42
1134	7.91	1.71
1377	8.98	4.51
1464	7.13	2.88
2457	6.69	2.56
2565	5.10	0.94
2810	9.31	2.92
2830	8.23	3.31
2866	7.75	2.48
4102	5.54	1.78
4228	6.88	2.14
4386	6.88	1.40
4446	5.65	1.46
4496	13.43	5.39
4501	6.94	3.00
4567	5.50	1.11
4623	9.74	3.25
4771	5.64	1.12
4881	7.30	2.92
4882	9.59	4.58
4982	10.43	6.86

5.7.4 Player Differences

As we mentioned earlier, to model each player's physiological responses to exercise, we must consider physiological differences between players and even differences for the same player on different occasions. For our Virtual Body Model, we can maintain a player characteristics database that can store a particular player’s physiological data such as pre-exercise heart rate, body mass, or gender. The database can also store parameters for empirical models, such as those in this heart rate response model that might have no direct physiological mapping.

5.8 Summary

Computer games involving physical exercise have been around in some form for more than 20 years. The Virtual Body system addresses some of the issues that make developing and testing such systems difficult. Having tested the model with different intensity patterns on separate occasions, we have found that we can obtain a very good fit.

One problem we found with the model is the need to start simulation from the players being at complete rest. Particularly in an exergame situation, there is a reasonable likelihood that the player may have already undertaken some physical exercise, perhaps previous sessions of the game. Further work is needed to allow the model to counter for situations where the modelling does not start from the point with the player at complete rest.

Additional we still need work to determine how well the model works for various age, gender, health, and environmental parameters and investigate variability over time; however the current results suggest that the approach is valid, and it has certainly been a significant aid in the development of the systems used in this study.

The development of the Virtual Body software allows us to develop an exergame system based on the use of heart rate as a measurement. In our study we have chosen heart rate measurement as a means of applying the effectiveness attribute of the Dual Flow Model.

6 Methodology

In this chapter, we discuss the setup for the trial undertaken as part of this study. The procedures and protocol for each of the different sessions is covered. At the end of the chapter we also cover the tools used in the recording of data collected during the sessions.

As previously discussed in Chapter 4, the exergame system developed for this study was developed to work in the following four different game modes:

- Static mode (Mode S) – Statically pre-planned workout intensity with linearly increasing game challenge.
- Intensity controlled (Mode I) – Dynamically controlled workout intensity with linearly increasing game challenge.
- Challenge controlled (Mode C) – Statically set workout intensity with dynamically controlled game challenge.
- Full control (Mode F) – Dynamically controlled workout intensity with dynamically controlled game challenge.

In addition a non-game mode for instruction and calibration was used.

By having subjects use the exergame system in each of the different modes, we can compare results in order to test the Dual Flow Model. In this chapter we detail the setup of the trial that was performed.

6.1 Trial

In order to test the Dual Flow Model using our developed exergame system, subjects who could attend for five, 1 hour sessions on different days within a two week period were recruited to participate. The first session involved the use of the non-game mode of the exergame. For each participant, the remaining four sessions corresponded to the four game based workout modes. Each of the different game based workout modes were assigned in a random order.

6.2 Subjects

For the study, 25 subjects were recruited. Of the 25 subjects, due to scheduling issues four subjects were unable to complete the trial. 21 subjects, 8 male and 13 female subjects completed the trial. All of the subjects were between the ages of 21 and 41. Of those who completed the trial, three subjects reported that they did no regular exercise, three exercised 10 or more hours each week, and the remainder exercise between 1 and 7 hours per week.

6.3 Session Setup

Each session in the trial involved a 30 minute workout. In all modes, the workout commenced with a 5 minute warm-up period. After 2 minutes of the warm-up, the intensity ramps up for three minutes to be at full intensity at the end of the warm-up; the 5 minute mark of the session. After this warm-up, a 20 minute workout session commences. At the end of the workout, there is a 5 minute cool down period. This period starts at full intensity and then ramps down for three minutes. Following the ramp down, the intensity stays constant for a further 2 minutes before the end of the session, see Figure 48.

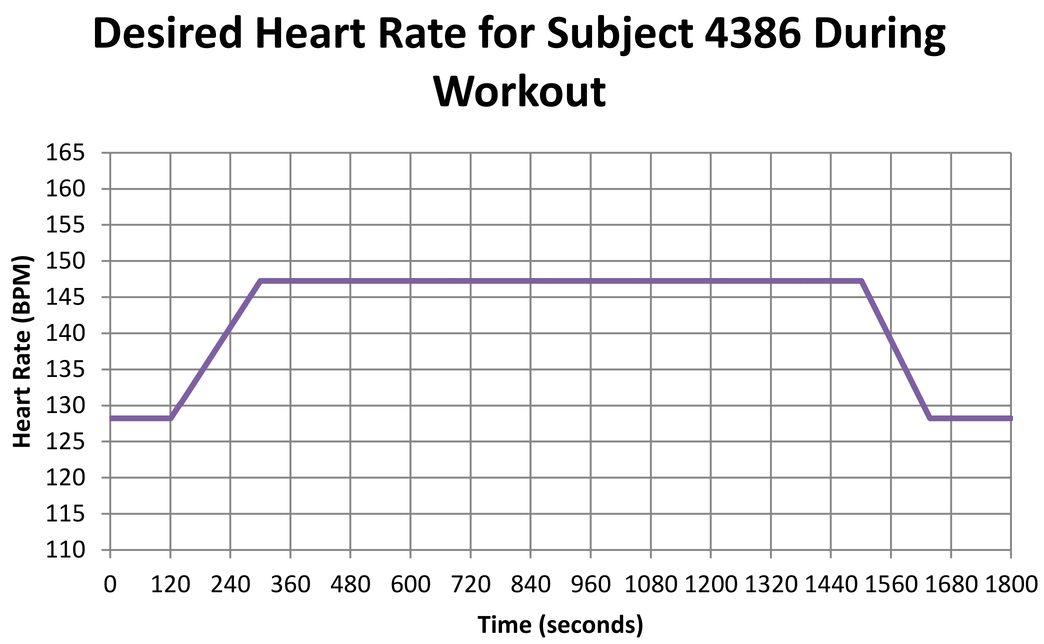

Figure 48 Desired heart rate profile for a specific subject during a workout.

The ideal result for a workout is that the heart rate for the subject closely matches the graph shown in Figure 48. We calculate this desired rate as 60% of Heart rate reserve. Heart rate reserve is the difference between the resting heart rate and the maximal heart rate, which we calculated based on Inbar, et al. (1994), see Equation 2.

The real heart rate will not perfectly match the plot, but our expectation is that the resistance setting would produce a result which was within several beats of the calculated levels. The desired rate for different subjects may be higher or lower than that shown in order to match the 60% maximal heart rate reserve calculated for the particular subject.

6.4 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 adjusted to be at a comfortable height. The seat height was recorded and maintained constant for each of the following sessions.

6.4.1 Resting Heart Rate

The subject sat on the bike in a resting state for five minutes while the heart rate was measured. The resting period allowed the subject's heart rate to return to its normal resting state, in case the subject's heart rate 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 subject's resting heart rate. The resting heart rate was used in conjunction with the subject's age to determine a heart rate level of approximately 60% of the heart rate reserve. See 4.3.1.1 for a discussion on calculation of the maximal heart rate and heart rate reserves. This heart rate was the target level for the workouts.

Based on the 70 RPM desired for the workout, as shown in Figure 49, we needed to set the Gamebike resistance correctly to achieve the calculated heart rate for this subject. In order to calculate the resistance required a ramp-up test was used.

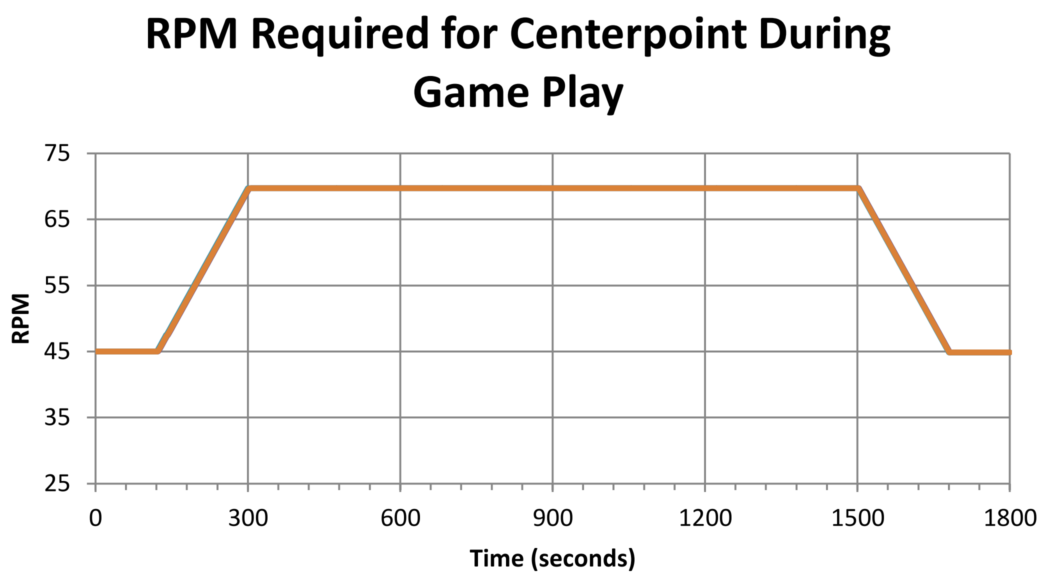

Figure 49 The RPM required to maintain the centre point during game play of a session without dynamic control of the intensity.

6.4.2 Ramp-up Test

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.

In Figure 50 we can see the data from a ramp-up test. The last minute of each three minute section has been highlighted and a trend line drawn.

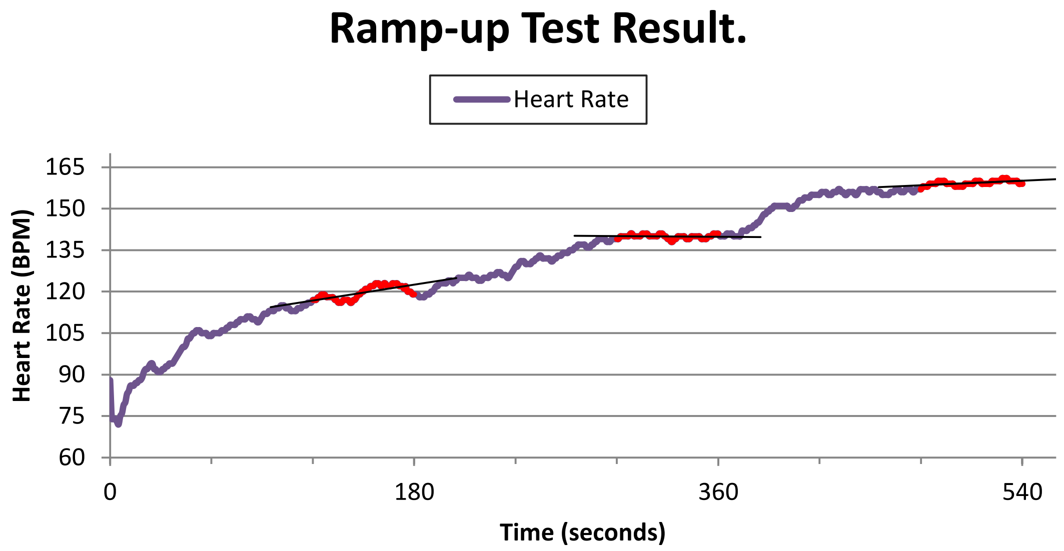

Figure 50 Subject heart rate during ramp-up test. The subject is cycling at 70 RPM with resistance steady and increased after every three minutes. The last minute of each of the three minute block has been highlighted and a trend line drawn. The levelling off of the heart rate can be seen as the subject approached three minutes at a specific resistance. This data is used to manually determine an appropriate resistance for the subject; one which is most likely to generate the target heart rate at 70 RPM.

In the first session, 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 video game playing and exercise behaviours.

Following the break they did a 30 minute workout on the bike which did not include the game. The session consisted of the following:

- 5 minute warm-up period. The player was required to cycle at 45 RPM for the first 2 minutes. The cycling rate was 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. The centre point varied continuously around 70 RPM in attempt to simulate actual game variations as discussed in 6.4.3. The workout was at a resistance which was calculated to bring the subject close to the target heart rate.
- 5 minutes cool down period. The required RPM's 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 ensure that everything is setup correctly for the gaming sessions, and acted as a double check to ensure that the resistance had been correctly set.

6.4.3 Cycling Noise

During normal game play, the RPM's of the player would not remain constant but would fluctuate as they moved up and down to collect the marker. To simulate this condition during the non-game session, the RPM's required to centre the marker fluctuated around the nominated centre point. During the workout the player needed to cycle at approximately 70 RPM to keep the marker entered. The actual RPM which keeps the marker in the centre alternately moves above and below the nominated 70 RPM centre point. The value changes to be randomly 1 to 5 RPM below the nominated centre and then drifts back up at a rate of 0.25 RPM per second until is it 1 to 5 RPM above the 70 RPM centre point. It then switches over and commences a downward cycle until it is again 1 to 5 RPM below the centre point. This process continues creating a rough saw tooth pattern. This methodology cause the user RPM to fluctuate during the non-game sessions. The artificially generated fluctuation turned out to be significantly smaller and smoother than that of an actual workout session, as can be seen in Figure 51.

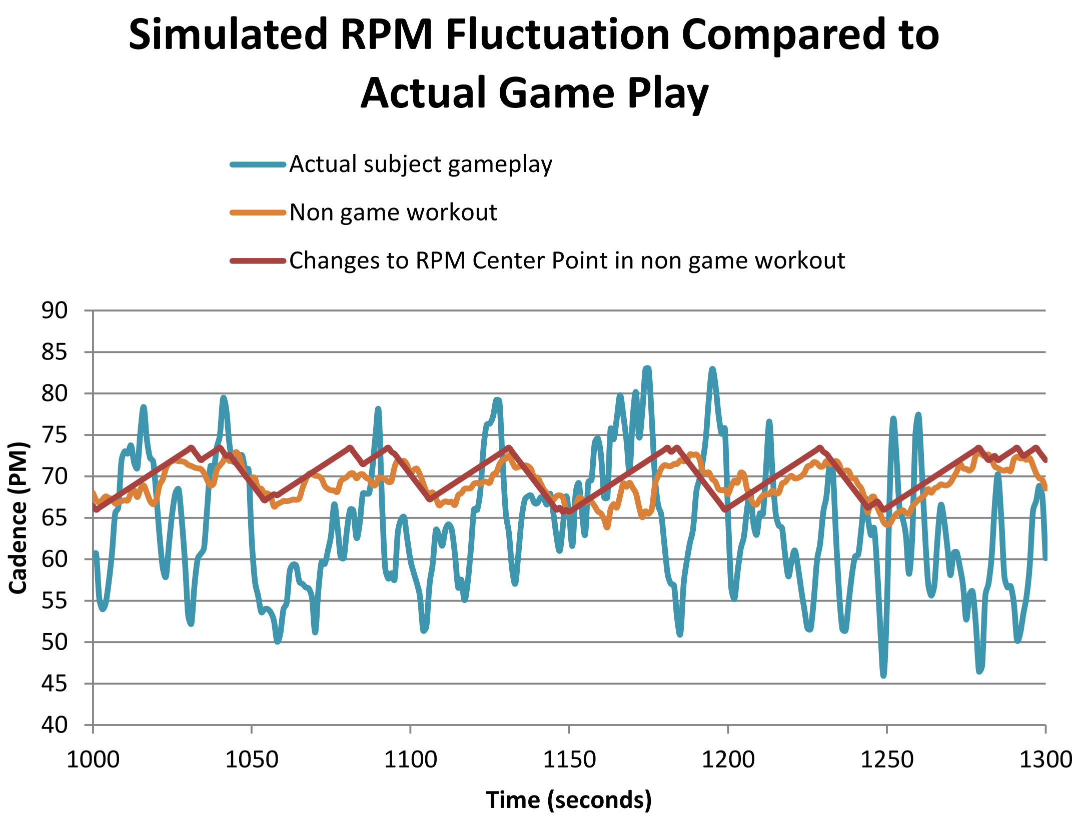

Figure 51 The artificially stimulated RPM fluctuation of a subject during the non-game session is contrasted with the RPM fluctuations for a normal workout session. The non-game RPM fluctuations are significantly smaller and smoother than an actual game situation.

Also it can be difficult to determine the manner in which the player will play the game. From session to session the player may make generally smoother or more erratic changes in cycling rates. An example of an erratic session is shown in Figure 52, where the subject focused on killing the aliens.

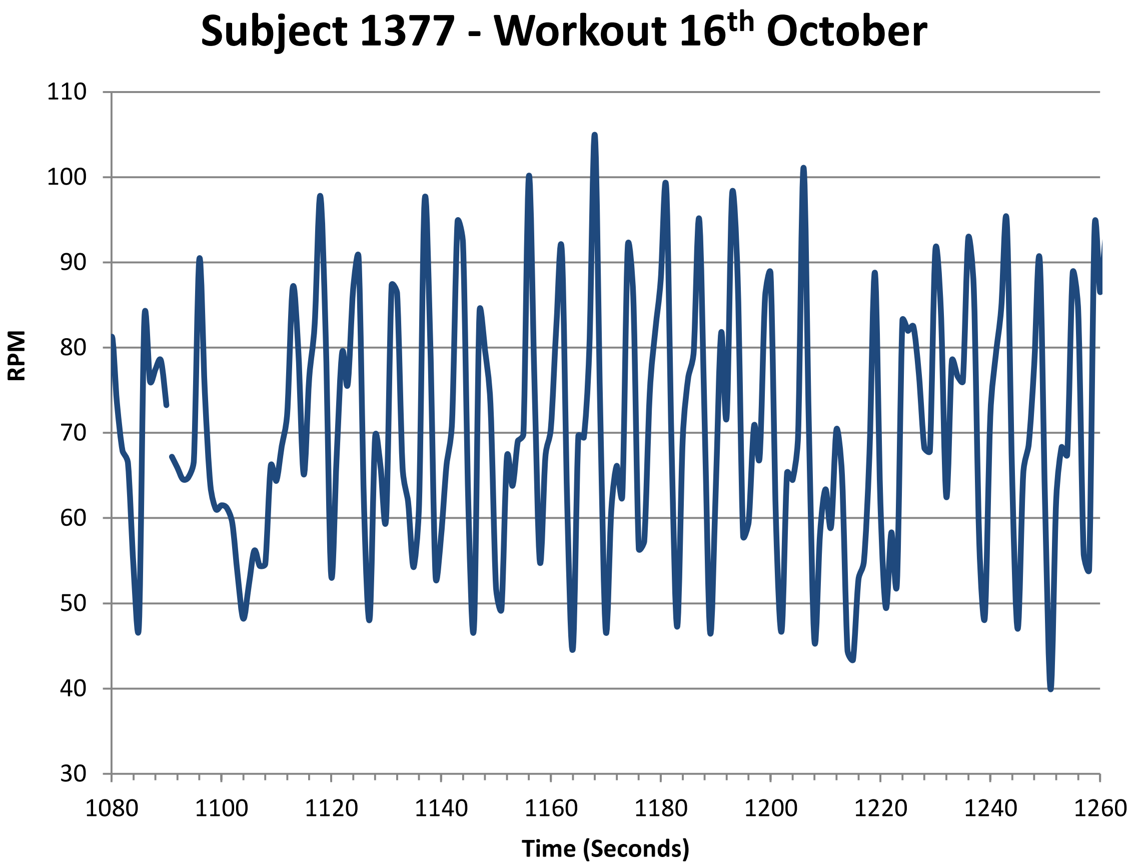

Figure 52 Example of widely fluctuating RPM during game play. The subject involved in this game session was focused on killing all of the aliens which resulted in high erratic cycling rates.

6.5 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 24 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.

6.5.1 Statically Set Intensity

There are two statically set intensity modes, Mode S and Mode C, for our exergame where the resistance required was calculated and set at the start. The RPM’s required to keep the game craft centred in the play area stayed constant throughout the entire workout part of the session, see Figure 49.

Mode S has statically preconfigured workout intensity and linearly increasing game difficulty. Mode C also has the same statically preconfigured workout intensity, but the game challenge varies based on dynamic difficulty adjustment. For both of these modes, the intensity settings are the same in the sessions by the same subject.

6.5.2 Dynamically Controlled Intensity

In the dynamically controlled intensity sessions, the heart rate was controlled by the software using the PID control loops discussed in 4.3.2.3. In Modes I and F, we wanted to obtain better heart rate patterns than when we use statically controlled intensity. The intensity of the workout was managed by changing the RPM required to keep the game vehicle in the centre of the screen. Increasing the RPM centre point increased the intensity for the player, while decreasing the centre point reduced the intensity for the player see Figure 53.

Mode I has the dynamically controlled intensity, and linearly increasing game difficulty. Mode F also has the dynamically controlled intensity, but has game challenge varied based on dynamic difficulty adjustment.

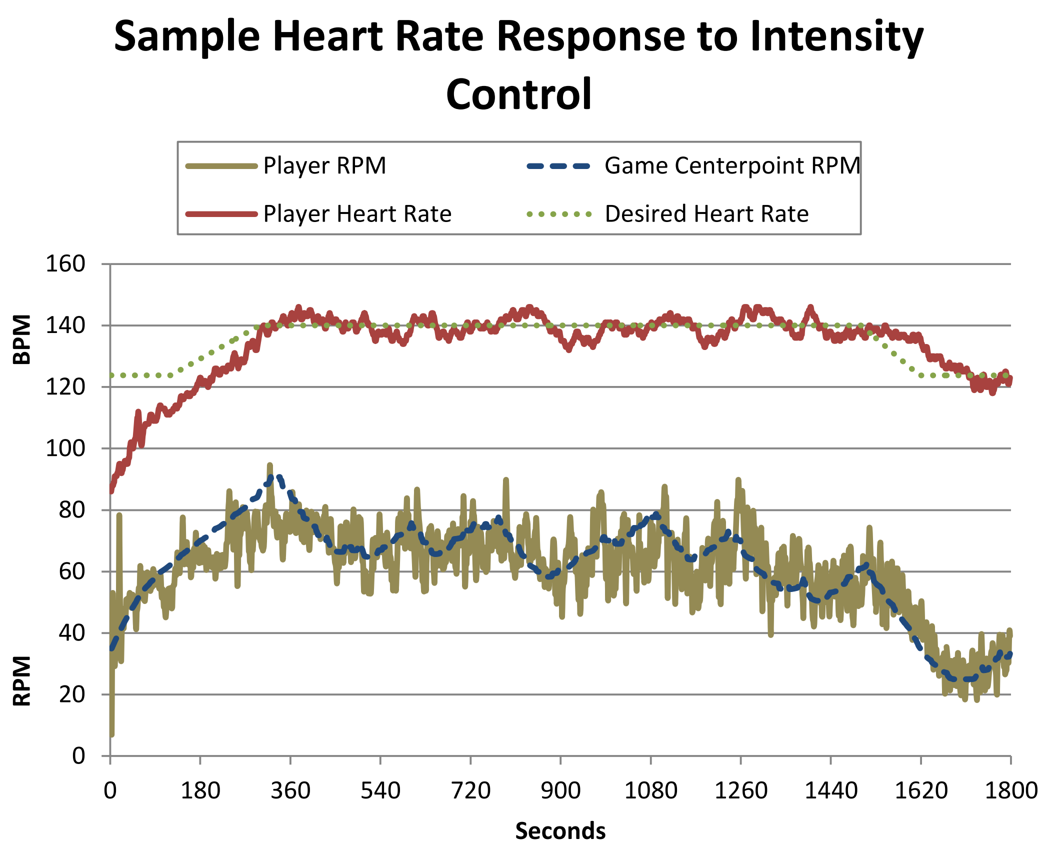

Figure 53 The heart rate response of subject 4228 for an intensity controlled exergame session. Notice here how the game centre point RPM continues to change in order to push the player cycling rate up or down. This is used to manage the heart rate of the player and to successfully achieve the desired player heart rate.

Figure 54 Subject involved in exergame play.

After each session the subjects completed a questionnaire designed to help evaluate the different control mechanisms. After the completion of all four workout sessions, the subjects were also asked to complete another questionnaire which asked the subject to compare the different game sessions.

6.6 Data Processing

Microsoft SQL server 2008 Express was chosen as the database server to store the data obtained from the study. Microsoft SQL Server Express is a free small scale database server for Windows which was suitable for our application. It can also be coupled with Microsoft's free reporting service which can be used to generate graphs and chart from the data. The charts and data can be easily exported into pdf and word formats.

As was mentioned in 4.4.2, our exergame software recorded detailed logs for each session. These logs were written out by the software as text files containing comma separated values. A software utility was written to read the logs and insert them into the database. Additionally a simple form based front end was developed for the database which allowed the transcription of the data into the database. The database allows the detailed analysis of our game log data and our questionnaires to look for relationships, to see if the data supports our Dual Flow Model.

6.7 Summary

In this chapter we looked at the trial we have run with the exergame system that we developed. Extensive game data and questionnaire information was collected during the trial. In Chapter 7 we present the analysis of the data obtained during the trials, and consider what it tells us about the Dual Flow Model and exergaming.

7 Analysis

In Chapter 4 we saw how we developed and built an exergame system focused on the two key areas of the Dual Flow Model; effectiveness – the management of exercise intensity, and attractiveness – the management of game challenge control. By selectively switching the control methods in these two areas, we generated an exergame system that can operate in four different modes:

- Static pre-planned mode (Mode S)
- Intensity controlled (Mode I)
- Challenge controlled (Mode C)
- Full control (Mode F)

Remember that in Mode S and Mode C the intensity is set based on a plan devised for the particular individual. The plan is based on the previous data obtained from the subject. The plan is designed to achieve the desired heart rate for the subject with a cadence of 70 RPM.

We subsequently designed a series of trials in order to compare these different modes and allow us to draw conclusions about the Dual Flow Model. 21 subjects were recruited and they completed five workout sessions, on different days, using the Gamebike setup. The subjects each undertook one session where they worked to keep a marker central on the screen and four sessions where they played the exergame in one of each of the different modes.

For each of these sessions we have the collected data on heart rates, cycling speeds and game play information that was logged during the workout sessions.

Along with the logged data, we have the session questionnaire data that the subjects completed. The subjects also completed questionnaires, which provide us with medical and demographic information.

In this chapter, we will analyse the data to see what it tells us, but before we analyse the data, let us recall what it is we are looking for in the data. Recall from chapter 3 that one of the aims of this research is to test the validity of the proposed Dual Flow Model. The Dual Flow Model emphasises the importance of controlling the attractiveness - mental challenge and skill balance, and the effectiveness – exercise intensity and physical capacity balance.

In order to demonstrate the validity of the Dual Flow Model, the research examines the following three principles in relation to exergames:

- Challenge must be correctly controlled to meet the skill level of the player.
- Workout intensity must be correctly controlled to meet the fitness level of the player.
- The two factors together give better results that a single factor.

The structure of this chapter is as follows:

In the following sections, we examine how the intensity control and challenge control systems impacted on the subjects. We first examine the effectiveness side of the Dual Flow Model to see if the subject received better exercise intensity levels when the workout intensity was adjusted. We then examine the attractiveness side to see how the control system effected the subjects' engagement with the exergame system.

After we have reviewed the effects of our control systems on the subject's sessions, we draw some conclusions about the meaning of these effects in the next chapter.

7.1 Exercise Intensity Control

Firstly we examine the physical exertion side of the workouts. As was discussed in 3.1, the control of workout intensity is the key to the effectiveness side of the Dual Flow Model. It is important to work at a level which will allow you to meet your goals without the risk of burnout or injury.

7.1.1 Intensity Control Outcomes

Let us examine the success or otherwise of this exercise intensity control. In Table 10 for every subject we present the arithmetic mean of the absolute difference, in beats per second, between the desired heart rate and the actual heart rate achieved. In the columns we show the arithmetic mean of the heart rate difference for each of the sessions.

Table 10 The average absolute error in heart rate over each mode.

	Mode			
Subject	**S**	**C**	**I**	**F**
1076	14.38	13.73	6.67	6.68
1134	15.81	10.15	5.16	5.36
1377	20.95	9.23	6.62	6.06
1464	9.48	8.74	4.53	4.22
2457	18.42	10.78	5.32	4.92
2565	13.28	9.36	4.28	4.89
2810	7.00	11.44	6.26	8.13
2830	14.00	13.46	5.10	5.14
2866	5.63	9.86	5.46	4.37
4102	6.90	10.07	4.82	5.15
4228	8.74	10.61	4.53	5.23
4386	7.66	12.83	6.28	5.27
4446	9.39	9.28	6.49	4.43
4496	32.73	19.63	6.22	9.11
4501	4.58	4.50	5.49	4.69
4567	9.07	9.17	5.07	6.67
4623	17.59	10.64	6.48	5.34
4771	7.53	7.77	7.17	6.23
4881	15.42	9.01	6.70	6.26
4882	8.62	10.59	6.40	6.62
4982	12.60	16.20	5.14	5.74
Mean HR Difference	12.37	10.81	5.73	5.74
Std. dev.	8.56	5.93	5.90	9.63

If we examine the difference in heart rates of the players compared to the desired result, we can see that the workout intensity controlled sessions, modes I and F, produced results much closer to the desired levels of intensity. From Table 10 we can see that the overall arithmetic mean of the error for the intensity controlled sessions is roughly half that of the non-intensity controlled sessions.

If we perform paired t-tests on this data we see that there is no statistically significant difference between the intensity controlled modes I and F (p value =

0.952), and no statistically significant difference between the non-intensity controlled modes, S and C (p value = 0.188). If we compare Mode S with the intensity controlled Modes I and F, we see a statistically significant difference, in both cases p value = 0.000. Repeating the tests to compare Mode C against the intensity controlled modes, we again see a statistically significant difference, in both cases p value = 0.000.

Furthermore it is important to note that the improvement is there in nearly every subject. The improvement in the heart rate control, when using the PID loops instead of relying on the statically set values, is consistent. We summarise this data in Table 11.

Table 11 Summary of results from t-tests comparing the different modes.

Modes		P value from t-test
I	F	0.953
S	C	0.188
S	I	< 0.001
S	F	< 0.001
C	I	< 0.001
C	F	< 0.001

Note that for modes S and I, the challenge level is linearly increasing and should be approximately the same over time for both sessions. For Mode S and Mode C the workout intensity is fixed and should be approximately the same across the sessions for the subject.

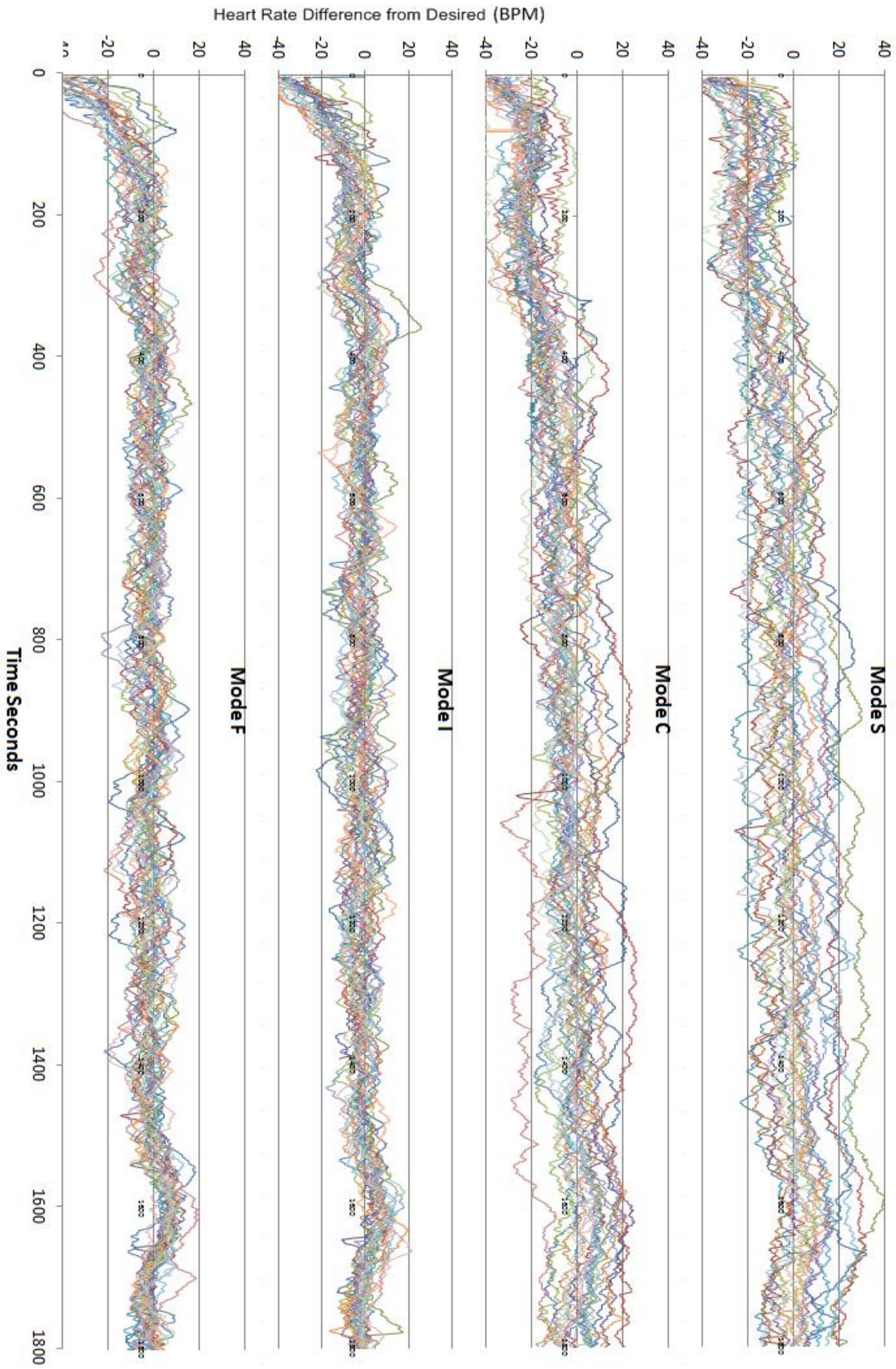

Figure 55 Subject heart rate difference from the desired level across the different modes. See the tighter banding in Mode I and Mode F.

Figure 55 visually shows the difference in the subjects' heart rate difference from the desired heart rate for each of the different modes. From this we can see that Mode I and Mode F (third and fourth chart respectively) show a tighter banding towards across the zero point.

Additionally, in Figure 55 it is possible to see a continual slight rise in the heart rates error in Mode C and Mode S. This upwards trend is known as cardiovascular drift, see 5.6.1.1. In the controlled modes, this rise is eliminated by the PID control systems.

In order to make the heart rate difference from the desired level for the different control methods easier to see, in Figure 56 we show just the average heart rate absolute error for the intensity controlled sessions and for the static managed intensity sessions.

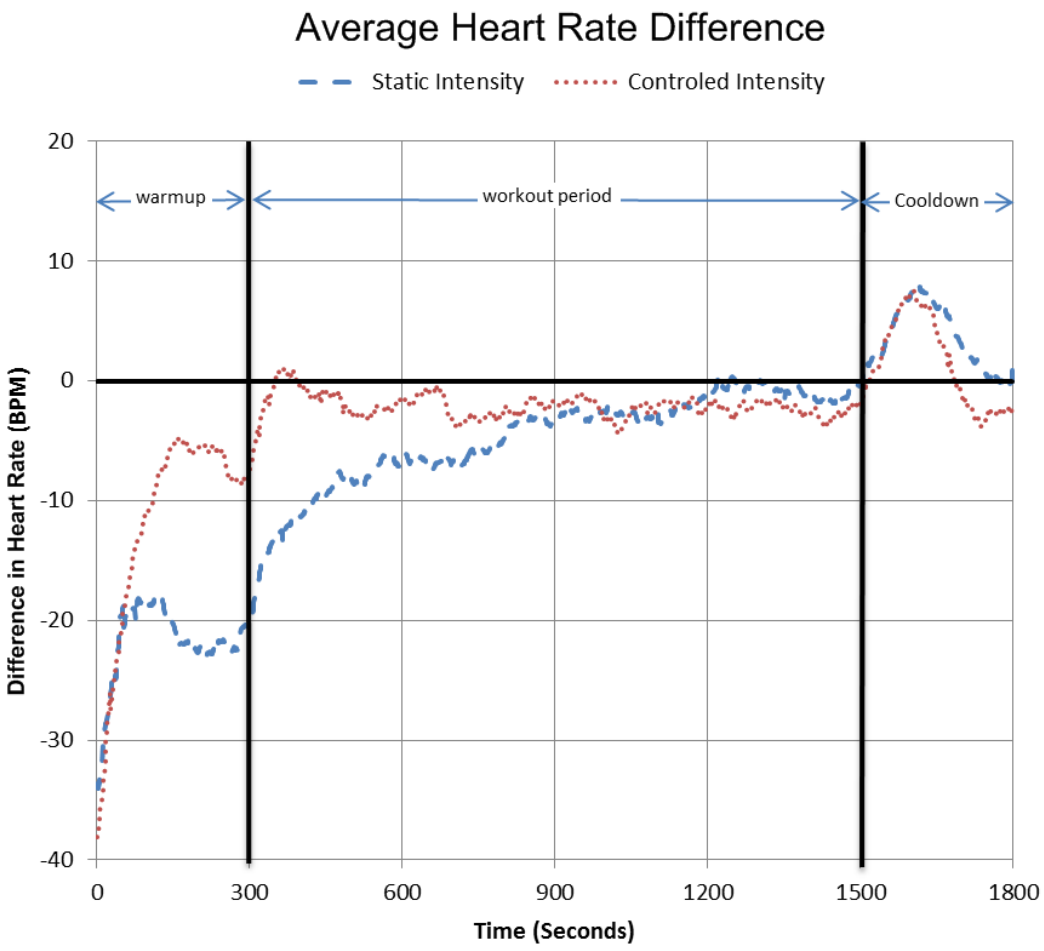

Figure 56 The average absolute heart rate different from the desired level for the sessions, split by static intensity sessions and intensity controlled sessions. Note that controlled Intensity (dotted red line) is relatively flat, while the uncontrolled intensity shows more of a slowly rising slope.

When we examine the average heart rate across all the sessions, split by the different intensity control types, in Figure 56 we can see the distinct differences in the data. The overall pattern is that during warm-up the intensity is lower ramping up to the desired level. The heart rate levels out for the period of the workout. The hump at the end is caused by the lag between desired heart rate dropping off for the warm-up, and the actual heart rate dropping down to match.

Looking at the differences for the two plots, we see that the intensity controlled sessions reached the desired heart rates faster and maintain a reasonably flat value. The statically defined intensity sessions were slower to reach the desired rate and showed the distinct upward trend, known as cardiovascular drift, as the exercise continued.

When we look at Figure 56 we might infer that a lot of the improvement in the error for the intensity controlled sessions, which was shown in Table 10, occurs due to the virtue of the fact that the intensity controlled sessions reach the desired levels much sooner. We can question how well the intensity control mechanism performs once the subject’s heart rates reach the desired levels. In Table 12 we show the mean of the error in the heart rate for only the workout part of the session.

Table 12 The average absolute heart rate difference during the workout part of the sessions.

	Mode			
Subject	**S**	**C**	**I**	**F**
1076	13.56	11.66	6.21	6.88
1134	14.59	8.39	3.94	4.57
1377	19.13	6.04	5.89	5.48
1464	7.80	5.51	3.80	2.49
2457	17.95	9.51	3.83	4.02
2565	12.66	7.42	2.67	2.72
2810	5.40	10.38	5.87	6.83
2830	12.68	12.84	4.08	3.87
2866	4.81	7.75	5.37	3.74
4102	3.89	7.63	3.45	3.33
4228	5.78	6.99	2.48	2.05
4386	4.54	8.56	4.00	4.12
4446	8.15	5.23	4.94	3.81
4496	35.39	17.33	4.03	5.59
4501	3.55	3.26	4.98	4.43
4567	6.52	6.01	3.69	5.89
4623	14.15	8.42	5.44	3.36
4771	4.68	4.54	6.11	4.89
4881	15.40	6.87	5.23	5.19
4882	5.09	8.27	4.80	5.79
4982	9.76	13.29	4.33	3.80
Mean HR Difference	10.74	8.37	4.53	4.42
Std. dev	8.91	6.17	3.62	3.59

In Table 12 we again see the same improved performance in the intensity controlled sessions (Mode I and Mode F). Performing our paired t-tests, there is no significant difference between the intensity controlled modes I and F, p value = .641 and no significant difference between the non-intensity controlled modes, p value = .088. There is significant difference between Mode S and the Intensity Controlled modes, p value = 0.001 in both cases, and for Mode C there was also a statistically significant difference with p Value = 0.000 in both cases.

Over the previous section, we saw that the control of the intensity using the PID control loop kept the subjects' heart rate closer to the desired level. Management of the subject heart rate is an important element in obtaining good exercise outcomes.

7.1.2 Challenge Control Heart Rate Effects

In Table 10 we saw a difference between Modes S and Mode C which was unexpected. This may have been due to normal variations in heart rate but this is not certain. In the intensity controlled sessions any normal variance in heart rate, for example, due to some prior exhaustion before the session, is eliminated by the intensity control mechanism.

If we look at the error for the sessions in absolute terms, that is not only the distance from the desired point, but also including the direction of the error, we get the results as shown in Table 13.

Table 13 The average heart rate difference from the desired level during the workout sessions in the different modes.

	Mode			
Subject	**S**	**C**	**I**	**F**
1076	13.47	11.38	-2.20	-2.85
1134	-14.59	-7.18	-2.51	-2.37
1377	18.41	0.11	2.60	-1.32
1464	-7.79	2.60	-1.66	-0.84
2457	-17.95	-9.44	-1.90	-1.55
2565	-12.66	-6.50	-0.84	-1.27
2810	-4.36	-10.32	-1.02	-3.02
2830	12.45	11.41	-1.28	-2.00
2866	-2.27	-7.64	-3.88	-1.68
4102	-0.12	-6.08	-0.62	-1.04
4228	-0.76	-6.40	-0.28	-0.22
4386	0.94	2.28	-1.44	-1.79
4446	7.21	2.69	-1.91	-1.48
4496	-35.39	-17.33	-2.81	-4.05
4501	-2.66	0.50	-2.56	-1.66
4567	1.17	-3.11	-1.94	-2.64
4623	8.39	-7.96	-2.41	-0.92
4771	-0.53	-1.26	-0.77	-1.24
4881	-15.40	-6.81	-1.29	-1.63
4882	-4.32	-8.15	-2.58	-2.01
4982	-9.65	-13.29	-2.79	-2.13
Mean HR Error	-3.16	-3.83	-1.62	-1.80
Std. dev.	12.206	7.2824	1.309	0.86

In Table 13 we are not as much interested in mean value of the error, as in the standard deviation of the error. We perform a 2-Sample Standard Deviation Test between the intensity controlled modes S and C, and find the standard deviation is not significantly different, p value = 0.258. Between the non-intensity controlled modes the standard deviation is also not significantly different with p value = 0.126. When we compare a non-intensity controlled mode with an intensity controlled mode, in all four cases the standard deviation is statistically significant with p value = 0.000 in all cases.

What we also see here is that overall, in all sessions the heart rates were lower than the desired rate more than they were above. The bulk of this difference is caused by the ramp-up to the appropriate heart rate taking longer than the planned 5 minute warm-up period. If we repeat the same data, but just look at the last 10 minutes of the workout, we get the results Table 14.

From this data, we can see that overall, the sessions were centred on the desired value, with less than 2 beats difference in the average. In this table, we can see the difference between the spread (standard deviation) of the non-intensity controlled sessions and the intensity controlled sessions.

We can also see a difference here between the two non-intensity controlled modes, static mode, Mode S, and the challenge control mode, Mode C. On a 2-Sample Standard Deviation Test, we get a p value = 0.82 which is significant with an alpha value of 0.1. This difference is discussed in 7.2.1.

Table 14 The average heart rate difference from desired level during the last 10 minutes of the workout.

	Mode			
Subject	**S**	**C**	**I**	**F**
1076	15.34	15.67	-3.51	-3.01
1134	-11.89	-1.95	-2.29	-1.39
1377	26.76	4.69	1.74	-1.72
1464	-5.44	6.67	-1.91	-1.45
2457	-17.61	-4.62	-2.12	-0.78
2565	-11.93	-2.10	-0.22	-1.35
2810	-2.28	-8.64	-2.05	-3.00
2830	17.58	16.80	-1.00	-2.27
2866	-2.62	-7.85	-4.61	-1.29
4102	2.85	-0.55	-1.10	-1.34
4228	4.59	-2.66	-0.83	0.39
4386	4.30	8.58	-1.79	-2.23
4446	10.98	4.34	-2.95	-0.70
4496	-37.80	-19.38	-1.59	-6.09
4501	-1.28	1.82	-3.03	-1.83
4567	7.24	0.85	-2.48	-1.63
4623	19.26	-5.25	-1.57	-1.91
4771	2.89	1.75	-0.74	-1.37
4881	-11.59	-6.08	-0.03	-0.51
4882	-3.55	-4.80	-3.75	-3.39
4982	-6.01	-10.67	-3.32	-2.46
Grand Total	-0.01	-0.64	-1.86	-1.87
Std. dev.	13.99	8.27	1.41	1.28

7.1.3 Smoothness of Heart Rate Control

We saw in 7.1 that the PID loops caused the heart rates of the subject to be closer to the desired settings. However, it is important to also look at the heart rate smoothness of the different control methods.

Since we are using a controller for the heart rate in our exergame, we need to be aware of any repercussions. Ideally, the controller will produce a flat line see Figure

57. It is unrealistic to expect perfect control, and there will be some degree of variation like in Figure 58, and as we have seen previously for example. What we want to ensure does not happen, is for the control system to produce continuous large fluctuations like Figure 59.

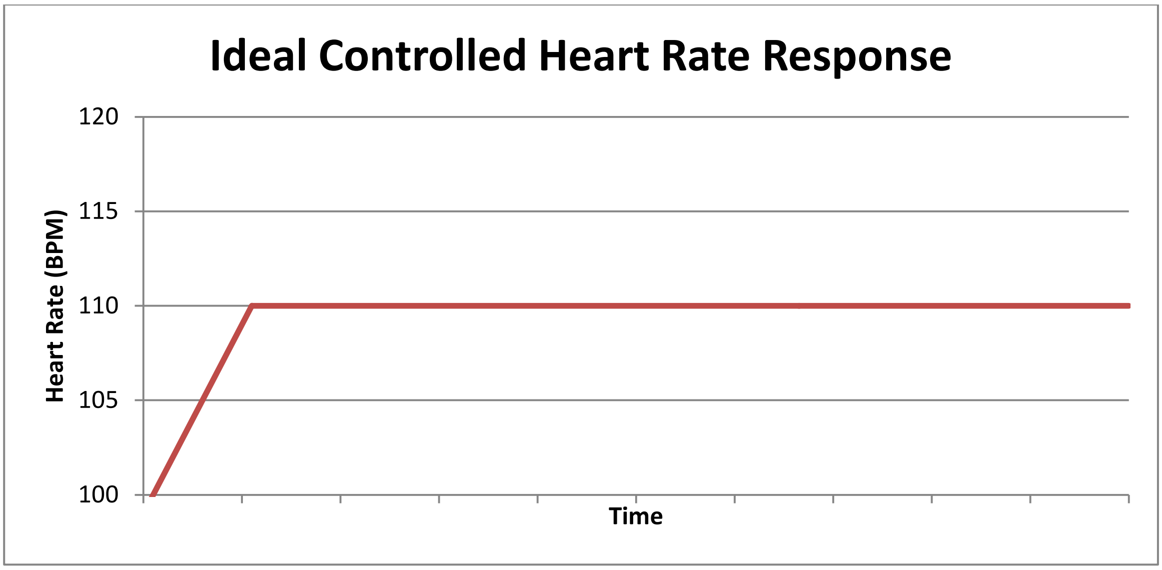

Figure 57 Ideally the controlled heart rate will rise to the correct level and remain flat. In reality, this is an unrealistic expectation.

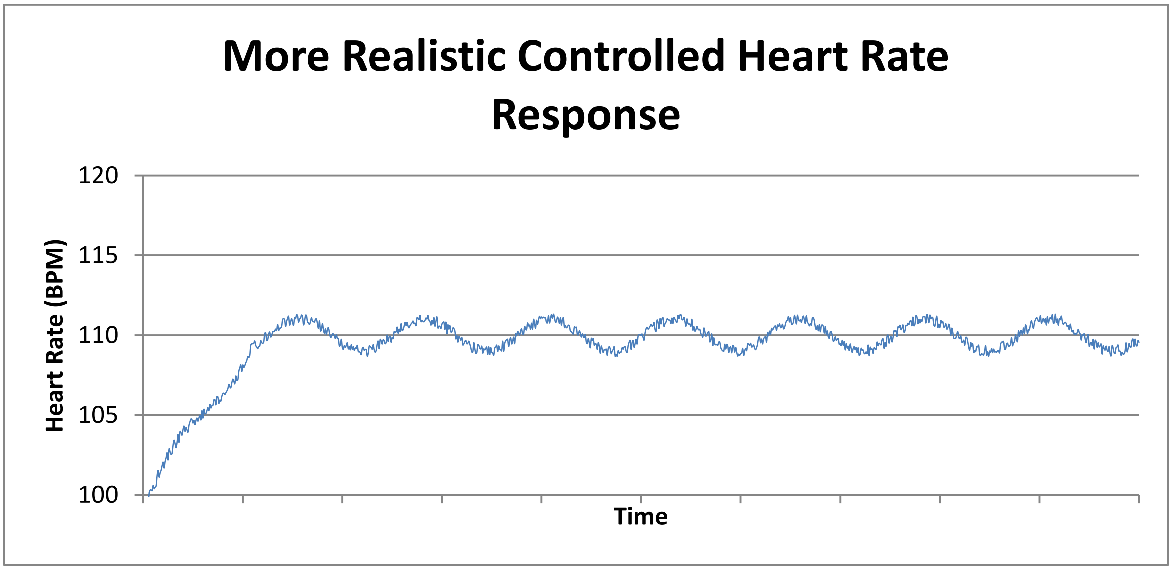

Figure 58 The heart rate rises to the correct level and then fluctuates around the desired level.

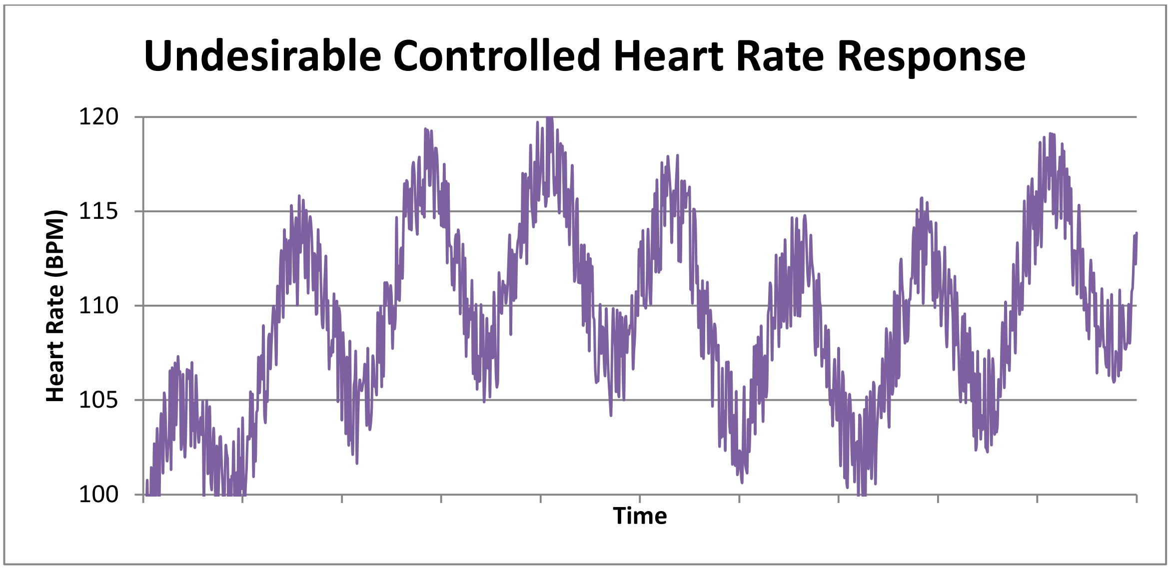

Figure 59 The heart rate rises to the correct level and fluctuates around the correct level, but the fluctuations are undesirably large.

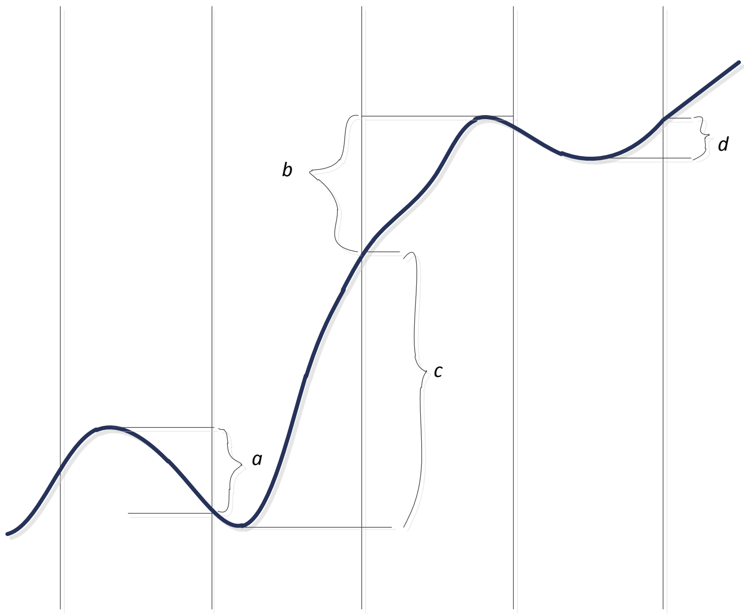

Figure 60 An example of measurements made on an imaginary curve to determine the general level of smoothness. The range between the highest value and lowest value within the 4 defined periods a, b, c and d are averaged to determine an overall smoothness of the curve.

We examine the heart rate responses of the subjects in our trial, in order to determine the smoothness of the responses. If we look at the range of heart rate readings, the difference between the lowest reading and the highest reading over defined periods, we should be able see a reasonable indication of the smoothness of the different control methods (see Figure 60).

Table 15 Average range of heart rate readings over ten second intervals to provide indication of smoothness of control mechanism.

Subject	Modes S	C	I	F
1076	3.01	2.84	2.99	3.56
1134	3.43	3.34	3.27	3.15
1377	2.20	2.96	3.53	2.81
1464	2.63	2.09	2.55	2.30
2457	2.98	2.74	2.74	2.82
2565	2.77	2.97	2.68	2.55
2810	2.91	2.88	3.96	3.77
2830	2.19	2.23	2.70	2.74
2866	3.09	3.40	3.02	3.31
4102	2.56	2.63	2.70	2.56
4228	2.39	2.69	2.42	2.34
4386	2.50	2.32	2.72	2.31
4446	2.06	3.22	2.57	2.36
4496	2.58	2.78	2.49	2.66
4501	2.70	2.40	2.92	2.64
4567	2.49	2.93	2.42	2.70
4623	3.05	2.78	2.98	3.01
4771	2.57	4.01	3.15	3.08
4881	3.25	2.90	3.23	2.92
4882	2.74	2.75	2.77	3.07
4982	2.87	2.49	2.68	2.73
Mean HR Difference	2.71	2.83	2.88	2.83
Std. dev.	0.346	0.422	0.375	0.389

In Table 15 we summed the range between the highest heart rate reading and the lowest heart rate reading in every 10 second interval. The total of these times slices should give a reasonable indication of smoothness. The statically controlled mode appears to have a slightly lower fluctuation with the three other modes which were all quite close. A paired t-test of the means shows a p value = 0.078 between Mode S and I which is significant with an alpha value of 0.1. Tests show no statistically significant difference between the other modes.

Table 15 includes the variability across the whole session. As we saw earlier in this section, the dynamic intensity controlled sessions reached their desired levels faster. This could result in some bias in the calculation of smoothness, so it is worth looking at these figures over the workout period. We repeat the data looking at only the last 15 minutes of the 20 minute steady workout period, which we show in Table 16.

Table 16 Average range of heart rate readings over ten second intervals for the last 15 minutes of the steady workout.

	Modes			
Subject	**S**	**C**	**I**	**F**
1076	2.69	2.51	2.92	3.22
1134	3.03	3.62	2.75	3.16
1377	1.86	2.89	3.18	2.41
1464	2.66	2.07	2.42	2.09
2457	3.12	2.41	2.66	2.70
2565	2.80	2.58	2.71	2.49
2810	2.44	2.58	3.99	2.96
2830	1.73	1.76	2.51	2.41
2866	3.24	3.51	3.16	3.20
4102	2.42	2.68	2.62	2.36
4228	2.09	2.42	2.20	1.89
4386	2.12	1.73	2.17	1.99
4446	1.74	2.26	2.54	2.00
4496	2.57	3.00	2.43	2.61
4501	2.58	2.28	2.88	2.52
4567	2.41	2.64	2.40	2.74
4623	2.96	2.59	2.68	2.97
4771	2.37	2.93	3.12	3.21
4881	3.27	2.49	2.66	2.72
4882	2.72	2.74	2.83	3.30
4982	2.86	2.29	2.74	2.80
Overall Mean of variance	2.56	2.57	2.74	2.65
Std dev	0.448	0.458	0.389	0.428

In Table 16 we see the static intensity modes, Mode S and Mode C, show less variability than the intensity controlled modes, I and F. The totals for both of these modes are very similar in value and approximately 4% to 5% lower than the intensity controlled sessions. These variations, when tested using a paired t-test, were not statistically significant, p value = 0.134 and 0.145. If we group the non-intensity modes S and C together, and the intensity controlled modes I and F together, then we get the results shown in table 17:

Table 17 Average range of heart rate readings over ten second intervals for the last 15 minutes of the steady workout.

	Modes	
	Non Intensity Controlled	Intensity Controlled
Overall Mean of variance	2.70	2.56
Standard Deviation	0.363	0.385

Performing a paired t-test on this results in a p Value = 0.088, which is statistically significant with an alpha value of 0.1.

What we conclude from this, is that our heart rate control system while producing results which were closer to the desired heart rate, caused greater fluctuation of the heart rates for subjects when they are working out. The difference is probably not caused by normal fluctuations in the heart rate, but is a function of the control system being used. Instability in the form of continuous oscillations is a common property of PID control systems. In the case of our controller, these oscillations are quite small and most likely have no impact on the player.

This is an area where further research could be carried out to determine how much effect the extra heart rate variations have, and if this is noticed by the subjects.

7.1.4 Individual Heart Rate Variations

The variability of heart rate response to exercise is quite considerable. It is well known that there are many factors which influence how heart rate responds to exercise (Julich Uli & Ho, 1998; Seiler, 1996; US Army, 2008). There were considerable differences in heart rate responses between subjects in the study we undertook. The heart rate for some subjects would rise very easily on the bike as soon as they undertook any cycling. For some other subjects, they needed to perform considerable amounts of exercise in order to raise their heart rate on the exercise bike.

In addition to the inter-subject differences, there were, for some subjects, significant inter-session differences. Looking at the heart rate response for two sessions of subject 1134, as shown in Figure 61, we can see considerable difference in the heart rate response.

The first session was on the 14th of October, the second was 13 days later on the 27th. In the first session, the lighter (green) line in Figure 61, the heart rate rises faster and stays generally higher than the second session, darker (blue) line. In the second session the heart rate was an average of nearly 6% lower.

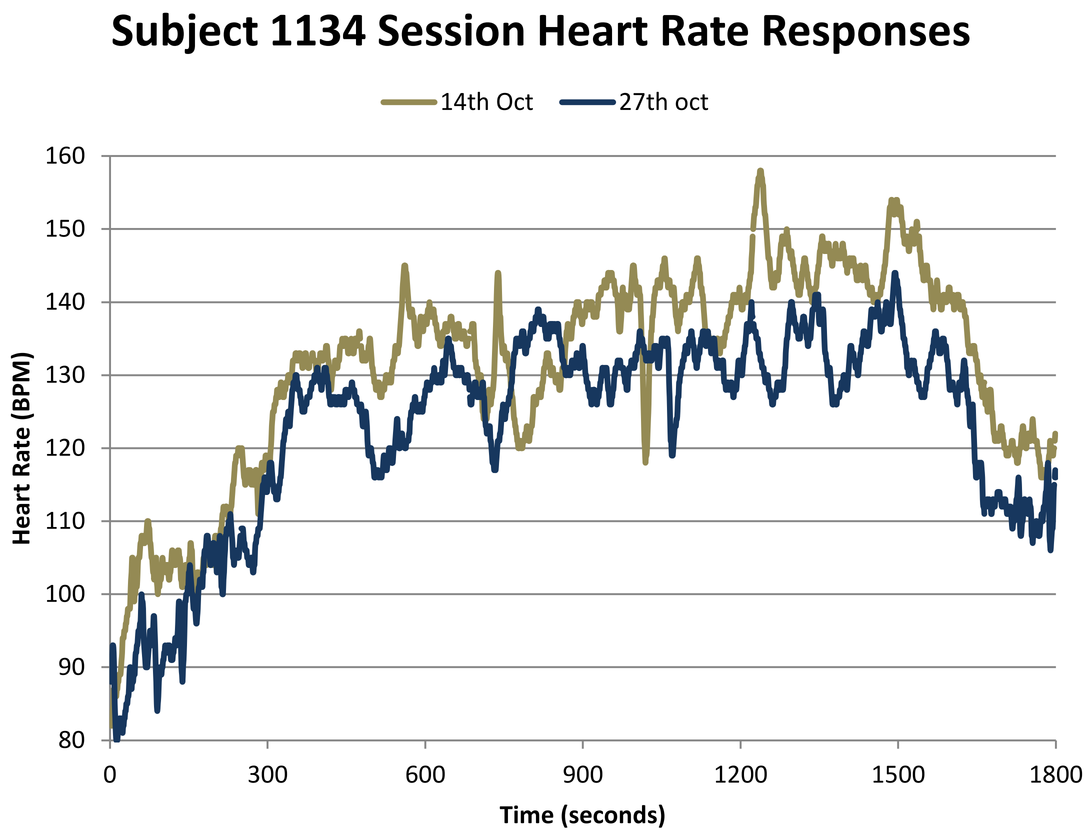

Figure 61 Subject 2810 heart rate response to Mode C sessions on the 16th October, is generally lower than the similar Mode S session 4 days later.

The bike resistance was set the same in both cases and the exergame control module was not adjusting the intensity. The game play styles were similar and so similar responses are expected. We see that the RPM's for the sessions, effectively the workload exerted by the subject, were nearly identical with an average of 70.75 on the 14th October and an average of 70.79 on the 27th October, see Figure 62.

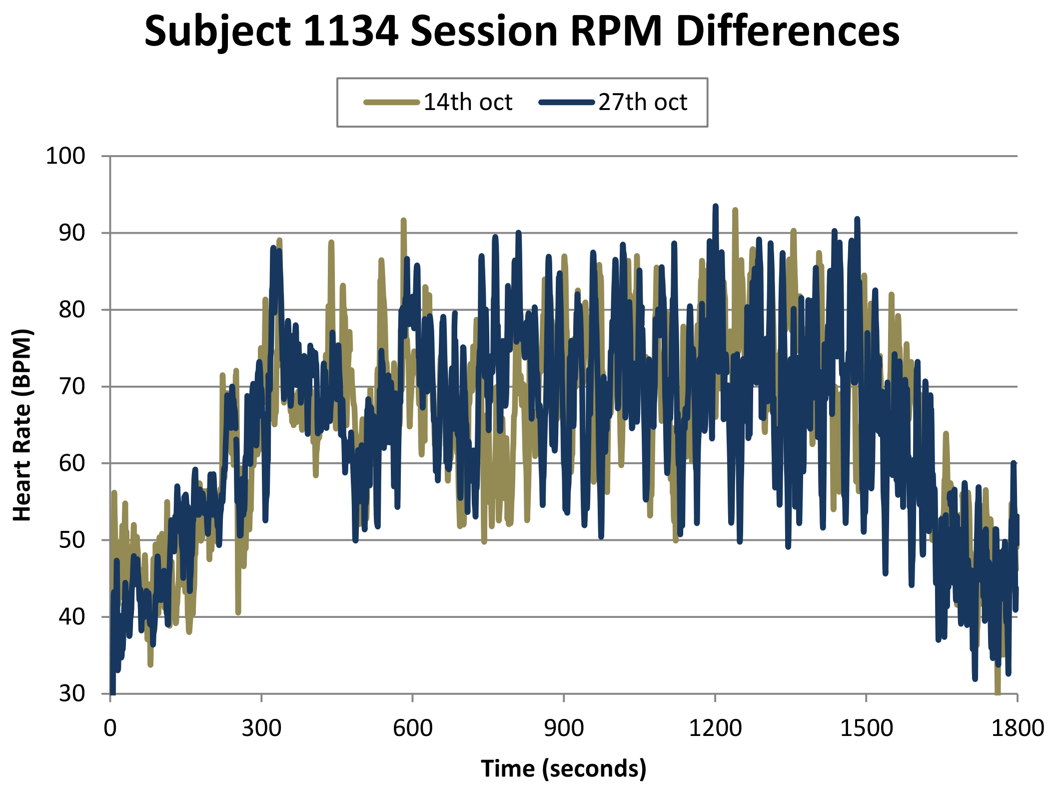

Figure 62 RPM for subject 1134 during sessions on 14th October and 27th October.

There are numerous factors which can contribute to differences between sessions in an individual subject. We cover these factors in 7.7.1.2.

7.1.5 Game Play Style Variability

The style in which the players played the exergame also varied quite considerably. Some players were focused on hitting the markers and collecting letters. Other players had a different focus, such as shooting the aliens.

Figure 63 and Figure 64 represent two sessions on consecutive days by the same player. Neither of the sessions was intensity controlled, so the resistance and the RPM for the centre point in both sessions remained constant. The focus of the game play in both the sessions differed, and we can see the impact of the different focus on the subject RPM's, and the effect this has on heart rate.

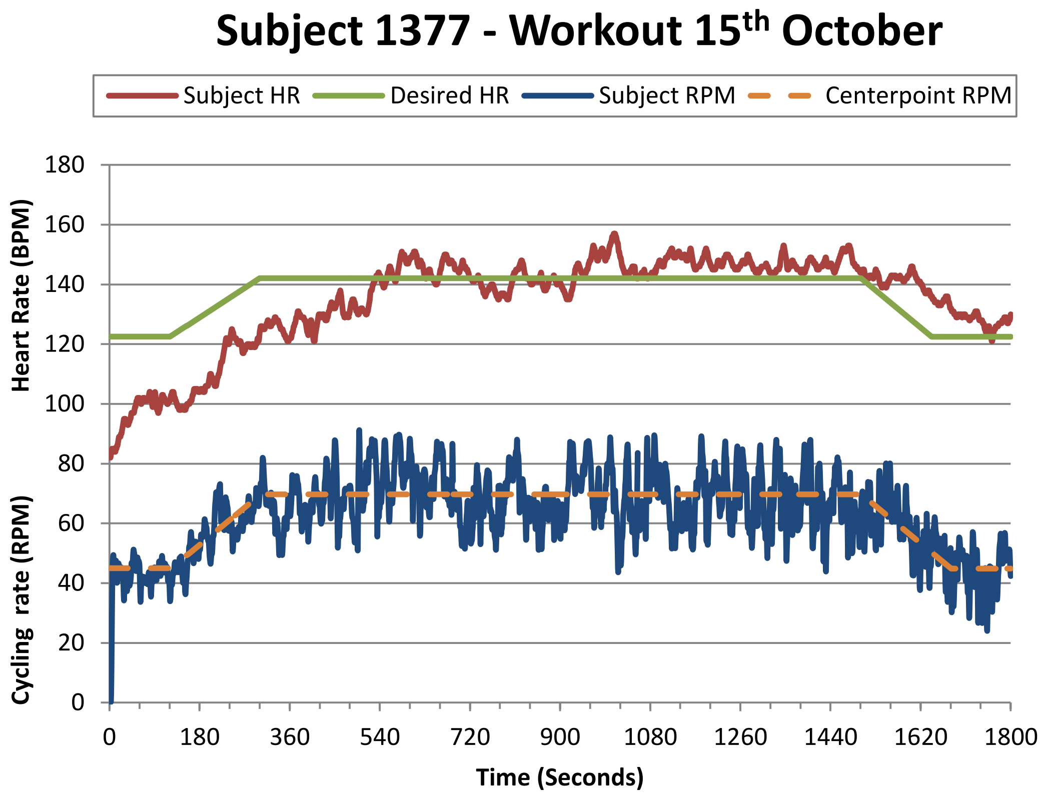

Figure 63 Plot of workout showing regular degree of cycling RPM variability – player was focused on collecting the letters.

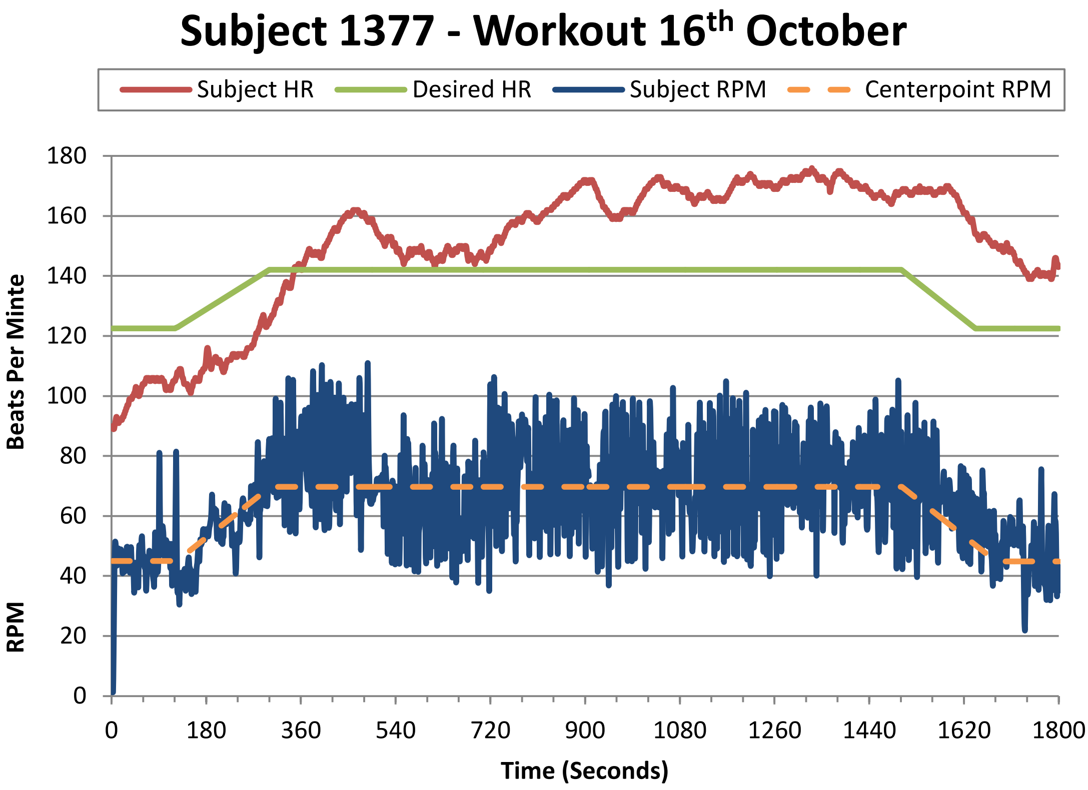

Figure 64 Plot of workout showing high degree of cycling RPM variability – player was focused on shooting the aliens.

In Figure 64, the player's RPM's varied considerably more than in the first session. In this case, the player was focused on trying to kill all of the aliens. This resulted in the player doing many sprints to try to get from the bottom of the screen to the top. The sprints resulted in considerably more exertion than normally generated by the game, particularly when focused on the collection of markers and letters. This extra exertion is clearly borne out by the significant differences in the heart rate readings between the two sessions, Figure 63 and Figure 64.

The game control in our exergame is designed to limit player cycling variations to a certain extent. If a player cycles too fast, then the player craft, the helicopter, crashes into the ceiling of the game play area. This resulted in an audible warning and a reduction in the forward speed of the craft. Alternately the same effects occurred if the player cycling rate dropped below a certain level and the player craft crashed into the floor.

At the end of each session the subjects were asked what their main focus was during the game, selecting one or more items from a list of six different options. From this constrained list, of the 21 subjects, only 3 answered with the same focus for all four sessions. 10 subjects, almost 50%, responded with three or more different game foci during the sessions. The trial only included the subject's first four sessions on the game bike, so it is expected that the subjects might experiment with different game play styles, in order to find one that suits. Long term we do not know how often subjects might change their playing style; they might find one that suits and then rarely change, or they might change regularly.

Regardless of how often subjects change playing style, it is not unreasonable to expect subjects to change game play style from time to time. This may have significant impact on the player's workout intensity. Without careful monitoring and control, the intensity level of the exercise for an exergame, could unexpectedly change, and potentially move outside of the desired range.

A study of video gamers playing Wii Boxing, (Marco Pasch, et al., 2008), identified three distinctly different playing styles, which resulted in significantly different energy expenditure during the play. The study found that different play styles could be attributed to the player motivation for playing the game. Different game play motivations, e.g. for entertainment, can result in different energy expenditure outcomes during the game play.

7.1.6 Importance of Heart Rate Measurement

What we can conclude from the heart rate results in this study is that the measurement of exercise intensity is critical. If we accept the premise that heart rate is giving a reasonably good indication of the intensity of the effort being expended by an individual, we can see that without control of the intensity, the intensity of the workout varied considerably.

In an exergame, a good measure of exercise intensity is critical. Without this measure it is very difficult to ensure that an appropriate exercise level is being achieved. The exercise outcomes of the exergame would then be dependent on the subject ensuring they achieve an appropriate level of exertion. As an example, the Wii Sports games are designed to be played standing up with large body movements. However there is, considerable anecdotal evidence to suggest that players very quickly learn to play these games sitting down with small wrist movements.

In (Masek, et al., 2009) the effects of different step types on a DDR pad were compared. Subjects performed the same sequence of button presses at the same rate, but using a number of different motions, one requiring larger movements of the leg. The study found that the longer, stretching movements made a considerable difference to the heart rate of the subject. From this study, we can conclude that merely monitoring the game inputs of the players, in this case button presses on the dance mat, would be insufficient to manage the energy expenditure of the player.

7.2 Actual Intensity of the Different Modes

We previously examined the intensity control across the four sessions. Now let us examine the difference on a per-subject basis across the four different modes. Because each subject has a different base heart rate, comparing absolute heart rates from one subject against other subject is not valid. What we are interested in is the change in heart rate for an individual subject across the different game modes. To do this, we do a pairwise comparison of results, looking at the heart rate changes occurring across sessions for the same subjects.

An individual subject's average heart rate, in a particular session, is compared against his or her average heart rate for each of other similar sessions. From these comparisons we will be able to observe if there was any particular bias in the intensity of the different sessions.

As an example, subject 2457 had the following average heart rates in each of the sessions as shown in Table 18.

Table 18 Subject score for workout intensity perception questions.

Intensity Controlled, Linear Challenge (Mode S)	117.84 BPM
Static Intensity, Linear Challenge (Mode I)	133.58 BPM
Static Intensity, Dynamic Challenge (Mode C)	128.94 BPM
Intensity Controlled, Dynamic Challenge (Mode F)	133.55 BPM

We compare the values across sessions that differ only by one factor, either intensity control, or game challenge control.

To examine the effects of the intensity control system on the workout, we compare the Mode S session heart rates against the Mode I session, and Mode C session heart rates against the mode F session score. This gives us a score for the intensity control's effect on the subject's workout intensity.

To examine the effects of the challenge control on the exercise intensity, we then compare the Mode S session to the Mode C session, and then the Mode I session to Mode F session score. This produces a result representing the game's challenge control effect on the subject's mean workout intensity.

$$\begin{aligned} &\mathit{Value\ on\ the\ Intensity\ Controlled\ axis} \\ &\quad = (\mathit{Mode\ I\ avg\ hr} - \mathit{Mode\ S\ avg\ hr}) \\ &\quad + (\mathit{Mode\ F\ avg\ hr} - \mathit{Mode\ C\ avg\ hr}) \end{aligned} \tag{18}$$

$$\begin{aligned} &\mathit{Value\ on\ the\ Challenge\ Controlled\ axis} \\ &\quad = (\mathit{Mode\ C\ avg\ hr} - \mathit{Mode\ S\ avg\ hr}) \\ &\quad + (\mathit{Mode\ F\ avg\ hr} - \mathit{Mode\ I\ avg\ hr}) \end{aligned} \tag{19}$$

Using the scores from subject 2457, as listed in Table 18, we perform the four comparisons as shown in Table 19 and Table 20.

Table 19 Calculation of mean heart rate difference on intensity axis for subject 2457.

Mode		Mode		Intensity Difference
S=	117.84	I=	133.58	15.74
C=	128.94	F=	133.55	4.61
				20.35

Table 20 Calculation of mean heart rate difference on challenge axis for subject 2457.

Mode		Mode		Intensity Difference
S=	117.84	C=	128.94	11.1
I=	133.58	F=	133.55	-0.03
				11.07

The results form a vector which can be displayed on a Cartesian plain. The vector value for each subject's responses was calculated, and the results are plotted in Figure 65. We can see in Figure 65 that subject 2457 is in the upper right quadrant of the plot.

The horizontal axis indicates the intensity control, so being on the right hand side means that for 2457 the dynamic intensity controlled modes, I and F were of a higher intensity than the preconfigured static intensity modes, S and C.

The vertical axis in the plot is an indicator of the challenge control. This shows us that for subject 2457 the dynamic challenge control modes, C and F, resulted in a higher intensity than the linear challenge control modes, S and I.

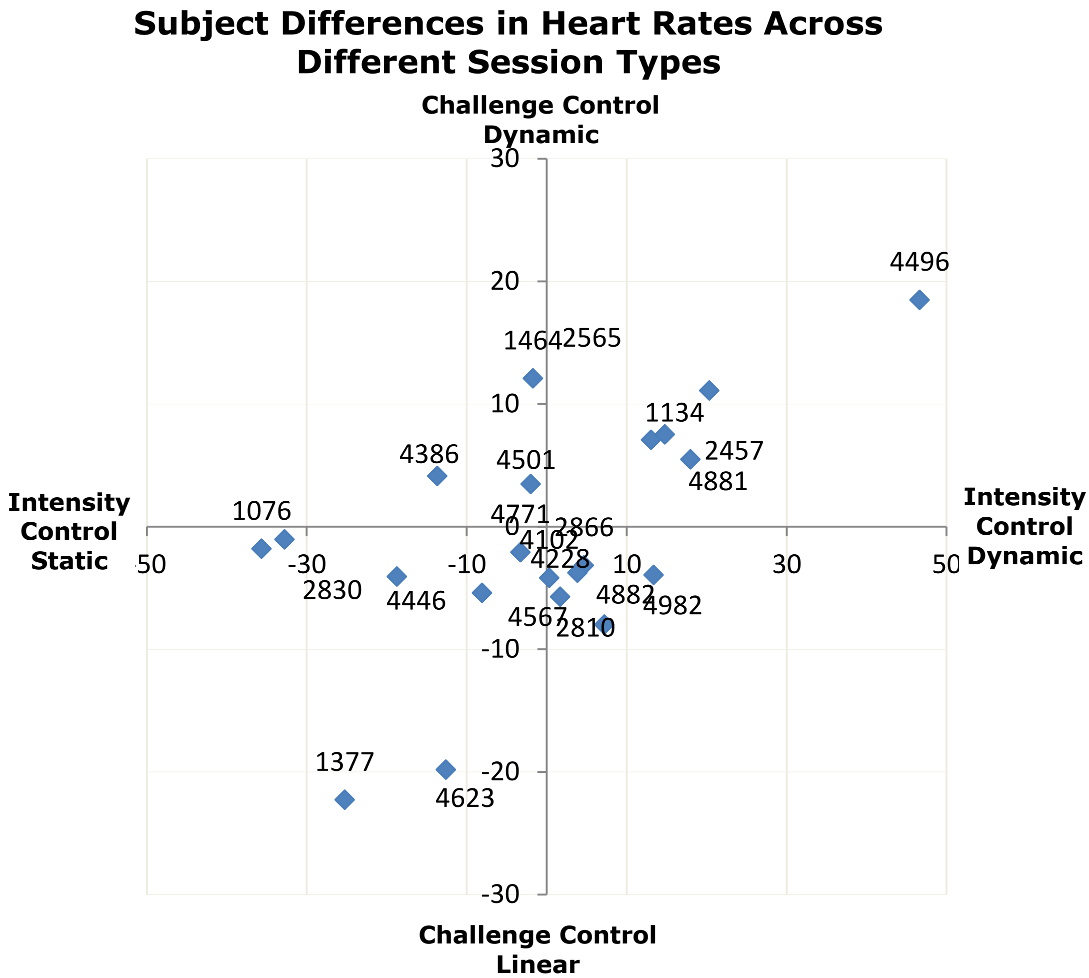

Figure 65 Difference in subjects' average heart rates, when contrasted by challenge control, vertical axis, and by intensity control, horizontal axis.

We can see a relationship between the intensity control and the challenge control. In a subject where the intensity controlled session was more strenuous than the statically controlled intensity sessions, the challenge controlled sessions were more strenuous than the linear challenge sessions. On the other hand, if the intensity controlled sessions were less strenuous than the statically preconfigured sessions, the challenge controlled sessions were less strenuous than the linear challenge sessions.

We can calculate a bivariate correlation for this data, and calculate the Pearson product moment correlation coefficient. For our data we get a value of 0.592, which is significant at 0.01, and shows a positive correlation between the heart rate in the intensity controlled sessions and the heart rate in the challenge controlled sessions.

7.2.1 Challenge Control Effect on Intensity

Let us follow the previous section by splitting the subjects into two groups:

Group 1: The subjects on the left of Figure 65 where the preconfigured static intensity control mode is the more intense workout than the managed intensity sessions, that is, they had a higher average heart rate. Average heart rate for each mode of these subjects is shown in Figure 66. In this group, the average intensity for the dynamic challenge controlled session, lighter green solid line in Figure 66, is slightly lower than the linear challenge controlled session.

Group 2: The subjects on the right of Figure 65, where the managed intensity modes were at a higher intensity than the preconfigured static intensity sessions. Average heart rate for each mode of these subjects is shown in Figure 67. In this case, the converse occurs and the average intensity of the challenge controlled sessions, the lighter green solid line in Figure 67, is slightly higher than the corresponding linear challenge session.

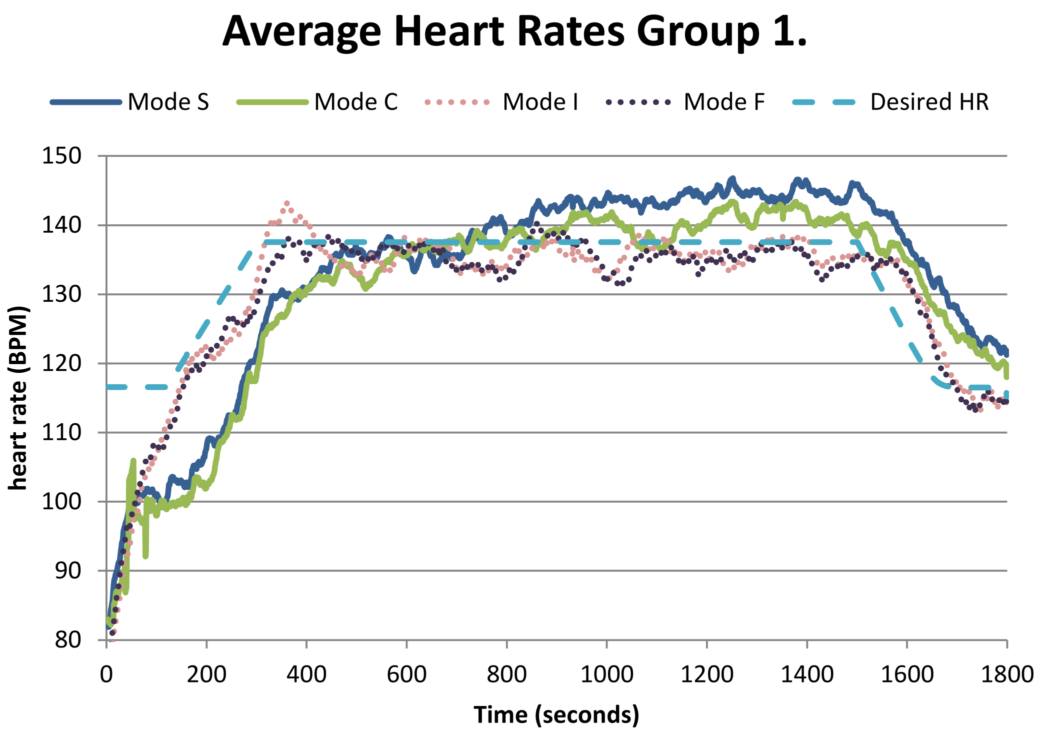

Figure 66 Average heart rates in different sessions for those subjects where the statically set intensity heart rates were generally higher than the heart rates on the intensity controlled sessions.

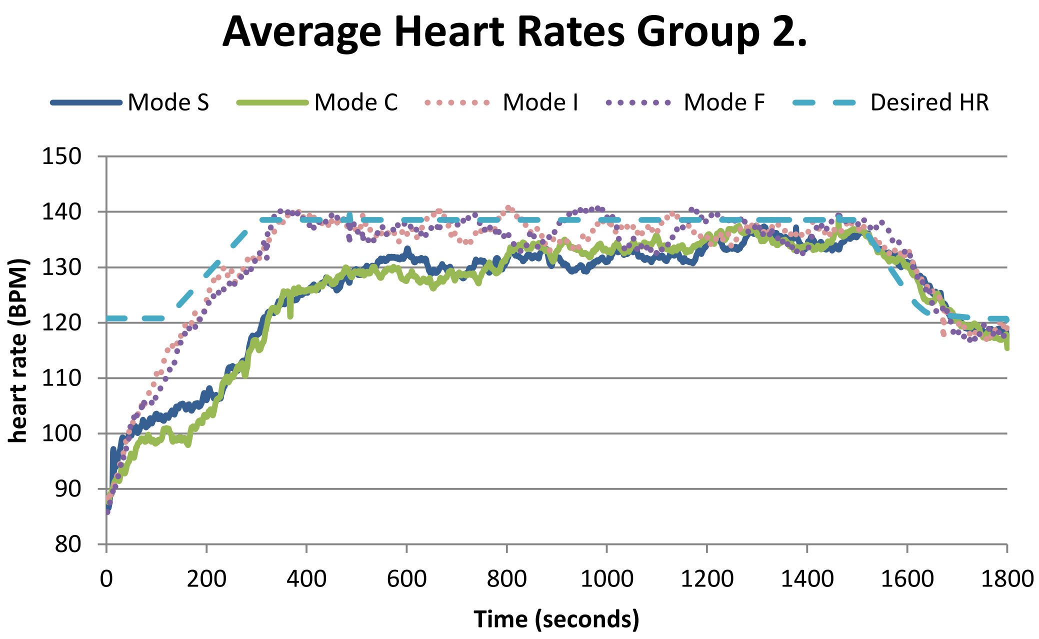

Figure 67 Average heart rates in different sessions for those subjects where the statically set intensity heart rates were generally lower than the heart rates in intensity controlled sessions.

To summarise what we can see in Figure 66 and Figure 67; the challenge controlled mode, Mode C, is closer to desired heart rate, than the non-challenge control mode, Mode S. Remember that here the two modes, Mode C and Mode S are run over the same preconfigured intensity plan and with the same resistance. The expectation is that these two modes would generate very similar workout intensities, where heart rate is used as the indicator of intensity. As we saw, the modes did not show the same response. The key difference between the two modes was the challenge control which we conclude is the cause of the intensity difference.

The actual difference may be difficult to see in Figure 66 and Figure 67 so let us look at the same data, but just focused in on the last 15 minutes of the workout.

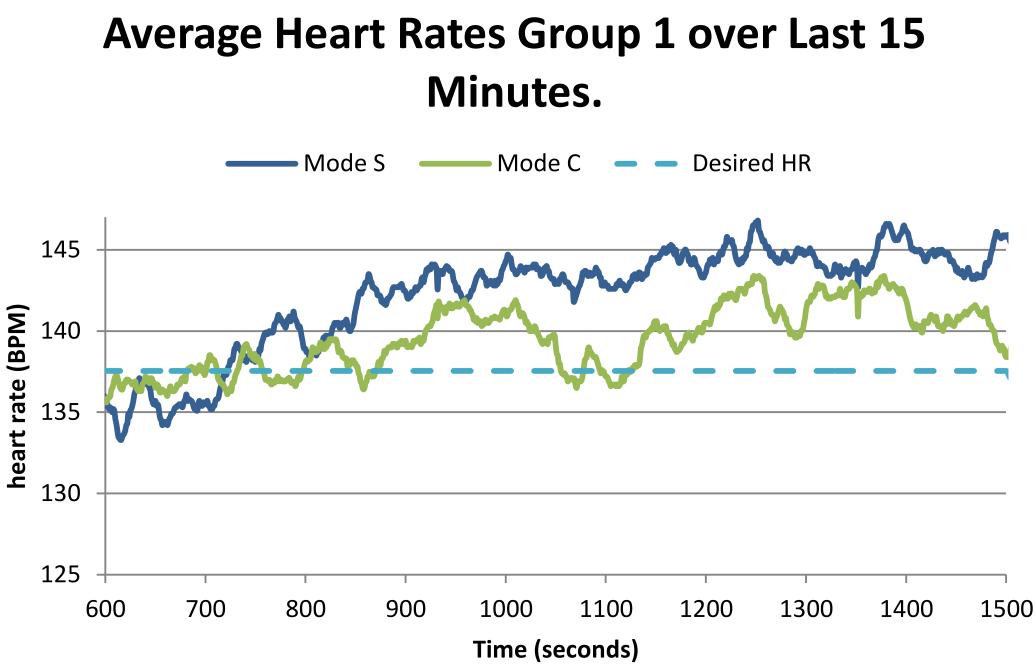

Figure 68 Average heart rates in the last 15 minutes of the challenge controlled and linear challenge sessions for those subjects where the statically set intensity heart rates were generally higher than the heart rates on the intensity controlled sessions.

We can clearly see in Figure 68 that the challenge controlled sessions, the lighter green line is several beats below the corresponding linear controlled sessions, darker blue line. In Figure 69 the inverse occurs. The challenge controlled sessions, the lighter green line is generally higher that the corresponding linear challenge sessions.

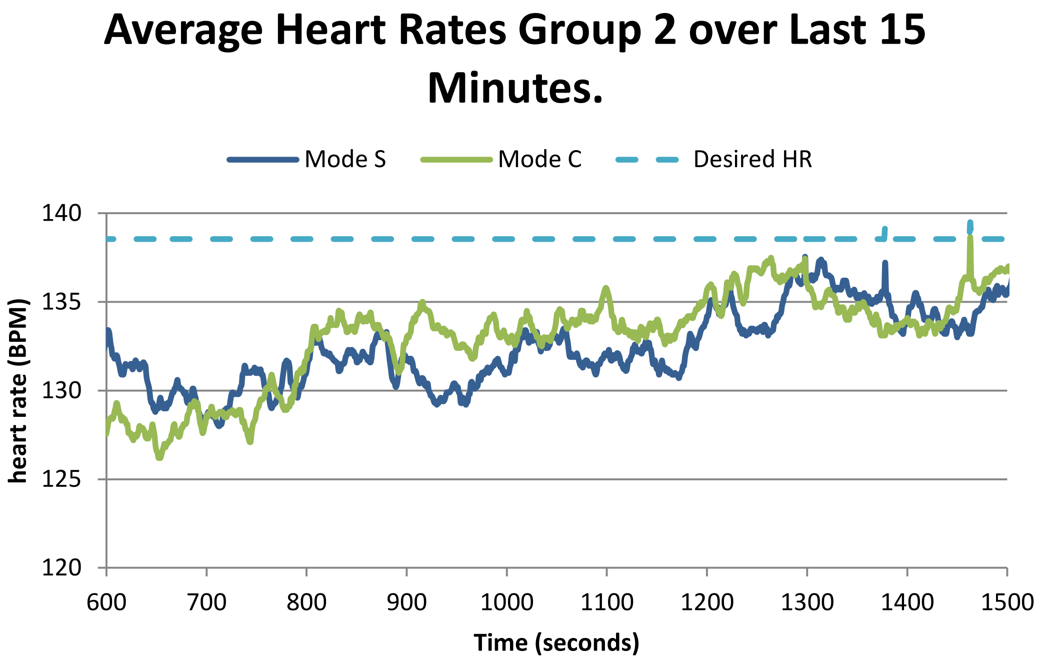

Figure 69 Average heart rates in the last 15 minutes of the challenge controlled and linear challenge sessions for those subjects where the statically set intensity heart rates were generally lower than the heart rates on the intensity controlled sessions.

We can also look at this effect by looking at the difference between the error in the static controlled mode (Mode S), and the corresponding difference in the error on the challenge controlled mode (Mode C) shown in Figure 70.

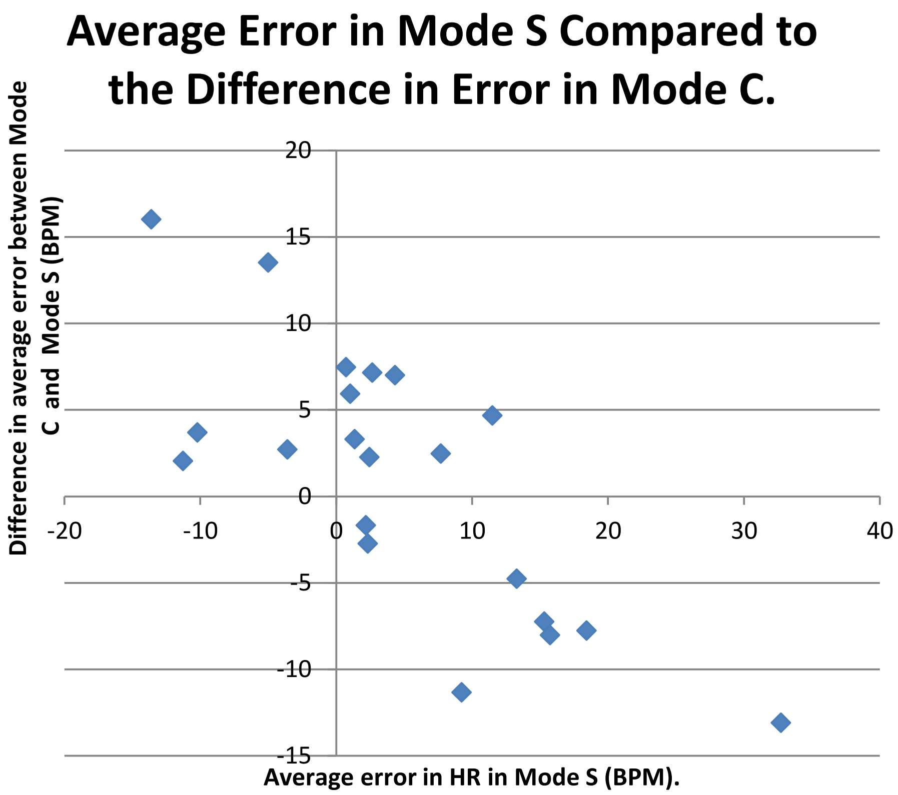

Figure 70 Difference in the error between the Mode S and Mode C session, compared to the actual average error from the desired heart rate in Mode S. The linear relationship is clearly visible. The greater the subject's intensity level above the desired level in the static mode (towards the right), the greater the reduction in heart rate difference during the challenge control mode.

We can conclude from this that the game challenge control we implemented, affected the intensity of the games. Remember that for the session shown in Figure 68, Figure 69 and Figure 70, the workout intensities were set at the same level. When working harder, we can surmise that the player played worse, causing the challenge control to ease off, resulting in a reduction in the intensity of the workout. When the player was not working so hard, it appears that the player played better, causing the challenge control to make it harder inducing higher intensity workouts. The change in intensity was not great but there was a strong correlation, the sane as we saw earlier in Figure 65.

This highlights the importance of the intensity control and challenge control being managed together as per the Dual Flow Model. When there was no intensity control, we saw an impact by the challenge control on the intensity of the workouts. Management of the intensity is required to cancel out any effect caused by the challenge control.

7.3 Player Perception of Intensity

Now that we have looked at the physical data on the intensity, we investigate the player's perception of the workout intensity. After every session, the players filled out a questionnaire related to the workout session that they had just undertaken. The first four questions were related to the subjects' perception of the exercise intensity.

- Question 1 In terms of exercise how strenuous do you feel today's workout was on a scale of 1 to 5? (1 = Too easy, 5= Too strenuous).
- Question 2 What do you think about the appropriateness of the length of time the workout took? (1 = Too short, 5= Too long).
- Question 3 How exhausted do you feel? (1 = Not at all, 5 = Very)
- Question 4 Do you feel that you got a good workout? (1=No, 5= Yes)

We can sum the results from these answers to get an indicator of the subject's perception of the workout intensity. The results for each of the sessions can then be compared to the other three sessions in the same manner that we compared the raw heart rates earlier.

Again, for this data we are not concerned with the absolute values, but more so the differences in response to the different session. The individual subject's response value is compared against the subject's answers to the questions for each of the different sessions. From these comparisons, we generate an indicator of which of the sessions was perceived by the subject to be more strenuous than the others.

For example, subject 1377 scored the following cumulative result for the first four questions in each of the different modes:

Table 21 Subject score for workout intensity perception questions.

Static Intensity, Linear challenge (Mode S)	15
Intensity Controlled, Linear challenge (Mode I)	10
Static intensity, Dynamic challenge (Mode C)	12
Intensity Controlled, Dynamic challenge (Mode F)	11

We compare the values across sessions that differ only by one factor, either intensity control, or game challenge control. To do this, we compare the Mode S session score against the Mode I session, and Mode C session score against the mode F session score. This gives us a score for the intensity control's effect on the subject's perception. We then compare the Mode S session to the Mode C session and Mode I session to Mode F session score. This produces a result representing the game's challenge control effect on the subject perception.

$$\begin{aligned} &\mathit{Intensity\ Controlled\ axis} \\ &\qquad = (\mathit{Mode\ I\ score} - \mathit{Mode\ S\ score}) \\ &\qquad + (\mathit{Mode\ F\ score} - \mathit{Mode\ C\ score}) \end{aligned} \tag{20}$$

$$Challenge\ Controlled\ axis$$
$$= (Mode\ C\ score - Mode\ S\ score) + (Mode\ F\ score - Mode\ I\ score) \quad (21)$$

Using the scores from subject 1377, as listed in Table 21 we perform the four comparisons as follows in Table 22 and Table 23

Table 22 Calculation of intensity perception score on intensity axis for subject 1377.

Mode		Mode		Result
S=	15	I=	10	-5
C=	12	F=	11	-1
				-6

Table 23 Calculation of intensity perception score on challenge axis for subject 1377.

Mode		Mode		Result
S=	15	I=	12	-3
C=	10	F=	11	+1
				-2

The results can then be used to form a vector which can be displayed on a Cartesian plain. The vector value for each subject response was calculated, and the results are plotted in Figure 71.

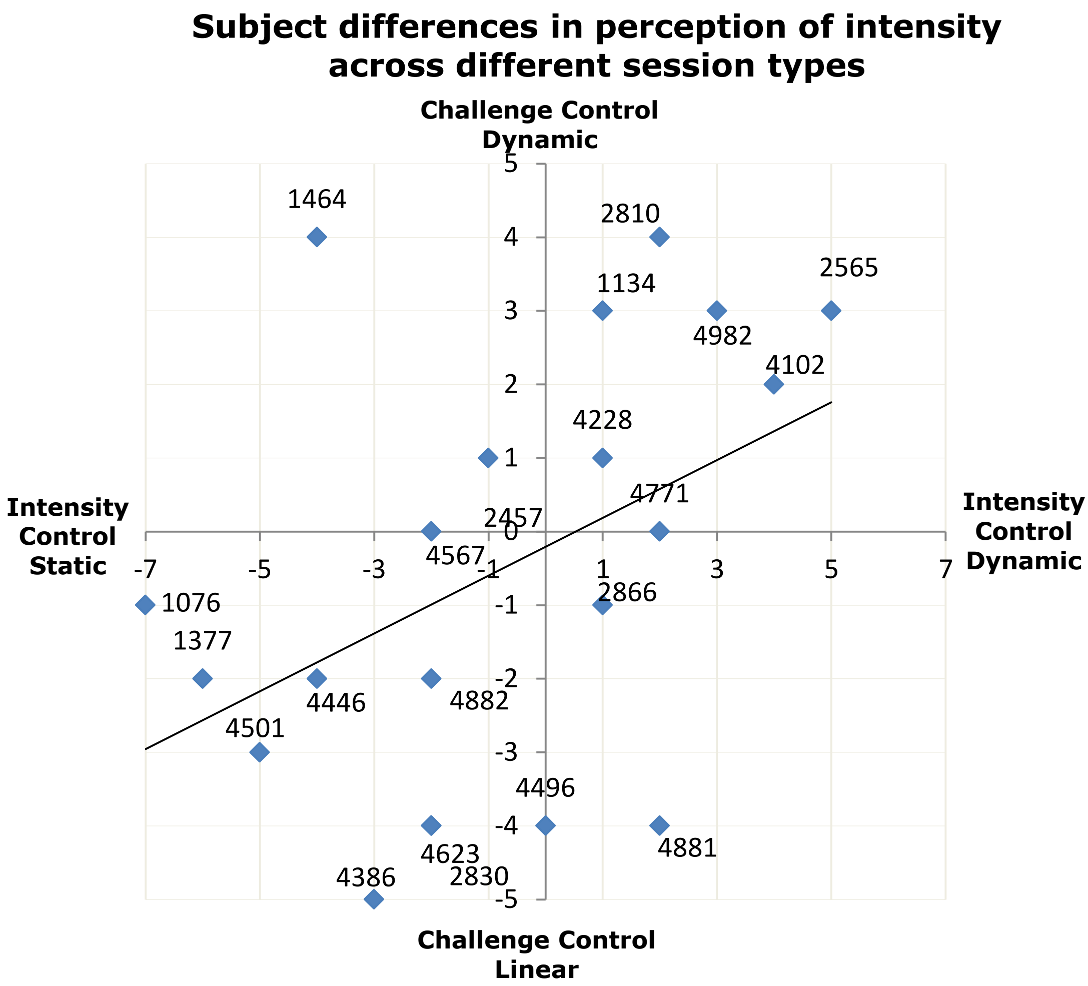

Figure 71 Difference in subjects' responses on intensity related questions, when contrasted by challenge control, vertical axis, and by intensity control, horizontal axis.

Here again we see the same correlation as before when we looked at actual heart rates, see Figure 65. The Pearson product coefficient is 0.444, which is significant at 0.05 and shows us there is still a good positive correlation, though not as strong as before. There is a correlation between the different modes and players perception of the intensity of the workouts. The players' perception of intensity across the modes was aligned with the actual intensities.

While the change in intensity was not large, generally +/- 5 beats per minute, the player perception showed the same correlation between the modes as before. This indicates that the intensity difference was noticeable by the players.

7.3.1 Perception Versus Reality

We can take a look at the comparison between perception and reality for the individual subject directly by examining the perception results compared to the actual intensity data. We take a look at the users' perception of intensity compared with actual intensities. In order to check that changes in the perception of intensity correlates with actual changes in the physical intensity we need to have a baseline to compare to. Using the static intensity, liner challenge control session, Mode S, as a baseline we calculate each subjects change in intensity perception and change in heart rate across each of the three remaining sessions, see Figure 72. Each point plotted in Figure 72 represents a session in any of the three modes I, C or F, for the subject, compared to the Mode S session for the same subject.

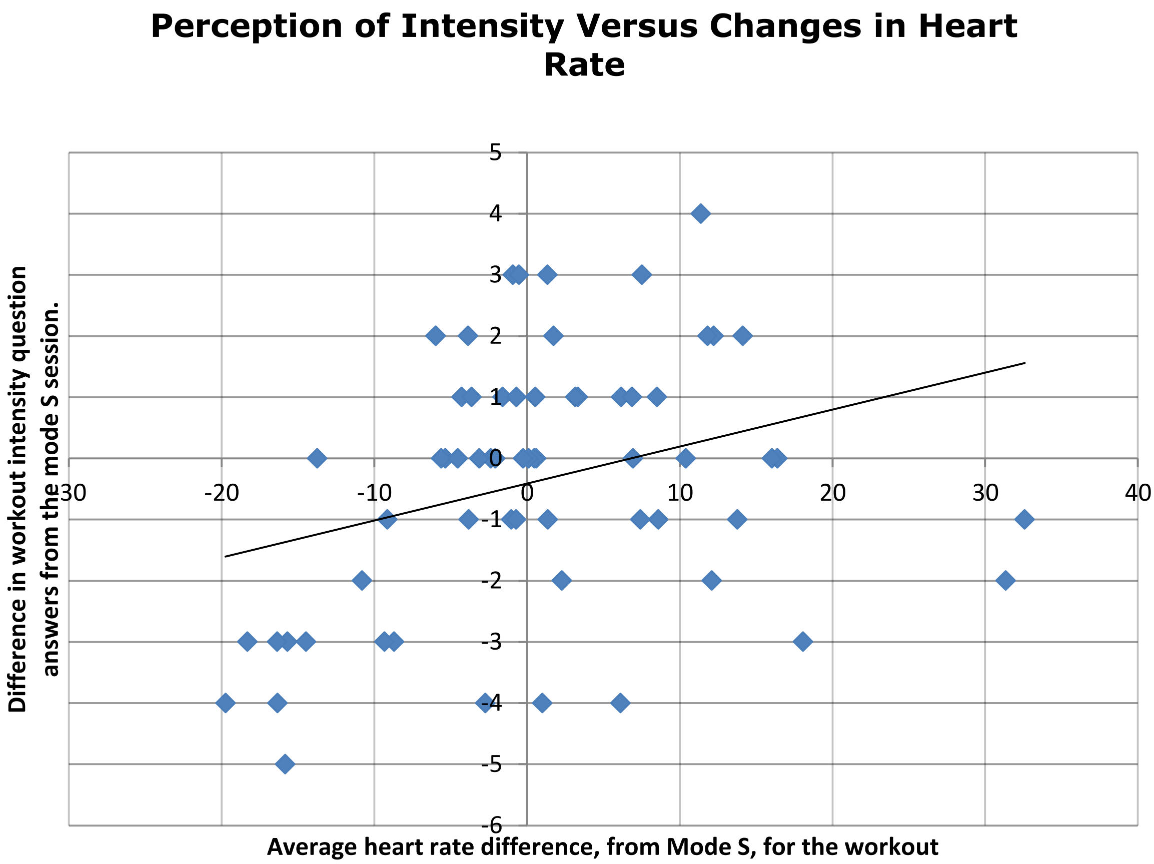

Figure 72 The subjects' answers to the intensity related questions, plotted against the actual changes in Heart Rate show a strong correlation.

The Pearson correlation coefficient here is 0.309 which is statistically significant at 0.05. The subjects' perception of intensity correlated with the actual change in heart rate.

The variations in intensity had a mean difference of 7.11 beats per minute and a standard deviation of 10.65 beats per minute. The correlation here between the player perception on intensity and actual intensities indicates that this level of difference is enough to be noticed by the subjects.

7.4 Player Engagement

For the dynamic challenge control side of the Dual Flow Model, we want to examine how engaged the subjects were in the different session types. Unlike the intensity side of the equation, where we can measure heart rate, there is no easy measurement of how engaged a subject is with the exergame. In our attempt to measure to engagement, and the attainment of the flow state, we examine questions from the questionnaires.

Let us look at session questionnaire questions 6, 7 and 8:

- Question 6 On a scale of 1 to 5 how interesting did you find today's game?
- Question 7 How quick did the time pass during the exercise period?
- Question 8 During the workout, roughly how much of the time were you focused on the time remaining?

For each of these questions let us compare the responses across the sessions. In the same manner as before, we pair up the different responses of the subjects based on the different modes. Mode S with Mode C and Mode I with Mode F for the Challenge, Mode S with Mode I and Mode C with Mode F. This results in 42 paired answers on sessions that differ only by intensity, and another 42 paired answers that differ only by challenge control for each subject. We compare the dynamic challenge controlled responses with the linear challenge controlled sessions on the vertical axis, and we compare the statically controlled workout intensity with the dynamically controlled workout intensity on the horizontal axis.

We can do some statistical tests to determine if there are any statistical differences in the pairings. The five value scale used in the questionnaires is non-continuous ordinal data, so we do a nonparametric test of the data using the Wilcoxon signed rank test. This results in a p value of 0.639 on the intensity session and 0.435 on the challenge session values, which indicates no statistically significant difference in the responses for the different sessions.

If we group each subject's responses together we can plot the axis representing intensity control and challenge control as we did before, see Figure 73. In Figure 73 we have shaded the quadrant where, based on the Dual Flow Model, we would expect the bulk of the results to fall.

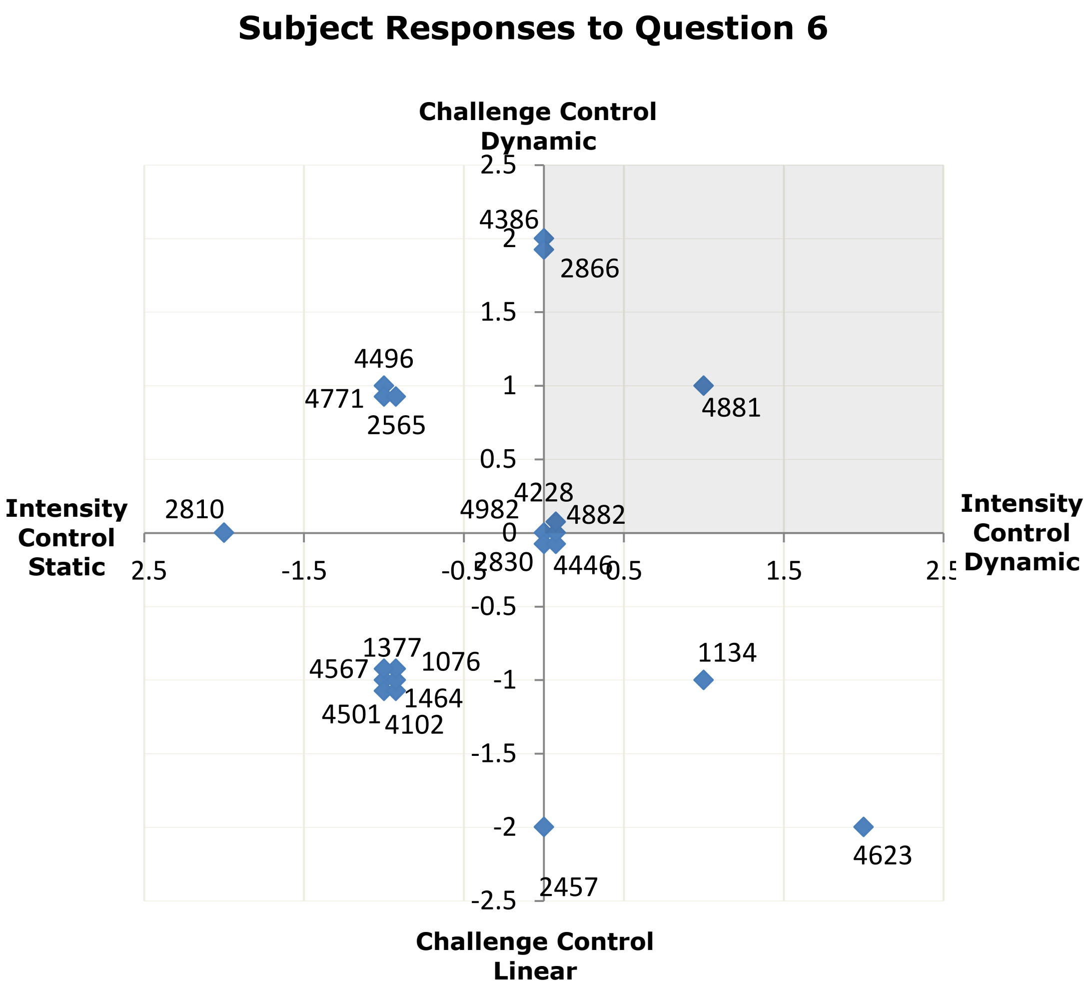

Figure 73 Subject responses in relation to how interesting the session was. There is no discernable favouring of any of the different modes.

If we examine Question 7, related to how quickly the time passed, Figure 74, we see what looks like a leaning towards the static intensity and linear challenge controlled session. Again, in Figure 74 we have shaded the quadrant where, based on the Dual Flow Model, we would expect the bulk of the results to fall.

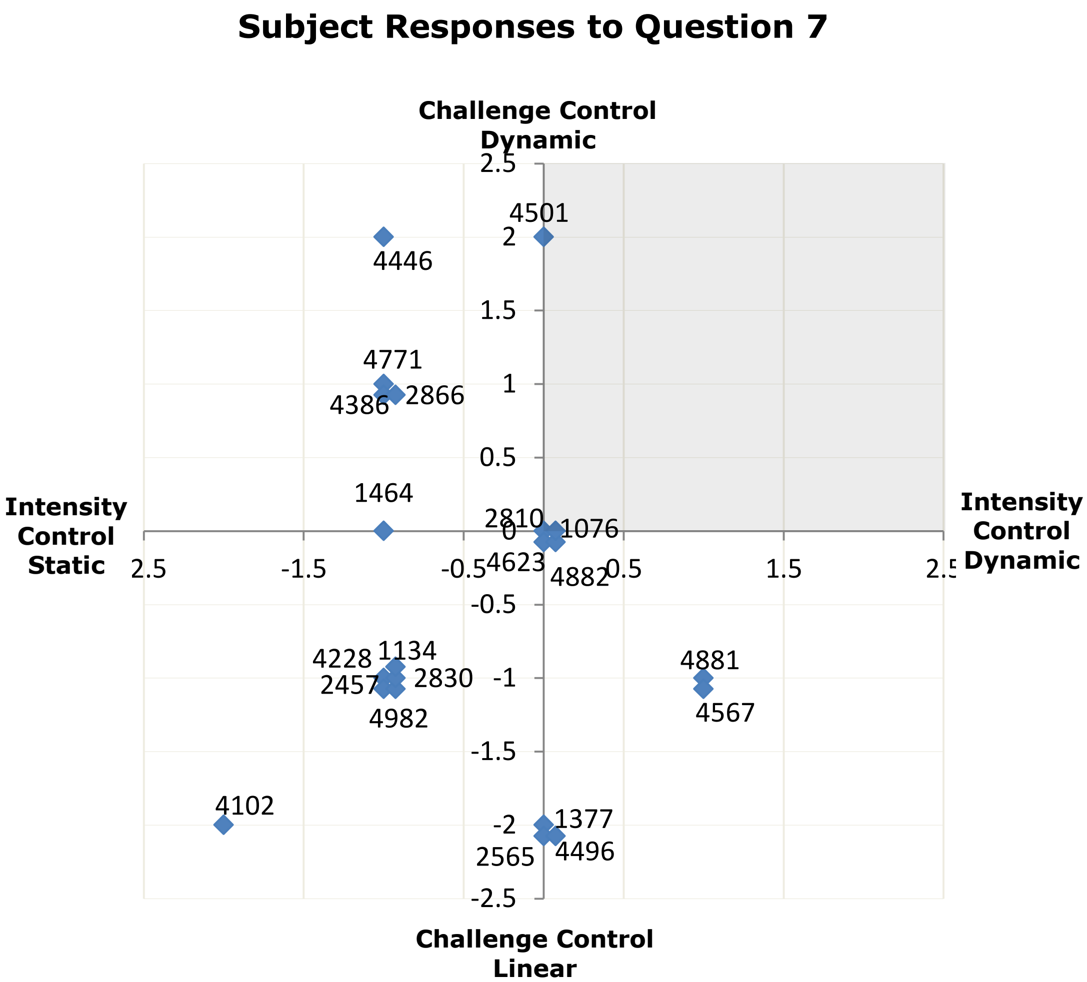

Figure 74 Subject responses to questions on how quickly the time passed. A leaning towards the static intensity, linear challenge can be clearly seen.

Testing the values on the pairs where the intensity differs using the Wilcoxon signed rank test results in a Wilcoxon statistic of 38.5 and a resulting p value of

0.043. This indicates that the subject thought that time passed faster in the static intensity sessions, rather than the intensity controlled sessions. On the challenge side of this question we get a p value of 0.495, so no significant difference in responses for the challenge controlled sessions.

Question 8, asking the amount of time spent focused on the time remaining, shows what looks like an indication, that during the intensity controlled session the subjects spent more time looking at the clock, see Figure 75. Spending more time looking at the clock is a negative indicator of engagement, so the Dual Flow Model indicates that subjects should be in the lower left, shaded, region of the chart. Performing our statistical tests on this, for intensity we get a p value of 0.068, and for the challenge values we get a value of 0.838, indicating there was no statistically significant difference in responses on this question.

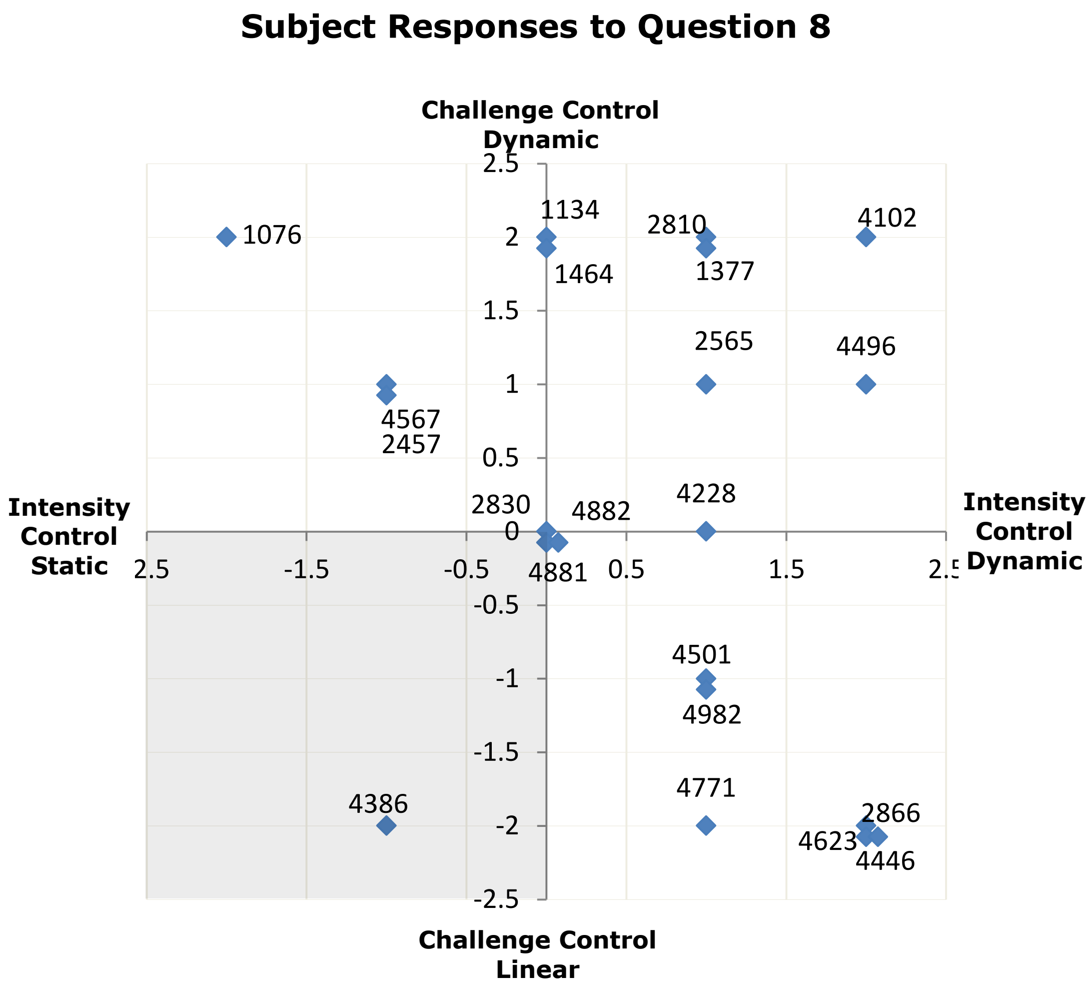

Figure 75 Subject response to questions on how much time they spent focused on the time remaining.

Let us examine the results from these questions together. In order to do this we need to invert the results from Question 8, remember that a positive value for Question 8, more time spent looking at the time remaining, is a negative indicator of engagement. When we combine all three results, Figure 76, we can see a clear leaning to the static intensity mode.

Using the Wilcoxon signed rank test, we get a p value of 0.003 on the intensity values and a p value of 0.407 for the challenge control. From this we can conclude that the static intensity sessions were more engaging than the intensity controlled sessions. On the other side of the equation the challenge control did not have a statistically significant impact on the engagement of the player.

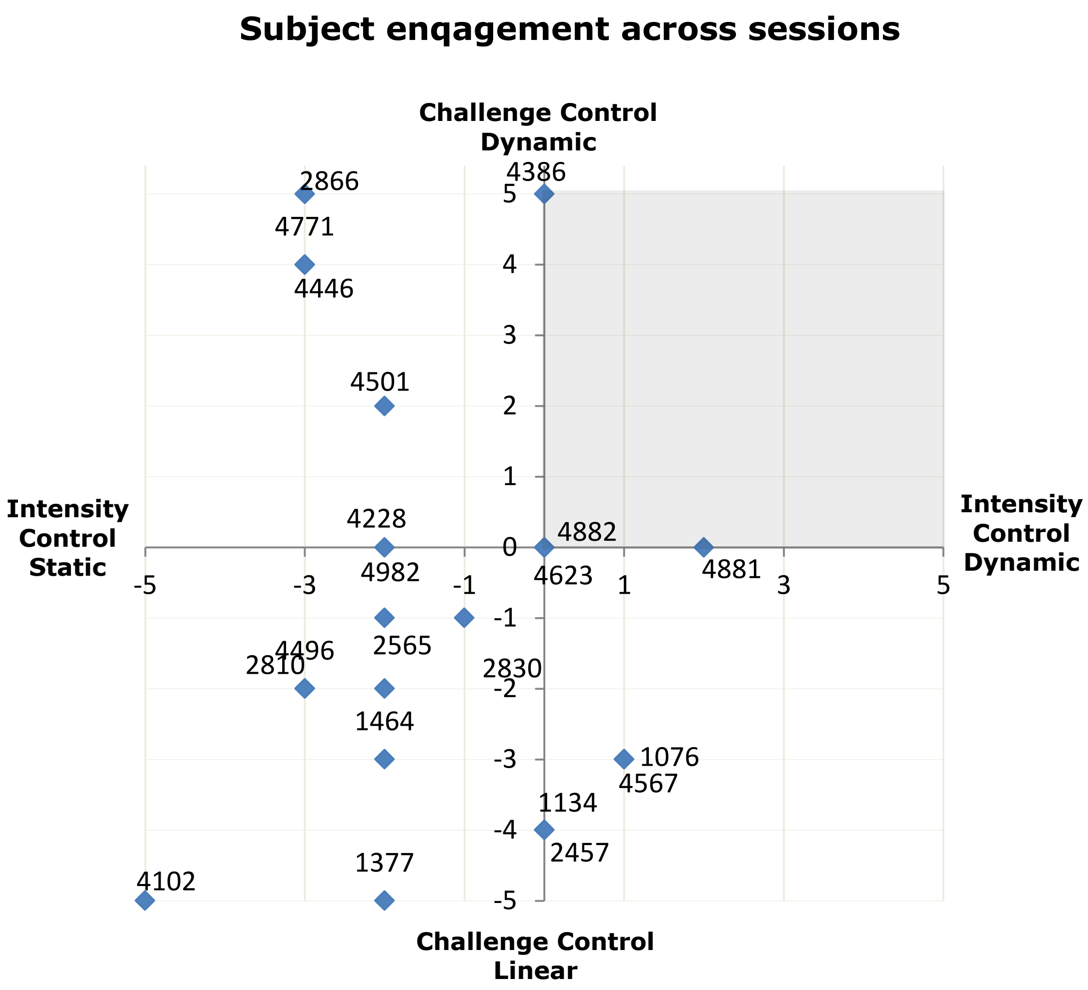

Figure 76 Subject engagement in different sessions.

What is interesting from Figure 76, is the lack of points plotted in the upper right (shaded) quadrant of the plot. From the Dual Flow Model, we would expect there to be the majority of responses in this area. From the results of our trial, there were no subjects who indicated better overall engagement on the dynamic intensity dynamic challenge mode of the exergame.

7.4.1 Overall Challenge Perception

At the end of the sessions the subjects were asked to identify which, if any, of the sessions were more challenging. The results were spread as shown in table Table 24.

Table 24 The number of subjects who identified the particular game mode as more challenging than the other game modes.

Mode S Static Intensity Linear Challenge 1 subjects	**Mode I** Intensity Controlled Linear Challenge 2 subjects
Mode C Static Intensity Dynamic Challenge 4 subjects	**Mode F** Intensity Controlled Dynamic Challenge 4 subjects

This data shows that the subject thought that the dynamic challenge sessions were more challenging. The subjects were also asked to identify which, if any, of the sessions were less challenging.

Table 25 Number of subjects who identified the particular game mode as less challenging than the other game modes.

Mode S Static Intensity Linear Challenge 3 subjects	**Mode I** Intensity Controlled Linear Challenge 0 subjects
Mode C Static Intensity Dynamic Challenge 2 subjects	**Mode F** Intensity Controlled Dynamic Challenge 2 subjects

The answers to this as shown in Table 25 question partially cancel out the finding from the previous question, since some subjects found that the dynamic challenge sessions were less challenging than the other sessions. If we combine the results using a plus 1 for where a subject identified the session as more challenging and a minus one where the session was identified as less challenging, we get the following results in Table 26.

Table 26 Combined score from subject selection of more or less challenging sessions.

Mode S Static Intensity Linear Challenge -2 subjects	**Mode I** Intensity Controlled Linear Challenge 2 subjects
Mode C Static Intensity Dynamic Challenge 2 subjects	**Mode F** Intensity Controlled Dynamic Challenge 2 subjects

Here in Table 26 we no longer see the bias to the dynamic challenge side. We see that the static intensity, linear challenge was more often selected as less challenging. We now compare these results with the actual challenge level determined by the software during the subject sessions.

7.5 Challenge Control

With intensity control we have a clear measure of intensity, heart rate, and a clear mechanism through which to increase or decrease the intensity, increased or decreased RPM rates. With challenge control we do not have either of these clear cut variables. As discussed in Chapter 4, we used a fuzzy logic system to determine the player performance from in game factors. In this section we examine how well this control worked.

7.5.1 Subject Performance

Let us examine the calculated player performance in the game during the challenge controlled sessions. Recall that during the challenge controlled sessions, Mode C and Mode F, the level of challenge was increased or decreased over the period of the game, based on the measured performance of the subject. At the end of each level the player's nominal success on that level was used to adjust the difficulty on the next level. As previously mentioned in Chapter 4, the challenge of the game was modified by the use of three factors:

1. The speed of the game, essentially the forward speed of the helicopter.
2. The placement of the coins; reductions in the number of straight lines and more random placement of coins.
3. The pattern of the aliens and the propensity for them to move towards the player.

If the challenge control system was working perfectly, for a particular session we should see the challenge level in the game rise, or fall, to the appropriate level and then essentially stay around that level, gradually rising as the subject skill increased, see Figure 77. The challenge control in a perfect system should rise, or potentially fall, from some arbitrary point until it reaches the correct match for the player skill. After this point as the player skill increases, the challenge level will gradually rise to match.

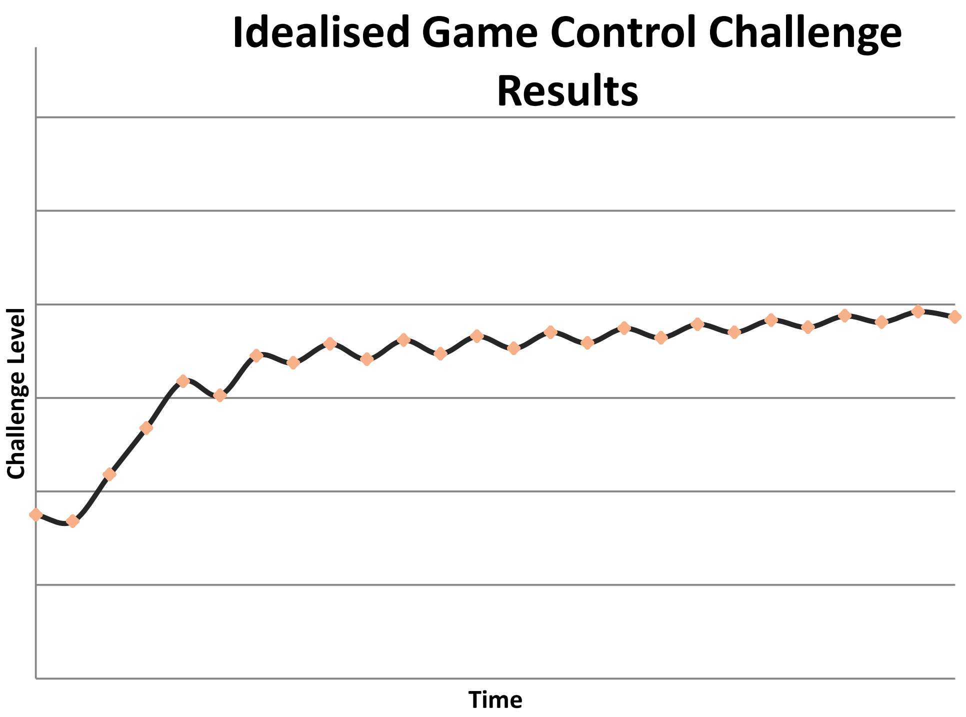

Figure 77 Game challenge control results achieved with imaginary perfect DDA control system.

In Figure 78 the level of challenge for each subject has been plotted. What this graph show is the relative challenge level at which the player is playing during the session. In this chart what we see is that it appears that the bulk of the players had not reached equilibrium before the end of the session.

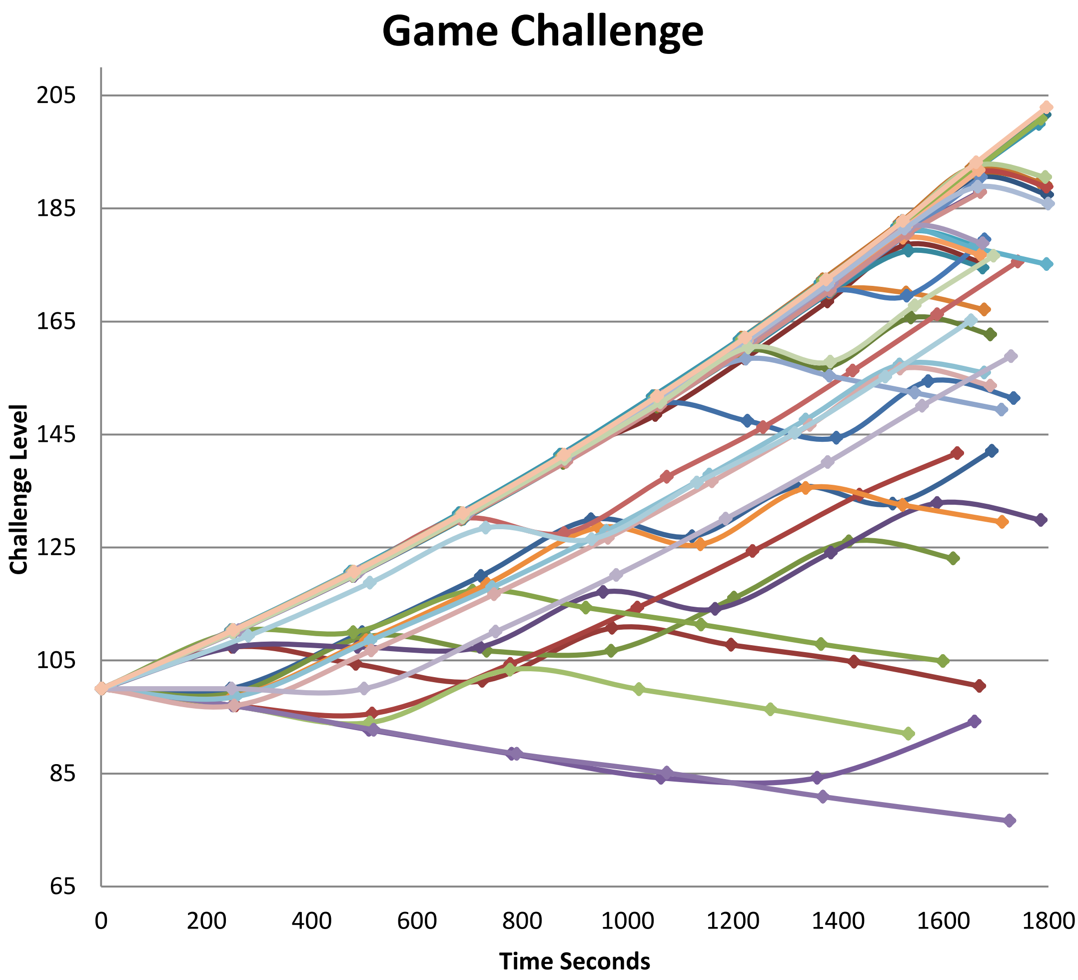

Figure 78 The challenge control applied to the player sessions.

There are many potential causes for this. Was the starting challenge point of 90 the correct point to start? We see in our system that the challenge level for some of the players fell from this starting point, however in the bulk of subjects, the skill level rose above this level. It appears that this level was a reasonable starting point for some of the players but not necessarily for all subjects.

In Figure 78 we see a large number of players where the challenge level was rising at a continuously high rate. In our system the rise achieved by these players was equivalent to the maximum limit set in the software. The limit was set to prevent unreasonable jumps in the challenge difficulty, which could cause large continual oscillation between easy and hard. However it is possible that this limit may have been set too low. It is possible that our challenge control system was unable to raise the challenge level fast enough. It is possible that the subjects would have reached a peak level of challenge, and an equilibrium state at some point if they had been able to continue playing for longer, given that exhaustion was not a factor.

Another problem with analysing the results of the challenge control is the difficulty of distinguishing cause and effect. If the challenge control system is continuously raising the challenge level, this could be caused by the determination of player success being wrong, which then determines the need to raise the challenge when it is not warranted. Alternatively, it could be caused by the mechanism by which challenge levels is raised being faulty, and not raising the challenge level by sufficient or desired amounts.

A potential area of further research is to examine dynamic difficulty adjustment on a game where the exercise component can be cleanly separated out. This would lead to better understanding of how the difficulty adjustment fits in with and interacts with the exercise component of an exergame. The difficulty here is whether a game system can be designed, in which it is valid to compare the game without the exercise component, to the game with the exercise component. Generally, it is likely that for an exergame, the physical component will form a part of the skills required in the playing of the game.

When we look at the challenge control, we also note that the challenge control levels were quite different for the same subject, between the two dynamically controlled sessions. Some of this can be attributed to differing play styles. As discussed earlier in 7.1.5, nearly all players reported playing some of the sessions with a different key focus in their game play strategy. The different play styles may have rated differently with the challenge control, whilst the player themselves may have performed significantly better with one strategy over another.

As mentioned previously, the play style is another factor which contributes to the difficulty in managing dynamic difficulty. Dynamic difficult adjustment needs to ensure that what it measures as success, and how it increases the challenge, fits in with the goals and motivation of the player. Imagine a racing game where a player was deliberately trying to crash other cars and knock them out of the race. A DDA system which was limited to looking at the player’s performance based on position in the race, might not achieve the desired outcomes.

7.5.1.1 Final Challenge Levels

Finally, for challenge control we take the final challenge level obtained in the challenge controlled sessions, and plot the value for the two challenge controlled sessions. The two values are plotted in Figure 79 in order of overall performance, with the individual subject sessions plotted in order of the date the session occurred. There are two key items that we can see here; different players have different abilities, and those abilities can change over time.

What we see in Figure 79 is also that in the bulk of cases the challenge control system indicates that the subjects performed better, or roughly the same, on the second challenge controlled attempt. This is as one would generally expect. The more experience at the game the more likely the subject is to produce a better performance. The measurement of skill in our challenge control system, at least on this facet, matches with real world expectation of skill levels.

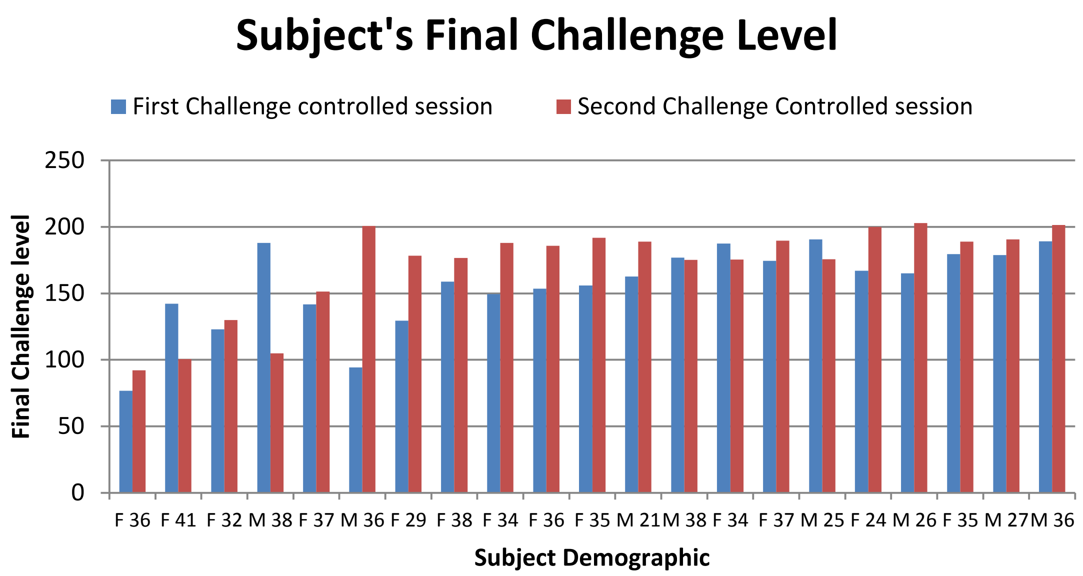

Figure 79 Subject performances on the challenge controlled sessions.

Looking at Figure 79 we can see different players achieved quite different results in the game challenge control. Some variation would be caused by random chance events in the game play, but we can see that some subjects played better on the two sessions than other subjects.

This success was further analysed by looking at the demographics for the subjects, as shown in Figure 79. There appeared to be no identifiable factor which was a determinate for the success of the subject. There was no correlation between gender or age and success at the gameplay. The normal level of video game play was a factor which we might expect to have a bearing. However, it also did not appear to be a factor in the determination of the success or otherwise of the game play. A number of the poorer performing players, on the left side of Figure 79, rated themselves as playing video games weekly. The only player to identify themself as playing video games several times a week, did in fact achieve the best overall performance, however the performance was not significantly better than other subject in the top 5, 3 of who identified themselves as never or rarely playing video games.

The general level of exercise and strenuous activities undertaken by the subject might also have been a predictor of success in the game play; however, the intensity management and setting of the resistance would tend to level this out, so we did not see any evidence that the success was related to the subject’s level of exercise.

7.5.2 Subject Engagement Outcomes

With intensity effects on engagement, it was expected that we would see a fairly even spread of subjects on either side of the centre, in Figure 76, left and right along the intensity axis. There were subjects where the intensity controlled sessions were at a higher intensity, and there were subjects where the statically set sessions were at a higher intensity. If the intensity level was a driver for subject engagement, the intensity controlled sessions were the logical choice to have generated a greater level of engagement. This was not the case for our subjects. The sessions where the intensity did not differ, stand out as being more engaging for our subjects.

On the challenge control side, we expected to see improvement in subject engagement when using the dynamic challenge control system. We saw little effect from the challenge control system in terms of engagement. It did not produce the desired result of improving player engagement through attainment of the flow state.

7.6 Overall Rating of Different Modes

At the end of each session the players were asked to give an overall rating of the exergame system as a form of exercise out of 10. This rating was generally the same for each session type. However, interestingly, the results show the full control mode, as being substantially lower than the three other three modes. According to the Dual Flow Model, this mode is the best mode for the building of exercise games. It was the mode in which the subjects achieved the best exercise outcomes.

Table 27 Overall rating of the system as a form of exercise.

Mode S Static Intensity Linear Challenge Total Rating 146 Out of a possible total of 210	**Mode I** Intensity Controlled Linear Challenge Total Rating 148 Out of a possible total of 210
Mode C Static Intensity Dynamic Challenge Total Rating 145 Out of a possible total of 210	**Mode F** Intensity Controlled Dynamic Challenge Total Rating 145 Out of a possible total of 210

7.7 Discussion

Now that we have looked at the data from the trial, let us summarize what conclusions we draw from this data.

7.7.1 Exercise Intensity

From existing literature we know that the correct intensity for exercise workout is important. If you exercise too lightly, you may not meet your fitness or weight-loss goals. If you push yourself too hard, you may increase your risk of soreness, injury and burnout (Mayo Clinic, 2009). As workout intensities increase, exercise can switch from aerobic to anaerobic exercise. It is important to maintain the correct intensity for the desired exercise.

7.7.1.1 Obtaining the Correct Intensity Levels

Producing the correct level of intensity for an exergame is difficult. In order to get the correct workout intensity levels during our study, we ran two tests, a ramp-up and a non-game session, which were then used to set the resistance levels for the subject for static sessions. With careful monitoring of the heart rate during these two tests we were able to set reasonable accurate levels of workout intensity.

However, because of the numerous factors that affect subject workouts, some of these sessions were still quite a way off the desired level of intensity; either too high or too low. In the controlled environment of our study, we found that to get the desired level of intensity management, continual monitoring and automatic adjustment of the intensity settings worked significantly better to achieve the desired intensities.

In an uncontrolled home environment where an exergame system might normally be used, the number and magnitude of factors potentially affecting the exercise workouts will be significantly higher. It this case it is crucial that workout intensity is measured and controlled in order to produce the appropriate level of exercise intensity.

Along with the normal issues affecting exercise intensity, we also saw during our trials that the challenge control could impact on the intensity of the game session workouts. This impact is just another factor impacting on intensity which we need to be aware of, and, which reinforces the importance of carefully measuring and monitoring workout intensity. As emphasised by the Dual Flow Model, the considerations of exercise side of an exergame go hand in hand with the considerations of the game side of an exergame.

7.7.1.2 Factors Affecting Heart Rate Variability

During this study, we learned that heart rate is affected by a lot of factors. Some of the factors include:

Environmental Temperature and Humidity

The room used for the study was air-conditioned and generally stayed between 22 and 24 Celsius. The humidity of the room was not measured. According to Seiler (1996) this can have a considerable effect on the heart rate during cycling.

Time of Day

The human body shows diurnal (time of day) variations in many physiological responses (Frank A.J.L. Scheer, Doornen, & Buijs, 1999). The effect of exercising in the afternoon as compared to the morning, for instance, could have an impact of the heart rate response for a particular subject. As much as possible the subjects were scheduled for exercise at the same time of day for each session. Unfortunately, due to scheduling issues, this was not possible in all cases.

Psychological Stimulus

The human heart will respond to external psychological factors, such as fear, excitement, nervousness. Several studies have shown that different video games elicit considerable emotional arousal or stress related cardiovascular reactivity in terms of heart rate and blood pressure (Ravaja, Saari, Salminen, Laarni, & Kallinen, 2006).

During the study, the subjects were asked to play a video game. Some subjects were generally not video game players. This could potentially cause changes in heart rate responses due to nervousness or excitement; however, it is likely that for each individual the responses are likely to remain fairly consistent across the four games.

Body Position on Bike

The subject's position on the bike can influence the heart rate response. Sitting up or slouching over caused variations to heart rate response. This was quite noticeable in some subjects when they sat upright in order to take a drink. Bonzheim et al. (1992) found that at peak exercise the physiological differences between recumbent and upright cycling were not significant. However at submaximal exercise, there were statistically significant differences in heart rate, blood pressure and oxygen consumption.

Physical condition

The physical condition of the subject on any particular day can vary. Hydration levels, tiredness, prior exertions during the day are just some additional factors, which could cause different heart rate responses.

7.7.2 Challenge Control

In the trial we attempted to demonstrate that dynamic difficulty adjustment could be used to help exergame players enter the flow state. This we expected would lead to deeper engagement in the video game and be a better motivator for the subjects. We did not see this in our study. The sessions with the challenge control did not produce a higher level of engagement. This does not conclusively rule out the use of dynamic difficulty adjustment (DDA) in exergames. It is more an indication that the DDA that was implemented for the study did not help or cause the players to reach the flow state.

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. For game success there is no such easy way to judge the level of gameplay challenge relative to the subject's ability and capacity. For our exergame system, 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 pedalling 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. Chen (2006) points out the limitations of using conventional DDA to attempt to reach the flow state. The flow state is based around many factors while conventional DDA, as used in our trial, is centred on player performance in the game. It is, he argues, possible that the player reaches the flow state doing something that does not directly contribute to any of the measured performance attributes used by the DDA in the game. Chen complains that most of the standard DDA systems are overly focused on one aspect of flow, balance between challenge and ability; this is often to the detriment of one of the other key factors of flow, the sense of control.

Liu et al. (2009) also note the limits of basing DDA solely on player performance. They argue that a computer game's paramount evaluation factor should be the affective experience provided by the play environment. From our trial results, we conclude that DDA, and the attempted management of skills versus challenge, is insufficient for our Dual Flow Model.

When we look at the nine core points of "flow" construct developed by Csikszentmihalyi in 1975 (S. Jackson & Csikszentmihalyi, 1999) one item, which particularly stands out as a potential reason why the subject might have been more engaged, closer to the flow state, in the static intensity variants of the software is:

6 - A sense of personal control over the situation or activity.

Webster, Trevino, & Ryan (1993) performed research into flow in Human-Computer interaction. They questioned students after training classes in Lotus 1-2-3, spreadsheet software and also workers who used email software. The results indicated an important link between control and satisfaction.

Te'eni & Feldman (2001) performed research on player performance and satisfaction with adaptive websites. They found that while the adaptive website improved accuracy and performance it was not rated more satisfying, it “reduced the user’s sense of control”.

7.7.2.1 Intensity Effect on Engagement

As we saw earlier in this chapter, our dynamic intensity control worked well to meet the desired heart rate, but it also acted as a negative impact on player engagement. It is possible that the intensity changes within our exergame were too transparent. The cadence rate required to keep the game craft in the centre of the play area varied considerably in some sessions. For example, in the session for subject 4228, as shown in Figure 53, the centre point moves up and down considerably. The centre point cadence rises to 88 RPM at the start or the session and drops as low as 54 near the end of the session, while fluctuating up and down constantly throughout the session. These changes may have led to a lack of feeling in control. Unaware of the link to heart rate, a subject might have wondered why the game suddenly required higher, or lower, cadence levels to maintain the craft in the centre of the game area.

We also saw in 7.1.3 that the intensity controlled sessions resulted in greater variation in heart rates. It is possible that the subjects were, at least on some level aware of the heart rate fluctuation. This may have contributed to a level of dissatisfaction.

7.7.2.2 Challenge Control Effects on Intensity

We saw in 7.1.5 that the game play style of the player had an impact on the intensity level of the game. It is reasonable therefore, to conclude that the game itself, and as such any challenge control system, could have an impact on the intensity of the game.

We saw in 7.2 that the challenge control system appeared to have some small effect on the intensity of the workouts. When the intensity was high on the statically controlled session, relative to the desired heart rate, the challenge controlled sessions were lower in intensity than the equivalent non-challenge controlled session. This makes sense. When the intensity is too high, the players performed worse and the challenge control resulted in changes to the game which caused a reduction in game intensities. Our challenge control system did indicate that the game challenge control had a small impact on the intensity of the game.

7.8 Summary

In this chapter, we examined the results obtained from our study.

We knew from previous studies that setting the correct level for exercise intensity is important. We learned during our study that many factors can influence exercise intensity in an exergame. For this reason monitoring and control of exercise intensity is critical. The PID loops used to manage the intensity during our trial work reasonably well and performed significantly better at managing intensity than a preconfigured plan.

We knew from existing research that dynamic difficulty adjustment in games is difficult. The system used in our exergame did not give the expected results to fit our model. We discussed several potential reasons for this during the chapter and highlighted the potential for further refinement in this area.

In the next chapter, we recap what we have covered in this thesis and study. After that we will suggest further areas where this research could be continued and extended.

8 Conclusions

For this study, we have looked at the field of exergaming and seen that there is a growing interest in this area. Much of the interest is because it is seen as a possible tool in the combat against obesity. Obesity is an increasing problem in modern society (Booth, et al., 2004; Hersey & Jordan, 2007). The driver behind exergaming is that it can motivate people to undertake higher levels of exercise.

8.1 Existing Literature

Looking at the existing literature in the field of exergaming, we have seen a number of studies show that exergame systems do have the potential to be used as a form of regular exercise. Additionally, studies show that video games have the potential to motivate people to undertake more exercise. However there is a lack of study/research in the area of building exergames. What works better, and what should be considered in building an exergame?

With this in mind, we put forward two key areas that need to be addressed in the development of an exergame. Effectiveness; how effective is the exercise undertaken by people using the system, and attractiveness; how much does the system motivate people to want to exercise. The Dual Flow Model, which addresses these two key areas, has been proposed.

8.2 Dual Flow Model

The Dual Flow Model stipulates that in order to maximise the chances of making a successful exergame, the mental challenge of the game play needs to correctly balance with the player's game skill, while at the same time the workout intensity also needs to be correctly balanced with the physical capacity of the subject.

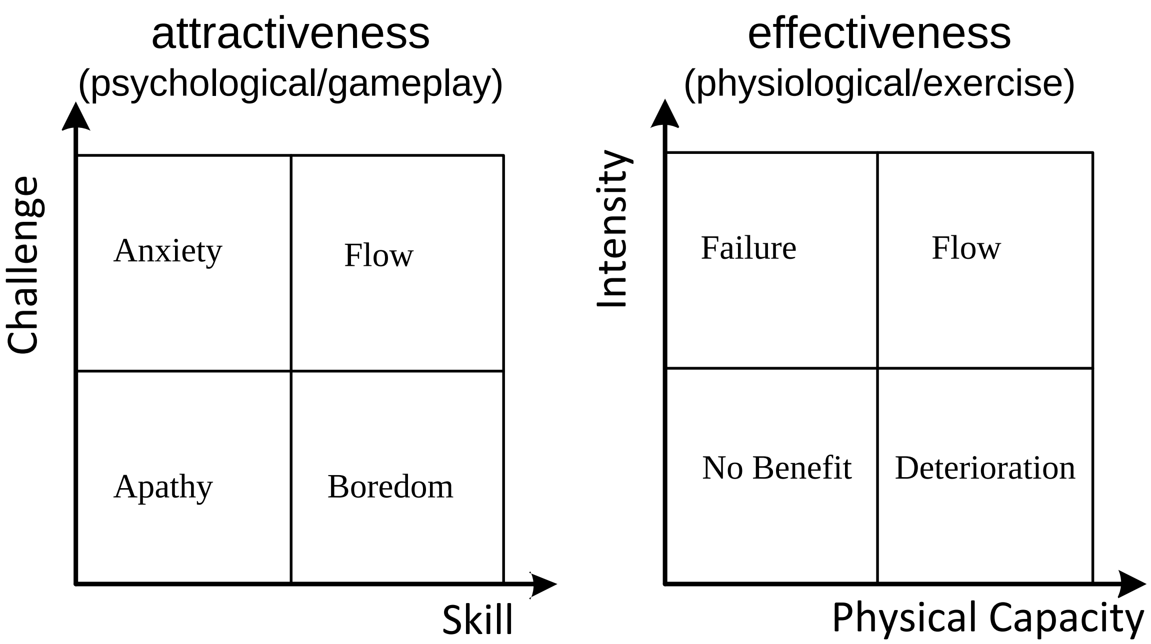

Figure 80 The Dual Flow Model for exergames. Challenge and skill need to be matched as well as intensity with physical capacity.

8.3 System Design for Dual Flow Model Exergame

As part of our research we designed and build an exergame system based on the Dual Flow Model. In order to do this, we designed and developed a high level conceptual software design for the building of exergames, based on the Dual Flow Model. Figure 81 shows the four key components which are required for the development of a Dual Flow Model based exergame system.

1. User Management Module
2. Exergame Control Logic Model
3. Game Play engine

4. Exergame Control Adaptor

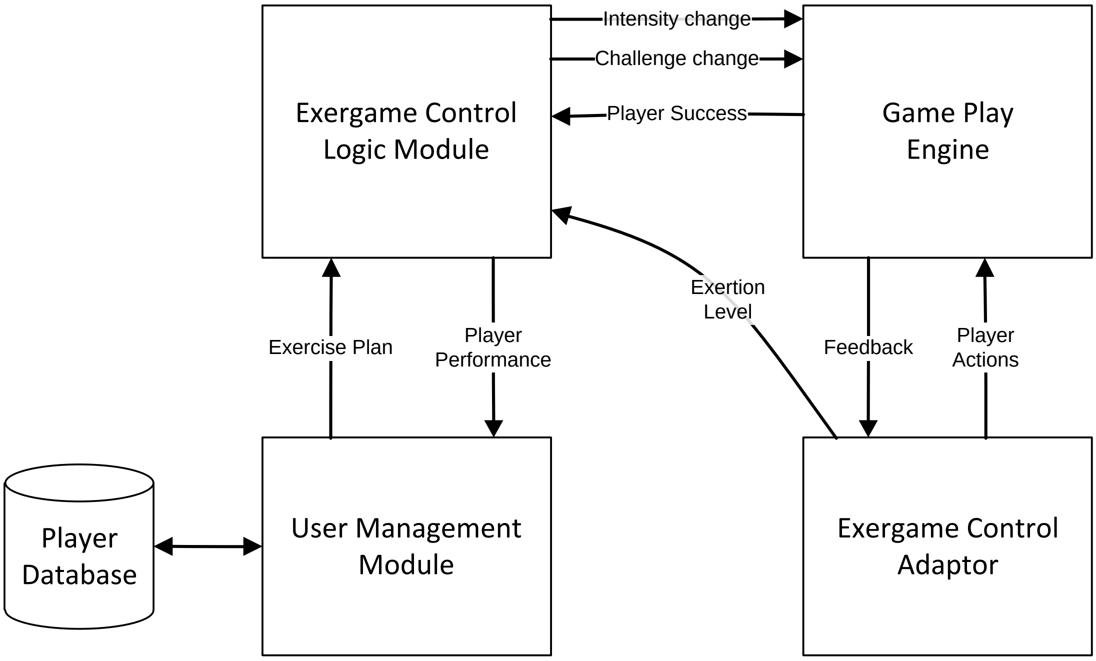

Figure 81 High level exergame system design showing the crucial components of an exergame system based on the Dual Flow Model.

The separation of the four modules gives an exergame system good flexibility and the ability to be extended. This model provides a good starting point for the build and development of any exergame system. It forces the developers to think about and consider the two key points of an exergame system, the exercise side and the game play side.

8.4 Exergame System Build

For this study we designed, developed and built a fully-fledged exergame system. The system was based on a Cat Eye Gamebike. The game bike initially comes as a direct replacement for the standard PS2 controller, containing its own exercise management computer and heart rate monitoring system. The bike was modified to allow a standard PC to be used to provided control of the resistance and perform monitoring of the user heart rate. A software application was built to allow the reading of the heart rate data from the exercise bike and provide the ability for applications to control the resistance settings on the bike.

The Microsoft XNA game development platform was used to build a game which could be used with the Cat Eye Gamebike. The XNA system is designed to use an X-Box game controller. Direct-X processing and control systems were implemented to allow the use of a standard PC Joystick as represented by the Gamebike. Processing software was written to support the conversion of the game bikes repeated button presses representation of cycling into a useful RPM value.

To work alongside the XNA game, Microsoft C# was used to implement a user management and exercise planning module. A game control module was built for the exergame system. This implemented the core game challenge and exercise intensity control systems needed by the Dual Flow Model.

8.5 Virtual Body

Early in the development of our exergame system, the difficulties involved in the testing of exergames were identified. As a means to overcome these difficulties, a simulation of heart rate response to exercise was required. Using this simulation, a system where an exergame could be played with a less strenuous interface, but with appropriate physiological data being generated at the same time, could be built. This would be a means to dramatically alleviate some of the problems involved in the development of an exergame.

There was no existing appropriate model for the simulation of heart rate responses in the context of an exergame. In this thesis, we designed and developed a model for the simulation of heart rate responses. We called this model the Virtual Body. The Virtual Body was verified against the trial data and proved to be quite accurate.

Our implementation of the Virtual Body Simulation package required three key pieces of development work.

1. A means to play a game using a standard joystick controller, while simultaneously reading the game joystick motions and converting them to exertion measurements, which can then be used to generate physiological data.
2. A mechanism to convert joystick motions of one type, as appropriate for hand held play, into other joystick inputs, those appropriately representing the inputs produced by the physically demanding exergame controller.
3. A means of generating appropriate physiological responses from physical exertion data.

8.6 The Trial

By selectively turning on or off different parts of the Dual Flow Model, the exergame system that we developed was designed to work in four different modes:

- Static mode (Mode S) – Statically set workout intensity with linearly increasing game challenge.
- Intensity controlled (Mode I) – Dynamically controlled workout intensity with linearly increasing game challenge.

- Challenge controlled (Mode C) – Statically set workout intensity with dynamically controlled game challenge.
- Full control (Mode F) – Dynamically controlled workout intensity with dynamically controlled game challenge.

The exergame system setup could also be run in a mode where there was no game involved and the subject only had to maintain the correct RPM levels. The different modes could then be used to test the different components of the Dual Flow Model.

21 subjects undertook 5 different sessions using the exergame system over a two week period. The first session was an introductory session where the system was used in the non-game mode. In the remaining sessions, the exergame was used in each of the different game modes. Extensive game data and questionnaire information was collected during the trial, which was then used to determine what the trial tells us about the Dual Flow Model.

8.7 Trial Data Analysis

The exergame had two separate control mechanism based on each of the Dual Flow Model factors of effectiveness and attractiveness. The data collected during the trial was analysed to see the influence of these control mechanisms within our exergame.

8.7.1 Effectiveness

The analysis indicated that the control of workout intensity through some means is critical. The mechanism used in the study proved quite successful in the control of the workout intensity through the control of subject heart rate. On the effectiveness side of the equation, the developed exergame system showed that measurement and control of the exercise intensity was important to improve in effectiveness of an exergame system.

8.7.2 Attractiveness

On the attractiveness side of the equation, the data indicated that our challenge control mechanism failed to have significant impact on the player engagement with our exergame system. As we previously saw in the literature, dynamic difficulty adjustment is difficult to get correct in video games which are not physically interactive. In an exergame where we have the extra component of exercise, getting DDA correct is even harder.

Our DDA implementation was a plausible attempt to manage the challenge level in our exergame system. Unfortunately during the actual trial it did not satisfactorily adjust the challenge level for the players. It did not result in improved engagement, and perhaps marginally reduce player engagement. Further work in the area of DDA control and how it relates to attractiveness is required.

8.7.3 Dual Flow Model

In this study we have proposed a Dual Flow Model for exergames, and tested the model by examining the three research aims:

That the control of challenge levels to match skills provides improved motivation.

The careful control of exercise intensity levels within an exergaming system improves motivation.

The application of control, to both the motivation and the exercise components of an exergaming system provides better motivation than control of only one of the factors."

In examining these concepts we saw the importance of managing and controlling the workout intensity in an exergame, and in reality any form of exercise. This idea forms one half of the Dual Flow Model. In the development of the Dual Flow Model, from previous works we realised the importance of considering the motivational aspects of an exergame. Consideration of the game play side of an exergame is important. The premise we put forward as the second half of the Dual Flow Model that challenge and skills should be matched, may be a little simplistic. We failed to show this facet of the Dual Flow Model in our study, and while it is possible that our implementation of this was the main cause of its failure, it is quite likely that the focus on the matching of challenge and skills is on its own insufficient. The attractiveness side of the Dual Flow Model needs to be expanded in order to better capture additional factors which will help to best motivate and engage an exergame user, for example, social interaction.

We can conclude that while in this study we were not able to conclusively demonstrate the Dual Flow Model, it is still of great benefit. The two key segments of the model, attractiveness and effectiveness are most likely valid. Our control of the intensity in an exergame proved successful. Additionally, the attainment of the flow state as a motivator, as detailed by Csikszentmihalyi (1975), has been widely accepted as a motivating factor. Exactly how we reach the flow state in an exergame needs to be investigated further, with different proposals put forward and tested.

The Dual Flow Model makes a good starting point to drive further research on the development of successful exergame systems. Hopefully the model can act as a catalyst to promote the desperately needed further research into the field of exergaming.

8.8 Future Work

During this study we looked at 21 subjects who undertook 5 workout sessions. On the first session, the players worked out using the exergame system, but without a game. For the four remaining sessions a different variant of the exergame was played.

What we saw is that there are many factors beyond our control which effect exercise. Additionally exercise affects different people in different ways. What would be useful is to have a deeper understanding of the subjects involved in the study. A study following subjects over a longer period, obtaining a more detailed picture of their physiological responses to exercise, we could reduce the possible impact of external factors. This would provide better data on the motivational aspect of exergaming.

When it came to the implementation of the dynamic difficulty adjustment in our exergame, the depth of the exergame posed some constraints. The game developed for use in this study, has proven to be a good vehicle to perform our exergame research; the basic game structure is solid and works reasonably well. However, now that the game has been given a serious workout, we have identified some places where the game needs further work and a number of avenues where the game could be enhanced and extended.

There were some issues with the physical layout of the exergame setup. The fire button on the right hand side was particularly uncomfortable for a couple of left handed players and generally not found to be comfortable for extended playing. Additionally varying of the resistance setting could have been better utilised rather than relying solely on cadence as a control of intensity. Particularly during the warm-up and cool-down periods, the cadence levels sometimes dropped down to a level which players found awkward to maintain.

The scoring system within the game was not explained clearly to the players and did not give bonuses for the completion of phrases. The scoring within the system could have been used to greater value in promoting social and competitive play. The completion of phrases was sometimes difficult because the required letters sometime did not appear for a long time.

By extending our exergame system, we will be able to provide greater depth and flexibility for the difficulty and challenge management in the game. As we pointed out before, adaptive difficulty is difficult to get right. After our initial efforts, we now have a greater understanding of the process, and will potentially be able to produce a higher quality DDA system.

One of the items noticed during this study, which was not covered by the Dual Flow Model, is the social context of exercise. Some of the subjects in the study did not know anyone else in the study, while some subjects always attended sessions with a friend. Some of the subject had an interest in how other subjects performed, and the social context may have caused some degree of competitive influence. The social context of exergames could have an impact on the motivational influences of an exergame in generating the desire to participate, and thus exercise. Further research is warranted in this area.

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Appendix A. Session Questionnaire

Game Workout Questionnaire

The following questionnaire is designed to help evaluate the software. Please answer all questions to the best of your ability. If you are unsure about anything please ask. If there are any question which you can't answer or do not wish to, feel free to leave the answer blank

Participant Details

Identification Number ____________ Date ________________

Select the best answer

	Too Easy		About Right		Too Strenuous
1) In terms of exercise how strenuous do you feel today's workout was on a scale of 1 to 5?	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
	Too Short		About Right		Too Long
2) What do you think about the appropriateness of the length of time the workout took.	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
	Not at all		Somewhat		Very
3) How exhausted do you feel?	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
	No	Not Really		Some what	Yes
4) Do you feel that you got a good workout?	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
	Too Easy		About Right		Too Hard
5) How difficult did you feel today's video game was on a scale of 1 to 5?	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
	Un-interesting				Interesting
6) On a scale of 1 to 5 how interesting did you find today's game?	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐

7) How quick did the time pass during the exercise period?

Slower than normal		Normal		Faster than normal
1	2	3	4	5
☐	☐	☐	☐	☐

8) During the workout, roughly how much of the time were you focused on the time remaining?

______ %

9) How difficult was it to focus on the game?

Not at all		Somewhat		Extremely difficult
1	2	3	4	5
☐	☐	☐	☐	☐

10) How difficult was it to control the game using the exercise bike?

Not at all		Somewhat		Extremely difficult
1	2	3	4	5
☐	☐	☐	☐	☐

11) During the Game my main focus was :

- ☐ Hitting the markers
- ☐ Collecting letters/completing phrases
- ☐ Shooting Aliens
- ☐ Score
- ☐ Time remaining
- ☐ Maintaining the correct RPM
- ☐ Other

____

12)As a form of exercise I rate this workout as a ___ out of 10

Any additional comments :

Appendix B. Final Session Additional Questions

Final Workout Questionnaire

The following questionnaire is designed to help evaluate the software. Please answer all questions to the best of your ability. If you are unsure about anything please ask. If there are any question which you can't answer or do not wish to, feel free to leave the answer blank

Participant Details

Identification Number ____________ Date ________________

1)Did you notice any particular differences between the four games sessions? ☐ Yes ☐ No

Describe any key differences noticed.

2)Did you find any of the game sessions to be overall **more** strenuous in terms of exercise as a workout? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ______________________

3)In any of the game sessions, did you find the game to be **more** challenging than other sessions? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ______________________

4)In any of the game sessions, did you find the helicopter particularly difficult to control? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ______________________

5)Did you find any of the game sessions to be overall **less** strenuous in terms of exercise as a workout? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ______________________

6)In any of the game sessions, did you find the game to be **less** challenging? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ____________________

7)In any of the game sessions, did you find the helicopter particularly easier to control? ☐ Yes ☐ No

Are you able to recall which, if any sessions? (only answer if reasonably sure which session) ____________________

	With Game was Better		The Same		**Without** Game was Better
	1	2	3	4	5
8)In terms of exercise how do you rate exercising with the game compared to without?	☐	☐	☐	☐	☐

	With Game was Better		The Same		**Without** Game was Better
	1	2	3	4	5
9)In terms of enjoyment how do you rate exercising with the game compared to without?	☐	☐	☐	☐	☐

	With Game was Better		The Same		**Without** Game was Better
	1	2	3	4	5
10)Overall and in general how do you rate exercising with the game compared to without?	☐	☐	☐	☐	☐

11)Any general comments about the trial, the exercise systems or the games:

Thank you for your participation in this study.

Appendix C. Fuzzy Logic Sets and Rules

Variable:	TimeSinceAlienCrashes	
Range:	0 - ∞	
Values:		Shape	Coordinates (x,y)
	short	Trapezoid	(0,0) (0,1) (2,1) (4,0)
	medium	Triangular	(2,0) (4,1), (6,0)
	long	Trapezoid	(4,0) (7,1) (∞,1) (∞,0)

Variable:	TimeSinceAlienShot		
Range:	0 - ∞		
Values:		Shape	Coordinates (x,y)
	short	Trapezoid	(0,0) (0,1) (2,1) (4,0)
	medium	Triangular	(2,0) (4,1), (6,0)
	long	Trapezoid	(4,0) (7,1) (∞,1) (∞,0)

Variable:	PercentMarkersCollected		
Range:	0 – 100		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (45,1) (60,0)
	low	Triangular	(50,0) (65,1) (80,0)
	medium	Triangular	(75,0) (80,1) (85,0)
	high	Triangular	(80,0) (90,1) (95,0)
	very high	Trapezoid	(80,0) (95,1) (100,1) (100,0)

Variable:	PercentAliensHit		
Range:	0 – 100		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (25,1) (45,0)
	low	Triangular	(20,0) (45,1) (60,0)
	medium	Triangular	(45,0) (60,1) (75,0)
	high	Triangular	(60,0) (75,1) (90,0)
	very high	Trapezoid	(75,0) (90,1) (100,1) (100,0)

Variable:	**HitMissRatio**		
Range:	0 – 100		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (25,1) (45,0)
	low	Triangular	(20,0) (45,1) (60,0)
	medium	Triangular	(45,0) (60,1) (75,0)
	high	Triangular	(60,0) (75,1) (90,0)
	very high	Trapezoid	(75,0) (90,1) (100,1) (100,0)

Variable:	**RowSets**		
Range:	0 – 200		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (10,1) (45,0)
	low	Triangular	(20,0) (45,1) (60,0)
	medium	Triangular	(80,0) (100,1) (120,0)
	high	Triangular	(110,0) (140,1) (170,0)
	very high	Trapezoid	(150,0) (170,1) (200,1) (200,0)

Variable:	**MatchedSets**		
Range:	0 – 200		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (10,1) (45,0)
	low	Triangular	(20,0) (45,1) (60,0)
	medium	Triangular	(80,0) (100,1) (120,0)
	high	Triangular	(110,0) (140,1) (170,0)
	very high	Trapezoid	(150,0) (170,1) (200,1) (200,0)

Variable:	**LettersMatched**		
Range:	0 - ∞		
Values:		Shape	Coordinates (x,y)
	veryLow	Trapezoid	(0,0) (0,1) (10,1) (45,0)
	low	Triangular	(20,0) (45,1) (60,0)
	medium	Triangular	(80,0) (100,1) (120,0)
	high	Triangular	(110,0) (140,1) (170,0)
	very high	Trapezoid	(150,0) (170,1) (∞,1) (∞,0)

Outputs

Variable:	gameChallengeChange		
Range:	-30 to 30		
Values:		Shape	Coordinates (x,y)
	VeryLargeReduction	Trapezoid	(-5,0) (-5,1) (-4,1) (-3,0)
	LargeReduction	Triangular	(-4,0) (-3,1) (-2,0)
	StandardReduction	Triangular	(-3,0) (-2,1) (-1,0)
	Reduction	Trapezoid	(-5,0) (-5,1) (0,1) (0,0)
	SmallReduction	Triangular	(150,0) (170,1) (∞,1)
	NoChange	Triangular	(-5,0) (0,1) (5,0)
	SmallIncrease	Triangular	(0,0) (5,1) (10,0)
	StandardIncrease	Triangular	(5,0) (10,1) (15,0)
	Increase	Trapezoid	(0,0) (0,1) (15,1) (15,0)
	LargeIncrease	Triangular	(8,0) (10,1) (13,0)
	VeryLargeIncrease	Trapezoid	(10,0) (14,1) (15,0) (15,0)

Rules

if PercentMarkersCollected is veryLow then GameChallengeChange is VeryLargeReduction

if PercentMarkersCollected is low then GameChallengeChange is LargeReduction

if PercentMarkersCollected is medium then GameChallengeChange is NoChange

if PercentMarkersCollected is high then GameChallengeChange is standardIncrease

if PercentMarkersCollected is veryHigh then GameChallengeChange is LargeIncrease

if HitMissRatio is veryLow then GameChallengeChange is SmallReduction

if HitMissRatio is low then GameChallengeChange is SmallReduction

if HitMissRatio is medium then GameChallengeChange is NoChange

if HitMissRatio is high then GameChallengeChange is SmallIncrease

if HitMissRatio is veryHigh then GameChallengeChange is SmallIncrease

if LettersMatched is veryLow then GameChallengeChange is SmallReduction

if LettersMatched is low then GameChallengeChange is SmallReduction

if LettersMatched is medium then GameChallengeChange is NoChange

if LettersMatched is high then GameChallengeChange is SmallIncrease if LettersMatched is veryHigh then GameChallengeChange is SmallIncrease

if PercentAliensHit is veryLow then GameChallengeChange is SmallReduction
if PercentAliensHit is low then GameChallengeChange is SmallReduction
if PercentAliensHit is medium then GameChallengeChange is NoChange
if PercentAliensHit is high then GameChallengeChange is SmallIncrease
if PercentAliensHit is veryHigh then GameChallengeChange is SmallIncrease

Appendix D. Subject Session Data

subject	Date	ControlCode	avgBPM	avgRPM	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1076	7-Oct	I	135.09	62.84	1	2	2	2	2	3	5	5	1	2	Hitting the markers, Collecting letters	7
1076	12-Oct	C	148.69	69.5	3	3	2	2	2	3	5	40	1	2	Hitting the markers, Collecting letters	6
1076	14-Oct	S	150.78	69.45	3	2	2	3	2	3	4	20	2	2	Hitting the markers, Collecting letters, Shooting Aliens	7
1076	15-Oct	F	134.45	58.89	1	2	1	2	1	2	4	30	2	2	Hitting the markers, Collecting letters, Shooting Aliens	5
1134	14-Oct	C	137.25	70.75	3	3	3	3	1	2	3	5	1	2	, Collecting letters	4
1134	15-Oct	F	142.04	64.44	4	3	4	4	2	2	3	4	2	2	, Collecting letters	3
1134	22-Oct	I	141.93	57.49	3	3	2	3	2	3	3	3	2	2	, Collecting letters	4
1134	27-Oct	S	129.83	70.79	3	3	3	4	2	2	4	2	2	3	, Collecting letters	4
1377	13-Oct	I	144.67	67.4	3	2	2	3	3	4	5	1	1	4	Hitting the markers, Collecting letters	6
1377	14-Oct	F	140.77	65.4	3	3	2	3	4	3	4	2	1	4	Hitting the markers, Score	5
1377	15-Oct	C	142.2	68.99	3	3	2	4	3	4	4	2	1	3	Hitting the markers, Collecting letters, Score	6

1377	16-Oct	S	160.51	71.76	4	3	3	5	3	4	5	0	1	3	Hitting the markers, Shooting Aliens	6
1464	19-Oct	I	130.88	61.58	2	3	2	3	3	3	3	0	1	2	, Collecting letters	9
1464	23-Oct	C	135.15	69.55	3	3	3	5	3	3	4	10	2	3	Hitting the markers	8
1464	26-Oct	F	131.7	66.21	3	3	4	4	3	3	4	20	2	1	Hitting the markers	8
1464	28-Oct	S	124.76	66.12	3	3	3	5	3	4	5	5	2	1	Hitting the markers	8
2457	26-Oct	C	125.77	67.74	3	3	3	4	3	3	5	50	2	1	, Collecting letters	5
2457	27-Oct	I	133.3	64.05	3	3	3	3	3	4	5	40	2	2	, Collecting letters	6
2457	28-Oct	S	117.26	67.28	3	3	3	3	3	4	5	50	2	2	Hitting the markers	6
2457	30-Oct	F	133.66	65.26	3	3	3	3	3	3	4	50	2	2	Hitting the markers	5
2565	20-Oct	C	129.09	71.71	3	3	3	4	3	5	4	10	3	3	Hitting the markers, Collecting letters, Shooting Aliens	8
2565	21-Oct	I	134.74	65.55	4	3	3	4	3	4	5	10	2	3	, Collecting letters, Shooting Aliens	10
2565	22-Oct	S	122.92	69.13	3	2	3	4	3	4	5	10	1	1	Hitting the markers, Collecting letters, Shooting Aliens	9
2565	23-Oct	F	134.3	72.02	4	3	4	5	3	4	4	15	2	3	Hitting the markers, Shooting Aliens, Maintining correct rpm	9

2810	13-Oct	F	135.29	60.13	3	3	2	5	3	4	5	5	1	4		8
2810	16-Oct	C	127.99	60.6	3	3	2	4	4	5	5	2	2	3	Hitting the markers	8
2810	20-Oct	S	133.96	58.66	3	2	2	3	2	5	5	0	1	2	Hitting the markers, Collecting letters, Shooting Aliens	10
2810	22-Oct	I	137.3	55.88	3	3	2	3	4	4	5	0	1	4	Hitting the markers, Shooting Aliens	10
2830	13-Oct	S	148.45	70.06	3	3	3	5	2	4	5	10	2	3	, Collecting letters	8
2830	14-Oct	F	133.98	65.78	2	3	2	4	3	3	4	5	2	2	, Collecting letters	8
2830	19-Oct	I	134.71	65.29	3	4	3	4	3	2	4	1	2	2	Hitting the markers	8
2830	20-Oct	C	147.42	69.61	3	3	3	4	2	1	4	0	2	2	, Shooting Aliens	7
2866	23-Oct	S	127.69	66.99	2	3	1	2	3	2	4	30	2	2	Hitting the markers	4
2866	26-Oct	F	128.29	60.39	2	3	1	2	3	3	4	25	2	2	, Score	4
2866	28-Oct	I	126.09	59.43	2	3	1	3	3	2	2	35	3	2	, Time Remaining	3
2866	29-Oct	C	122.33	66.87	1	3	1	3	2	3	4	20	2	1	Hitting the markers	4
4102	13-Oct	S	143.18	71.11	2	3	1	2	2	3	5	5	2	4	, Collecting letters	5
4102	14-Oct	I	142.66	70.19	4	3	2	2	3	2	4	15	2	4	, Collecting letters	5
4102	19-	C	137.21	69.64	2	3	2	3	3	2	4	20	3	4	, Collecting letters	6

	Oct															
4102	20-Oct	F	142.25	69.93	3	2	2	4	2	2	2	25	2	3	Hitting the markers	5
4228	21-Oct	I	139.73	66.07	3	2	2	4	4	4	4	2	2	3	, Collecting letters, Shooting Aliens	8
4228	23-Oct	S	139.25	69.78	3	3	1	4	2	4	4	2	1	2	, other	8.5
4228	26-Oct	F	139.8	71.24	3	3	2	4	4	4	3	3	1	4	Hitting the markers, Collecting letters, Shooting Aliens	8
4228	28-Oct	C	133.63	67.96	2	3	2	4	2	4	4	1	1	2	Hitting the markers, Collecting letters, Shooting Aliens, Score	8
4386	20-Oct	F	145.47	52.82	2	3	3	4	4	5	5	0	1	3	, Collecting letters	7
4386	22-Oct	I	145.82	57.03	4	3	4	5	3	4	4	30	3	3	, Collecting letters, Score	8
4386	26-Oct	S	148.2	64.77	4	3	4	5	3	4	5	30	2	2	, Collecting letters, Score	9
4386	29-Oct	C	149.55	65.8	3	3	4	5	3	5	5	15	2	2	, Collecting letters, Score	9
4446	22-Oct	C	137.53	69.04	3	3	3	5	3	2	5	5	2	3	Hitting the markers	8
4446	23-Oct	F	133.36	64.44	3	2	2	4	3	4	5	10	2	2	Hitting the markers, Shooting Aliens	6
4446	28-Oct	S	142.06	70.28	3	3	4	4	4	4	2	25	3	3	Hitting the markers, Shooting Aliens, Time Remaining	7
4446	29-Oct	I	132.92	68.74	5	3	3	2	4	3	1	50	3	5	Hitting the markers, Time Remaining	5

4496	15-Oct	F	130.42	76.68	3	3	3	5	3	4	4	60	NULL	2	, Collecting letters, Shooting Aliens	8
4496	19-Oct	I	131.66	65.66	4	3	3	5	4	4	5	50	1	1	, Collecting letters	9
4496	21-Oct	C	117.15	60.53	3	2	3	5	3	5	4	20	1	NULL	Hitting the markers, Collecting letters	9
4496	22-Oct	S	99.08	53.13	4	3	4	5	3	4	5	20	2	1	, Collecting letters, Shooting Aliens	8
4501	20-Oct	S	117.79	67.8	3	4	3	4	3	3	4	5	2	1	Hitting the markers, Shooting Aliens	6
4501	21-Oct	F	118.79	58.93	3	3	2	2	3	2	5	5	3	3	Hitting the markers, Shooting Aliens	5
4501	22-Oct	C	120.96	68.76	4	3	4	4	3	3	5	1	2	3	Hitting the markers, Shooting Aliens	7
4501	23-Oct	I	117.9	66.64	3	3	4	4	4	3	4	5	3	4	Hitting the markers, Shooting Aliens	7
4567	22-Oct	I	140.67	71.69	3	3	3	5	3	3	5	1	2	2	, Collecting letters	7
4567	26-Oct	S	143.79	69.56	3	3	3	5	4	4	5	5	1	3	, Collecting letters	7
4567	27-Oct	C	139.5	68.53	3	3	4	5	3	3	4	5	2	3	, Collecting letters	7
4567	29-Oct	F	139.98	92.1	3	3	3	4	3	3	5	5	2	3	, Collecting letters	7
4623	13-Oct	I	135.6	64.12	2	3	2	3	3	4	4	20	1	2	, Collecting letters	8
4623	14-Oct	S	146.41	70.9	3	3	3	3	2	2	4	10	2	3	, Collecting letters	7
4623	15-Oct	F	137.07	67.91	2	3	2	2	3	2	4	10	1	3	, Collecting letters, Shooting Aliens	7

4623	21-Oct	C	130.05	68.88	2	3	2	2	2	1	4	5	1	1	, Collecting letters, Shooting Aliens	7
4771	13-Oct	C	141.23	98.38	3	3	3	4	4	3	4	10	2	3	Hitting the markers, Collecting letters, other	7
4771	14-Oct	S	141.95	69.39	3	3	3	5	2	2	3	40	2	2	Hitting the markers, Shooting Aliens, other	7
4771	20-Oct	I	141.7	69.1	3	3	4	4	3	2	3	40	2	2	Hitting the markers, Collecting letters, Score, other	7
4771	21-Oct	F	141.25	64.55	4	3	3	5	3	2	3	30	2	2	Hitting the markers	7
4881	7-Oct	F	139.4	70.77	1	1	1	3	3	4	5	2	1	1	Hitting the markers, Collecting letters	6
4881	12-Oct	S	125.62	69.49	1	2	1	3	2	2	5	1	2	1	, Collecting letters	5
4881	14-Oct	I	139.75	74.68	3	1	1	4	3	2	5	0	3	3	, Collecting letters	6
4881	15-Oct	C	134.22	70.57	1	1	2	2	3	2	4	0	3	2	, Collecting letters	6
4882	13-Oct	F	136.6	65.66	3	3	2	4	3	3	5	15	2	3	Hitting the markers, Collecting letters, Shooting Aliens	7
4882	14-Oct	S	134.32	67.08	3	3	3	5	3	3	5	5	3	3	Hitting the markers, Collecting letters, Shooting Aliens	7
4882	15-Oct	C	130.46	66.85	4	3	4	5	3	2	2	30	3	4	Hitting the markers, Collecting letters, Shooting Aliens, Time Remaining	7

4882	16-Oct	I	136.05	64.77	4	3	4	5	4	2	2	30	4	3	Hitting the markers, Collecting letters, Shooting Aliens, Time Remaining	7
4982	27-Oct	I	148.19	59.46	3	3	2	4	3	4	4	20	2	2	, Collecting letters, Score	8
4982	28-Oct	C	137.68	69.91	3	3	2	4	3	4	4	10	1	2	Hitting the markers, Collecting letters, Shooting Aliens, Score	8
4982	29-Oct	S	141.32	71.03	2	3	2	4	3	4	4	10	2	2	Hitting the markers, Collecting letters	8
4982	30-Oct	F	148.84	64.32	4	3	3	4	3	4	3	10	2	3	Hitting the markers, Score	8

Appendix E. Subject Data

Subject	DOB	Gender	Height (cm)	Weight (kg)	Exercise (Hr per week)	Alcohol (drinks per week)	Gaming	Resting HR
1076	1/01/1975	F	175	74	4	4	Several times a month	70.1
1134	20/10/1988	M	177	63	0	2	Several times a week	73.6
1377	17/12/1973	M	175	80	0	15	Most days	83.0
1464	7/09/1968	F	169	94	5	2	Several times a week	84.3
2457	15/04/1977	F	180	72	6	0	Never	79.0
2565	20/07/1972	F	157	94	0	1	Very occasionally	97.8
2810	10/04/1972	F	163	65	0	4	Never	75.7
2830	19/12/1971	M	175	97	3	4	Several times a week	69.9
2866	5/06/1985	F			7	2	Never	80.9
4102	24/10/1974	F	156	61	5.5	2	Very occasionally	85.0
4228	27/11/1973	M	180	86	0.75	2	Several times a week	91.0
4386	25/05/1980	F	164	61	10	10	Weekly	89.8
4446	26/09/1984	M	175	81	10	2	Several times a month	54.8

4496	30/12/1973	F	168	75	0	2	Never	61.0
4501	16/09/1971	M	185	138	0	0	Never	70.0
4567	1/07/1975	F	168	83	4	6	Very occasionally	83.3
4623	8/01/1982	M	175	75	4	4	Weekly	63.7
4771	8/04/1974	F	167	58	13	0	Several times a week	85.0
4881	4/06/1973	F	178	73	4	4	Never	81.4
4882	28/03/1971	F	162	67	7	5	Never	77.5
4982	20/03/1983	M	196	64	6	0	Very occasionally	95.9

Appendix F. Game Data Variables Logged

The exergame system developed in the study logs the following variable on a second by second basis.

- Time in seconds since start.
- Current player RPM
- Current player heart rate
- Desired heart rate
- Internal desired RPM calculation value.
- The RPM where the helicopter would be centred.
- Number of aliens shot
- Number of aliens which escaped

The system logs the following variables at the end of each level within the game.

- Average time between aliens crashes.
- Average time between aliens shot.
- Percentage coins collected.
- Percentage aliens shot.
- Hit miss ratio.
- Letters matched.
- Game challenge change.
- Row seed.
- Player Level.

Appendix G. Final Session Data

Subject	Question	Session Selection
1076	More strenuous Sessions	C
1076	More challenging Sessions	C
1076	Less strenuous sessions	F
1076	less challenging sessions	F
1377	More strenuous Sessions	I
1464	More strenuous Sessions	C
1464	More challenging Sessions	C
1464	Less strenuous sessions	S
1464	less challenging sessions	S
1464	easier to control sessions	S
2565	More strenuous Sessions	F
2565	Less strenuous sessions	S
2810	More challenging Sessions	I
2810	Difficult to control sessions	I
2810	Less strenuous sessions	S
2810	easier to control sessions	S

2830	More strenuous Sessions	F
2830	Less strenuous sessions	S
2830	easier to control sessions	C
2866	More challenging Sessions	S
4102	More strenuous Sessions	S
4102	Less strenuous sessions	CF
4102	less challenging sessions	CF
4102	easier to control sessions	F
4228	More strenuous Sessions	F
4228	Difficult to control sessions	F
4386	More strenuous Sessions	I
4386	More challenging Sessions	F
4386	Difficult to control sessions	F
4386	easier to control sessions	C
4446	Difficult to control sessions	SI
4446	easier to control sessions	C
4496	More strenuous Sessions	F
4496	More challenging Sessions	F
4496	Less strenuous sessions	CS

4496	less challenging sessions	CS
4567	More strenuous Sessions	F
4623	More strenuous Sessions	F
4623	More challenging Sessions	F
4623	Less strenuous sessions	S
4771	More strenuous Sessions	I
4771	More challenging Sessions	F
4771	Less strenuous sessions	F
4771	easier to control sessions	F
4881	More strenuous Sessions	I
4881	Difficult to control sessions	F
4881	Less strenuous sessions	FSC
4882	More strenuous Sessions	I
4882	More challenging Sessions	CI
4882	Difficult to control sessions	I
4982	More strenuous Sessions	F
4982	More challenging Sessions	C
4982	Difficult to control sessions	F
4982	Less strenuous sessions	S

4982	less challenging sessions	S

Appendix H. Related Publications

Considerations for the Design of Exergames

Sinclair, J., Hingston, P., and Masek, M.

ACM Special Interest Group on Computer Graphics and Interactive Techniques, Perth Western Australia December 2007.

Abstract

Exergaming is the use of video games in an exercise activity. In this paper we consider game design for successful exergames. To do this, we review the history of exergaming and the current state of research in this field. We find that there exists some research aimed at evaluating the physical and health characteristics of exergames, but research on how to design exercise games is still in the early stages. From an analysis of this information, and drawing on established principles from sports science for the prescription of exercise programs, we then attempt to identify success factors to guide designers of exergaming systems.

Using a Virtual Body to Aid in Exergaming System Development

Sinclair, J., Hingston, P., Masek, M., & Nosaka, K.

IEEE Computer Graphics and Applications, March/April (2009), 39-48

Abstract

A framework for simulating physiological responses to exercise lets exergame developers more efficiently test their games during development. An example implementation combines software that simulates heart rate responses with a custom hardware setup. Simulated heart rate responses closely match the real physiological responses, demonstrating the approach's validity and potential.

Exergame Development Using the Dual Flow Model

Sinclair, J., Hingston, P., and Masek, M.

Australasian Conference on Interactive Entertainment, Sydney December 2009

Abstract

Exergaming, the merger of exercise and video games, tries to use the engaging experience of playing a video game to help people achieve their exercise requirements. To guide the design of such games the Dual Flow Model, an extension of the theory of flow to both mental and physical experience, has been proposed. This paper presents the development of an exergame system designed to demonstrate the validity of the Dual Flow Model, along with initial results from a pilot trial. The results show that such a game system can be used to deliver the required exercise across a range of participants.

Testing an Exergame for Effectiveness and Attractiveness

Sinclair, J., Hingston, P., Masek, M., & Nosaka, K

2nd International IEEE Games Innovation Conference (GIC) Hong Kong December 2010

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